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ANSYS Simulation Analysis of Stray Currents on Subway Shield Tunnel

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Abstract

In order to analyze the distribution rule and influence range of subway shield tunnel in different traction currents, a three-dimensional geometrical model and mathematical model of subway shield tunnel stray current field were built, and a finite element model was developed by Ansys. Simulating for homogeneous and stratified soil media were happened in the metro stray current field simulation, through different carry-currents of railway. Simulation show that the potential attenuation is nonlinear from the subway tunnel to the surrounding underground and along far away rail loading current of direction; The carry-current is different, the potential of surrounding media is different, and the greater the current, the greater the maximum potential. Each points stray current in situation of surrounding soil media subway tunnel shield can be analyzed by the three-dimensional finite element model, and provide the basis for the protection range of stray current and the protection at a specific location.

Keywords: *subway shield tunnel, stray current field, homogeneous soil media, stratified soil media, simulation analysis*

1. Introduction

In subway DC traction power systems, the running rails are used as the return path of the train’s current to the supply source. Due to the rails have a poor insulation from the ground, a part of current leaves rails to the ground. These leakage currents are called stray currents. Stray current causes a series of serious problems that electrical corrosion for buried metal structures [1-2]. Seriously affects the normal operation of urban rail transit. Therefore, countries around the world attach great importance to the protection and influence of stray current problem. Presently, the study dirctions are mainly the following aspects: the model of return circuit system at subway; influences and distribution of stray current; the monitoring system of stray current.

The model of return circuit system at subway: W.V.Baeckamnn had established a model of stray current field under the ideal conditions, respectively for variable with traction power current and the resistance of rail and the resistance of track-to-earth [2]. On this basis, a track-to-earth model of stay current with drainage net was established by Mou Longhua and Liu Yan [3-4]. An electric field which can solve underground electric field distribution was established by Ade ogunsola and Pang Yuanbing, thereby, current which leaves buried metal structrues was derived, and ultimately imputed to corrosion quantity as standard which to assess the hazards of stray current [5-7]. Multiple interval calculation program was written by Ardizzon for the model of return circuit system [8].

Influence and distribution of stray current: M.T.Soylemeze simulated the effects of traction voltage of DC1500V and DC750V on rail potential and stray current, and indicated that increasing the voltage level can effectively reduce potential and stray current [9]; C-H.Lee,Kinh D and Zhang Xiaoyu thought that the mainly factor of that is the distance between adjacent traction substation and rail resistance; Mou Longhua studied the effect of overall track bed reinforced strcture on rail potential and stray current. Under DC parameters, it has no effect on rail potential and obital current. But the stray current leakage is mainly composed of steel structure of circulation, reducing the damage to the outside [10-12]. The effects of earthing strategies on rail potential and stray currents in DC transit railway were studied by J.G.Yu, and the features and applications of these were pointed out [13]. B.Y.Ku and Li Wei had shown that

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diode-grounded system may result in high rail potential and stray current of drainage net at the same time, even if, it may reduce stray current corrosion [1, 14].

There is a difference between the results of these models and actual values. The major reason is that these models were established and simulated under the ideal conditions, it can only macroscopically and qualitatively analyze the effects of different factors on stray current. These models cannot be accurately simulated for complex structure of subway tunnel and geological conditions.

Thereby, this paper simulated the actual model of subway tunnel with FEM [15-18]. Because the type of subway tunnel in driving range is shied tunnels, so this paper chose the shied tunnel as simulation model. Under the multifarious conditions of non uniform track-to-earth resistance, soil resistance, rail resistance and in homogeneous soil media and stratified soil media, the simulation was developed by ansys, and the distribution of stray current was analyzed. To further analyze the effects of traction current on stray current field, different rail currents were loaded.

