Int. J. Electrochem. Sci., 10 **(2015)** 5950 - 5960

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

Research on Stray Current Corrosion Evaluation of Buried Metallic Pipeline in an Urban Rail Transit System

Shao-Yi Xu[1,2], *Wei Li*[1,*]

[1]School of Mechanical and Electrical Engineering, China University of Mining and Technology, Xuzhou 221116, China
[2]Jiangsu Key Laboratory of Mine Mechanical and Electrical Equipment, China University of Mining and Technology, Xuzhou 221116, China
[*]E-mail: Prof_liwei@126.com

Received: 28 March 2015 / *Accepted:* 12 May 2015 / *Published:* 27 May 2015

In this paper, a research is made on the stray current corrosion evaluation of buried metallic pipeline in an urban rail transit system. The long-term accuracy of the polarization potential measurement is found not to be perfect for the stray current corrosion evaluation, which is caused by the life cycle, the working condition and the IR drop error of the reference electrode. Furthermore, according to the Faraday's laws of electrolysis, an optical fiber sensing method is proposed to measure the stray current, which can be applied to evaluate the stray current corrosion status directly. The maximum of the stray current is found to be 20 A. And the design principle and configuration of the optical fiber sensing system are demonstrated. Moreover, the comparison is conducted between the polarization potential measurement results in 2004 and the results in 2010, which verifies the analysis results on the imperfect long-term accuracy. In addition, the transient response test and accuracy test of the optical fiber sensing system are conducted, which indicates that its response time and relative error are less than 0.73 ms and 0.4%, respectively. Finally, the stray current corrosion status of the pipeline $\varphi 76\times 10$ are evaluated based on the results of the direct measurement method, which indicates that the corrosion perforation will be caused in anode region if the corrosion time is greater than 2 months and 11 months at 20 A and 4 A, respectively.

Keywords: Stray current; Buried metallic pipeline; Corrosion status; Optical fiber sensing method.

1. INTRODUCTION

An urban rail transit system mainly includes the substation, the overhead line, the running rail, the train, the stray current collection system, and the buried metallic pipeline. It is well known that the running rail is often used as the return conductor for the traction current. This arrangement mainly focuses on the economic considerations since it does not require the installation of an additional return conductor. Due to the resistance of running rail, the rail potential will be caused by the traction current returning to the substation. Moreover, the resistance of running rail to ground is not infinite. Thus, most of the traction current will return to the substation while its remainder will leak into the ground, which is known as the primary stray current. Most of the primary stray current can be captured by the stray current collection system and then return to the substation again. The remainder of primary stray current will enter the buried metallic pipeline (such as the gas pipeline, the oil pipeline and the water pipeline), which is called the secondary stray current [1-4]. It has been found that the secondary stray current (stray current, for short) may cause the electrochemical corrosion of buried metallic pipeline, which may shorten its life cycle, strength and durability [5-6]. In a few extreme cases, some severe accidents (such as a serious gas explosion) have occurred as a result of stray current corrosion.

There are two special regions on the buried metallic pipeline, one is the cathode region where the stray current flows into, and the other one is the anode region where the stray current flows out. Thus, the stray current corrosion mechanism can be expressed based on the corrosion cell, that is, the metal Fe will be oxidized to the metal ion Fe^{2+} in the anode region [7]. Obviously, the stray current corrosion prevention is essential for the buried metallic pipeline in a real transit system. And the stray current corrosion evaluation is the basis of its prevention. At present, the polarization potential of buried metallic pipeline has been measured using the reference electrode, which can be applied to evaluate its corrosion status indirectly [8-9]. However, there are few studies on the disadvantage of this indirect method. Even, there is no other way to evaluate the stray current corrosion status.

This paper will illustrate the stray current corrosion evaluation of buried metallic pipeline in an urban rail transit system. Firstly, the polarization potential measurement method is demonstrated. And the main disadvantages of this indirect method are analyzed. Then, the stray current measurement based on the optical fiber sensing method is proposed, which is a novel direct method. Finally, the verification results on the indirect method, the performance test results on the direct method and the stray current corrosion evaluation results for the pipeline $\varphi 76\times 10$ are discussed.

The aims of this investigation are to study the long-term accuracy problem of the polarization potential measurement and answer the question 'Is it possible to evaluate the corrosion status by directly measuring the stray current?'.