2. Stray Current Field Model in Subway

2.1. Geometrical model

Based on apparatus [19], a three-dimensional model of stray current field computional domain in subway shield tunnel was built according to the actual size. The sectional view of computional domain of subway stray current field, as shown in Figure 1. Figure 1 illustrates that the ground was modeled with a length of 100m, a height of 60m and a width of 1000m cuboid. The top of this tunnel is located at a depth of 10m measured from the road surface. Figure 2 shows the structure of subway shield tunnel and railway. the tunnel has a circular cross section with an internal diameter of 2.6m, and a outside diameter of 2.75m. There are 0.05m between them. To simplify calculation, two rails were equivaled to two cuboids , which are separated from 1.435m, with a length of 0.15m, a height of 0.176m and a width of 1000m.

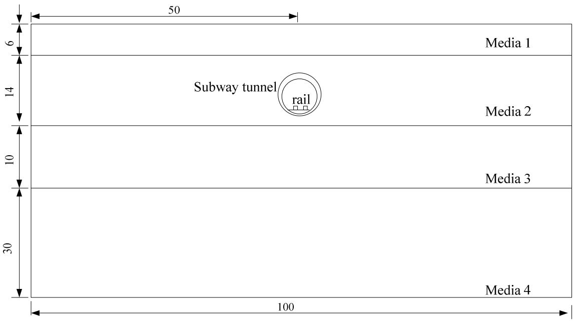

Figure 1. Sectional View of Computional Domain of Subway Stray Current Field

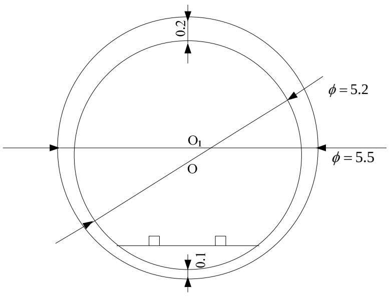

Figure 2. Structure of Subway Shield Tunnel and Railway

2.2 Mathematical model

Take any closed surface $\vec{s}$ from a space conductor whose volume current density is $\vec{j}$, according to the law of conservation of charge, the electric quantity that flows out of the closed surface per unit time, must be equal to the amount of charge that volume V which is surrounded by the closed surface S decreased in unit time, then the current continuity equation is gived as formula (1):

$$\oint_s \vec{j}d\vec{s} = -\frac{\partial q}{\partial t} = -\frac{\partial}{\partial t}\int_v \rho dv \qquad (1)$$

The current continuity equation in integral form is calcualted from the following Equation (2):

$$\oint_s \vec{j}d\vec{s} = -\int_v \frac{\partial \rho}{\partial t}dv \qquad (2)$$

Where ρ means the charge density (C/m3).

The current continuity equation in differential form is gived as formula (3):

$$\nabla \cdot \vec{j} = -\frac{\partial \rho}{\partial t} \qquad (3)$$

In a steady electric field, electric field and charge do not change with time, under a steady electric field, the current continuity equation in integral form is calcualted from the following Equation (4):

$$\oint_s \vec{j}\,d\vec{s} = 0 \qquad (4)$$

the current continuity equation in differential form is gived as formula (5):

$$\nabla \cdot \vec{j} = 0 \qquad (5)$$

According to Ohm's law, the current density components of three-dimensional steady current field are formula (6):

$$\begin{cases} j_x = -\gamma_x \dfrac{\partial \varphi}{\partial x} \\ j_y = -\gamma_y \dfrac{\partial \varphi}{\partial y} \\ j_z = -\gamma_z \dfrac{\partial \varphi}{\partial z} \end{cases} \qquad (6)$$

Where jx, jy and j_z represent current density component in the direction of x,y and z and γ_x, γ_y and γ_z represent conductivity in the direction of x,y and z; φ representspotential(V).