2. EXPERIMENTAL

2.1 Polarization potential measurement method

If the stray current corrosion is caused in the anode region of buried metallic pipeline, the metal at low potential will be oxidized to the metal ion at high potential. It means that the polarization potential will increase in the anode region. Thus, the stray current corrosion status can be indirectly evaluated by measuring the positive deviation of polarization potential in the anode region. Referring to China standard CJJ49-1992 [10], the average value of positive deviation in half an hour has to be limited to a maximum of 0.5 V. Moreover, European standard EN 50122-2 stipulates that the average value in an hour does not exceed 0.2 V [11]. Since the measurement time of European standard is the double of that of China standard, the limit deviations of these two standards are similar. In addition, American standard ASTM C876-91D is listed in Table 1. For reference electrode $Cu/CuSO_4$, the corrosion probability will be greater than 90% if the positive deviation is not smaller than 0.35 V [12].

Table 1. American standard ASTM C876-91D

Corrosion status \ Reference electrode	$(Cu/CuSO_4)$ /mV	(Ag/AgCl) /mV	(Hg/HgCl) /mV
No corrosion probability > 90%	< 200	< 106	< 126
Uncertain	200 ~ 350	106 ~ 296	126 ~ 276
Corrosion probability > 90%	> 350	> 296	> 276

The reference potential is very important in this indirect measurement method, which often applies the remote ground potential. However, it is difficult to obtain the remote ground potential in practice. Thus, the potential of a reference electrode (such as the saturated $Cu/CuSO_4$ electrode) is usually used as the ground potential. And the reference electrode will be placed in the soil near the buried metallic pipeline. Then, the polarization potential of buried metallic pipeline is measured with respect to the reference electrode, which is shown in Figure 1(a). And the configuration of $Cu/CuSO_4$ electrode is shown in Figure 1(b).

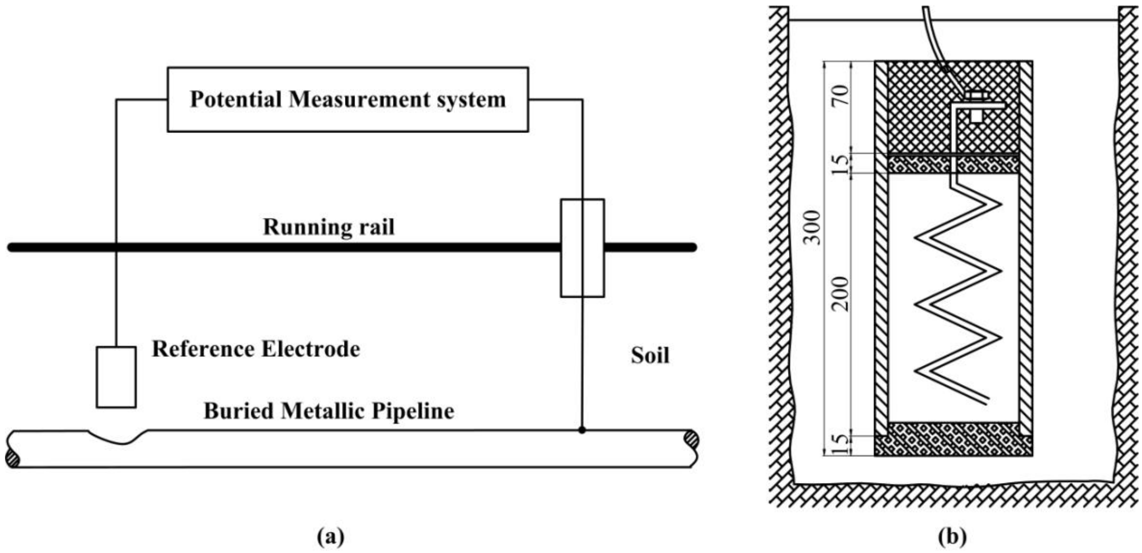

Figure 1. Polarization potential measurement method of buried metallic pipeline: (a) measurement system; (b) $Cu/CuSO_4$ electrode.

In Figure 1, the potential measurement system gets a constant value in absence of stray current, which is known as the steady-state polarization potential U_0 of buried metallic pipeline. If the buried metallic pipeline is electrically influenced by stray current, its polarization potential U_1 will deviate from the steady-state potential in the positive or negative direction. Thus, the polarization potential deviation is equal to the difference between U_0 and U_1.