According to equations(5), the current continuity equation in the direction of x, y and z will be as follow (7):

$$\frac{\partial j_x}{\partial x} + \frac{\partial j_y}{\partial y} + \frac{\partial j_z}{\partial z} = 0 \qquad (7)$$

According to Equation (5) and (6), we can get the potential basic equations of the stray current of the three-dimensional subway sheild tunnel,as shown formula (8):

$$\frac{\partial}{\partial x}(\gamma_x\frac{\partial\varphi}{\partial x})+\frac{\partial}{\partial y}(\gamma_y\frac{\partial\varphi}{\partial y})+\frac{\partial}{\partial z}(\gamma_z\frac{\partial\varphi}{\partial z})=0 \tag{8}$$

For a constant current field, only the boundary conditions are needed to list. The model shown in figure 1 is symmetrical to y axis, electric field lines passing through the y axis are perpendicular to y axis. The rate of potential variation the axis of symmetry in the x direction was 0, so that the boundary conditions are along to Neumann boundary conditions. Equation (9) gives the definite conditions of Equation (8).

$$\begin{cases}\dfrac{\partial\varphi}{\partial n}=0\\ \varphi_{\text{下表面}}=0\end{cases} \tag{9}$$

3.Simulation Results and Discusstion of Stray Current Field

Since the actual boundary shape of the stray current field computional domain in subway is complex and changeable, and the geological condition is diverse, the structure can be classified as a small unit by the finite element method. Thus, it is easy to simulate various structures of irregular shape. It can handle all types of boundary conditions. Also, it can simulate structure of varieties material [15]. Therefore, due to the distribution of stray current field analyzed by ansys with the method of finite element, it can better reflect any case on real tunnel surroundings. This paper analyzes and simulates the distribution of stray current field with FEM method in homogeneous soil media and stratified soil media separately.

3.1. Analysis of Stray Current in Homogeneous Soil Media

Figure 1 shows that media 1-4 are the same media in homogeneous soil media. The parameters of calculation are shown as Table 1.

Table 1. Simulation Parameters of Homogeneous Soil Media

Material Name	Ralative permittivity	Resistivity(Ω·m)	Element
Tunnel	6.4	150	
Rail	1×10^{7}	2.1×10^{-7}	SOLID231 PLANE230
Soil	30	100	

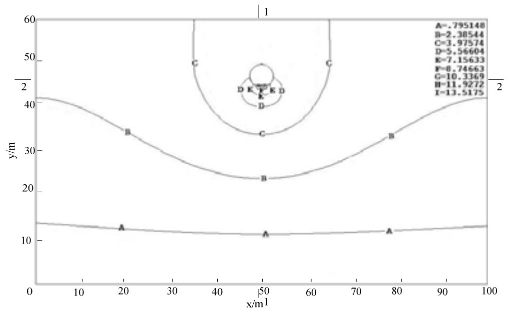

Figure 3. Electric Potential Contours in Homogeneous Soil Media (10A)

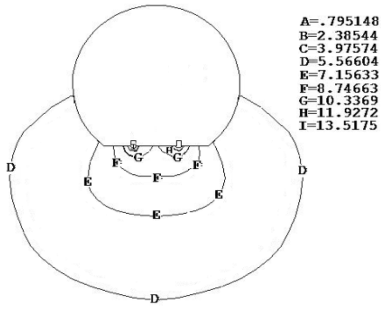

Figure 4. Electric Potential Contours of Neighboring Tunnel in Homogeneous Soil Media (10A)

In order to analyze the effects of different values of traction current on distribution of stray current field in homogeneous soil media, the values of traction current of 20A, 200A, 1000A, 2000A were calculated separately. The model simulated two rails, and the values of rail current of 10A, 100A, 500A, 1000A were loaded separately on one end of each rail. Figure 3 displays that the electric potential contours in homogeneous soil media when the value of rail current is 10A, and Figure 4 shows the neighboring tunnel in the same situation.

Different loading currents have the same contours. The only differences are potential value of contours, as shown in Table 2.

Table 2. Contour Potential Value Corresponding to the Different Loading Current

Traction current(A)	A(V)	B(V)	C(V)	D(V)	E(V)	F(V)	G(V)	H(V)	I(V)
10	0.795148	2.38544	3.97574	5.56604	7.15633	8.74663	10.33669	11.9274	13.5175
100	7.95148	23.8544	39. 7574	55. 6604	71. 5633	87. 4663	103. 3669	119. 274	135.175
500	39.7574	119.272	198.787	278.302	357.817	437.332	516.846	596.361	675.876
1000	79.5148	238.098	397.574	556.604	715.633	874.663	1033.669	1192.74	1351.75

In order to analyze the distribution of stray current from the rail to the surrounding, the longitudinal section was installed through the center of rail on the left, as shown in profile 1-1 of Figure 3. Figure 5 shows that the potential curve of different depths in the longitudinal section. The cross section was installed through the bottom of rail, as shown in profile 2-2 of Figure 3. Figure 6 shows that the potential curve of different locations in the cross section. Figure 7 shows that the Potential curve of railway in homogeneous soil media. On the diagram, 0 is the position of current-carrying.

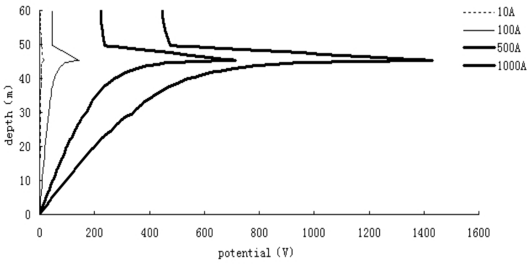

Figure 5. Potential Curve of 1-1 in Homogeneous Soil Media

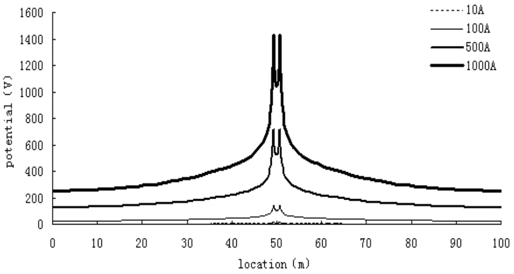

Figure 6 Potential Curve of 2-2 in Homogeneous Soil Media

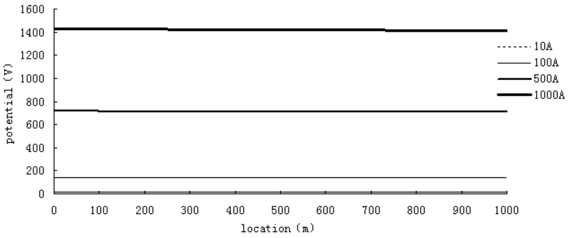

Figure 7. Potential Curve of Railway in Homogeneous Soil Media

Figure 5-7 show that the distribution of stray current from the rail to the surrounding with the different values of traction current, as shown in Table 3.

Table 3. Poential Distribution of the Railway to the Surrongding Underground Environment

Current(A)	Profile 1-1potential(V)		Profile 2-2potential(V)		Rail potential(V)	
	Maximum value	Minimum value	Maximum value	Minimum value	Maximum value	Minimum value
10	14.3127	0	14.3127	2.5272	14.313	14.154
100	143.127	0	143.127	25.272	143.13	141.54
500	715.633	0	715.633	126.36	715.63	707.7
1000	1431.27	0	1431.27	252.72	1431.3	1415.4

Figure 3-7 and Table 3 show that the potential attenuation is nonlinear from the rail to the surrounding underground. The farther from the rail and the more gently the curve is, the smaller the stray current strength it has. The distribution rule of potential solved by FEM in homogeneous soil media is consistent with the theoretical results projected under ideal conditions in apparatus [20].

From the analysis, in profile 1-1, the value of maximum potential increases with the increasing traction current. The value of minimum potential is 0. In profile 2-2, the value of maximum potential and minimum potential also increase with the increasing traction current. The value of rail potential increases with the increasing traction current, but declined by less extent. Simulation results show that the potential on each point from the rail to the surrounding underground has obtained, and providing the basis for the protection range of stray current and the specific location.

3.2. Analysis of Stray Current in Stratified Soil Media

In stratified soil media, Figure 1 shows that media 1-4 is the different medias. The type of element and parameters of tunnel and rail chosen are not changing. The Rsistivity Parameters of each Soil, as shown in Table 4.

Table 4. Rsistivity Parameters of each Soil

Number	Name	Ralative permittivity	Resistivity (Ω·m)
Media 1	Clay(wet)	8	10
Media 2	Soft soil	30	100
Media 3	Clay layer	40	500
Media 4	gravel	6	1000

In stratified soil media, similarly, the values of rail current of 10A, 100A, 500A, 1000A were loaded separately on one end of each rail. Figure 8 displays that the electric potential contours in stratified soil media when the value of rail current is 10A. Figure 9 shows the neighboring tunnel in the same situation.

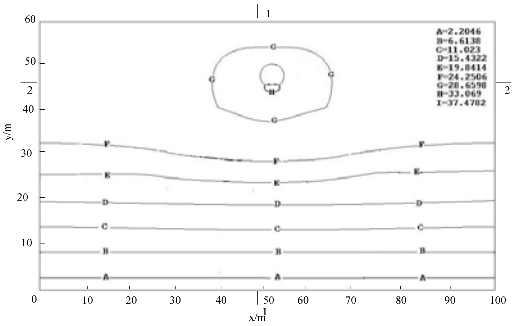

Figure 8. Electric Potential Contours in Stratified Soil Media (10A)

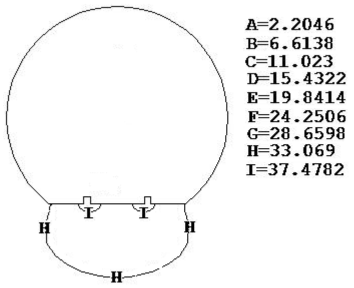

Figure 9. Electric Potential Contours of Neighboring Tunnel in Stratified Soil Media (10A)

Different loading currents have the same contours. The only differences are potential value of contours, as shown in Table 2.

Table 5. Contour Potential Value Corresponding to the Different Loading Current

Traction current(A)	A(V)	B(V)	C(V)	D(V)	E(V)	F(V)	G(V)	H(V)	I(V)
I=10A	2.2046	6.6138	11.023	15.4322	19.8414	24.2506	28.6598	33.069	37.4782
I=10A	22.046	66.138	110.23	154.322	198.414	242.506	286.598	330.69	374.782
I=500 A	110.23	330.69	551.15	771.61	992.07	1212.53	1432.99	1653.45	1873.91
I=1000A	220.46	661.38	1102.3	1543.22	1984.14	2425.06	2865.98	3306.9	3747.82

From the above datas show that the distribution rule of potential in stratified soil media is consistent with the homogeneous soil media.

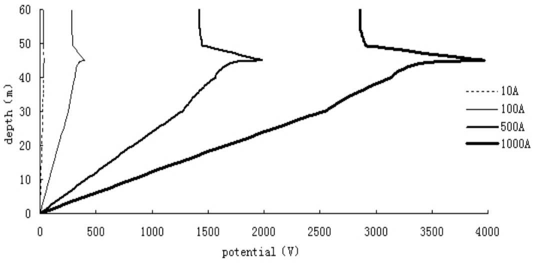

Figure 10. Potential Curve of 1-1 in Stratified Soil Media

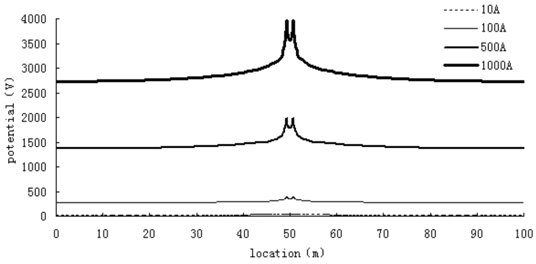

Figure 11. Potential Curve of 2-2 in Stratified Soil Media

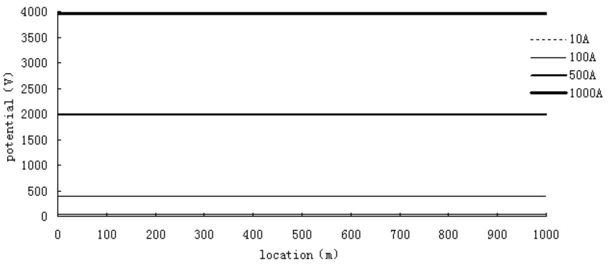

Figure 12. Potential Curve of Railway in Stratified Soil Media

Figure 8-12 and Table 5 show that the potential attenuation is nonlinear from the rail to the surrounding underground. The farther from the rail and the more gently the curve is, the smaller the stray current strength it has. The distribution rule of potential solved by FEM in homogeneous soil media is consistent with the theoretical results projected under ideal conditions in apparatus [20].

Figure 10-12 show that the distribution of stray current from the rail to the surrounding under environment with the different values of traction current, as shown in Table 6.

Table 6. Potential Distribution of the Railway to the Surrounding Underground Environment

Current(A)	Profile 1-1potential(V)		Profile 2-2potential(V)		Rail potential(V)	
	Maximum value	Minimum value	Maximum value	Minimum value	Maximum value	Minimum value
10	39.6828	0	39.6828	27.299	39.682	39.524
100	396.828	0	396.828	272.99	396.82	395.24
500	1984.14	0	1984.1	1364.9	1984.1	1976.2
1000	3968.28	0	3968.28	2729.9	3968.2	3952.4

Whether it is homogeneous or stratified soil media, the potential attenuation is nonlinear from the rail to the surrounding under environment. In the same value of traction current, I=10A, the Comparison of homogeneous soil media and stratified soil media, as shown in Table 7 and in Table 8.

Table 7. Comparison of Homogeneous Soil Media and Stratified Soil Media

Profile 1-1	*y*=54m potentia (V)	*y*=60m potentia (V)	Voltage drop(V)	*y*=30m potentia (V)	*y*=40m potentia (V)	Voltage drop (V)
Homogeneous soil media	4.57	4.47	0.1	3.42	5.63	2.21
Stratified soil media	28.58	28.55	0.03	25.42	31.42	6

As can clearly be seen in Table 7, the voltage drop in homogeneous soil media is obviously larger than the voltage drop in stratified soil media in 50-60m area of the profile 1-1. On the contrary, the voltage drop in homogeneous soil media is obviously smaller than the voltage drop in stratified soil media in 30-40m area of the profile 1-1. The main reason is that the voltage drop is mainly concentrated in the areas of high resistiviy ($\rho_1 < \rho_2 < \rho_3 < \rho_4$).

Table 8. Comparison of Homogeneous Soil Media and Stratified Soil Media

Profile 2-2	Minimum potential (V)	Maximum potential (V)	Voltage drop (V)
Homogeneous soil media	27.30	39.68	12.38
Stratified soil media	2.53	14.31	11.78

Table 8 shows that the voltage drop in homogeneous soil media is close to the voltage drop in stratified soil media in the profile 2-2. This reason is consistent with the above-mentioned. Similarly, Table 3 and Table 6 show the minimum potential maximum potential of rails and the voltage drop is no difference.

The greater the Resistivity is, the faster the speed it has, the less stray current leaks surrounding soil can get. But both of the rails, and tunnel near potential become greater.

4. Conclusion

In this paper the distribution rule and influnce range of subway sheild tunnel stray current in different traction currents have been carried out by ansys. Analyzing the simulation results can be noted that:

(1) With the increasingly value of current-carrying, the rail potential of the surrounding media and leakage current raise comstantly. The greater the resistivity of the surrounding media is, the less stray current it has.

(2) The two typical profiles show that the the potential attenuation is nonlinear from the rail to the surrounding underground. Increasing resistivity of rail and tunnel of surrounding media can effectively reduce the effects range of stray currents.

(3) Analyzing the simulation results can be known, Whether it is homogeneous or stratified soil media, the voltage drop trend from the rail to the surrounding under environment is showing no difference. The speed of voltage drop is related to resistivity. The greater the Resistivity is, the faster the speed it has, the less stray current leaks surrounding soil can get. But both of the rails, and tunnel near potential become greater.

(4) The three-dimensional finite element model can analyze every points stray current in situation of surrounding soil media subway tunnel shield. Because of this, provide the basis for the protection range of stray current and the protection of specific location can be inferred.

Acknowledgements

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