Although the polarization potential deviation of buried metallic pipeline is most frequently measured to evaluate its stray current corrosion status, the long-term measurement accuracy is found not to be perfect. The imperfect accuracy may come from three factors: (1) the reference electrode is placed near the buried metallic pipeline during the construction period of an urban rail transit system. In the initial operation of the transit system, the high insulation level can prevent the stray current corrosion on buried metallic pipeline, which usually occurs after years of operation. It is noted that the life cycle of reference electrode is limited; (2) the working condition of reference electrode needs to prevent dry, which is difficult to be kept in the transit system; (3) referring to Figure 1(a), the reference electrode cannot directly touch the buried metallic pipeline in the polarization potential measurement. Thus, the measurement results will include the IR drop error, which is hardly eliminated at present. And this long-term accuracy problem will be verified by the field test results.

2.2 Stray current measurement method

Since the long-term measurement accuracy of polarization potential deviation is not perfect, a novel evaluation method on stray current corrosion status should be studied. Moreover, the stray current corrosion of buried metallic pipeline essentially belongs to the electrochemical corrosion. Thus, its corrosion amount can be calculated based on the Faraday's laws of electrolysis [4], which can be obtained as follows:

$$\Delta FS = \frac{M}{nF} \cdot Q = k \cdot i \cdot t \qquad (1)$$

Where ΔFS is the corrosion amount of buried metallic pipeline within the corrosion time t, in kg; M is the molar mass, in g/mol; Q is the total charge within the time t, in C; n is the number of the lost valence electrons in the oxidation reaction; F is the Faraday's coefficient of electrolysis, 1F=96485C; k is the electrochemical equivalent, in kg/(A$\cdot$s); i is the stray current, in A. According to Eq. (1), the corrosion amount of buried metallic pipeline is found to be proportional to stray current. Thus, the stray current corrosion status can be evaluated directly by measuring stray current.

The stray current magnitude of buried metallic pipeline needs to be determined firstly. The maximum of primary stray current has been tested in Beijing Metro, which is within the range of 200 A to 326 A. Moreover, the efficiency of stray current collection system will be about 90% if the soil resistivity is about 0.1 $\Omega \cdot$km and the cross-sectional area of stray current collector cable is about 120 mm^2 [13]. Thus, the maximum of stray current is about in the range of 20 A to 32.6 A on buried metallic pipeline. When the electrochemical equivalent k in Eq. (1) is about 0.7466×10^{-7} kg/(A$\cdot$s) [14], the stray current corrosion amount of buried metallic pipeline is about 47 kg at 20 A and 76.76 kg at 32.6 A in a year. Considering the practical corrosion situation in a real transit system, the maximum of stray current is about 20 A. Furthermore, the stray current has been proven to be the random current under the influence of train running modes [15]. It is noted that the optical fiber current sensing method has the advantages of high accuracy [16] and high sensitivity [17]. And this method has been applied to measure the direct current, the alternating current or the pulse current. Thus, considering the small magnitude and randomness of stray current, the optical fiber current sensing method might be one of the best measurement choices.

The optical fiber sensing system to measure stray current is shown in Figure 2. Its optical structure consists of a super luminescent diode (SLD), a polarizer, a coupler, a sensing head, a mirror, a polarization controller (PC), and a polarization beam splitter (PBS). It is noted that the sensing head includes a multilayer solenoid and the sensing fibers. A heat insulation cavity is set between the solenoid and the sensing fibers, which fills the glass cotton to cut off the heat-transfer path. When the stray current flows into the solenoid, its magnetic field is produced along the axial direction of the solenoid. Moreover, the sensing fibers also pass through the solenoid along the axial direction. Thus, according to Faraday magneto-optic effect, i.e., Eq. (2) [18], the polarization plane of linearly polarized light in the sensing fibers will be rotated by the magnetic field produced by stray current. Since the rotation angle is proportional to the magnetic field intensity, the stray current can be obtained by measuring the rotation angle. It is noted the optical structure will be placed in the equipment cabinet along the running rail in the transit system.

$$\theta = V\int \mathbf{H}\cdot \mathrm{d}\mathbf{L} \qquad (2)$$

Where θ is the rotation angle, in rad; V is the Verdet constant of sensing fibers, in urad/A; $\mathbf{H}$ is the magnetic field intensity produced by stray current, in A/m; $\mathbf{L}$ is the length of sensing fibers in the magnetic field, in m.

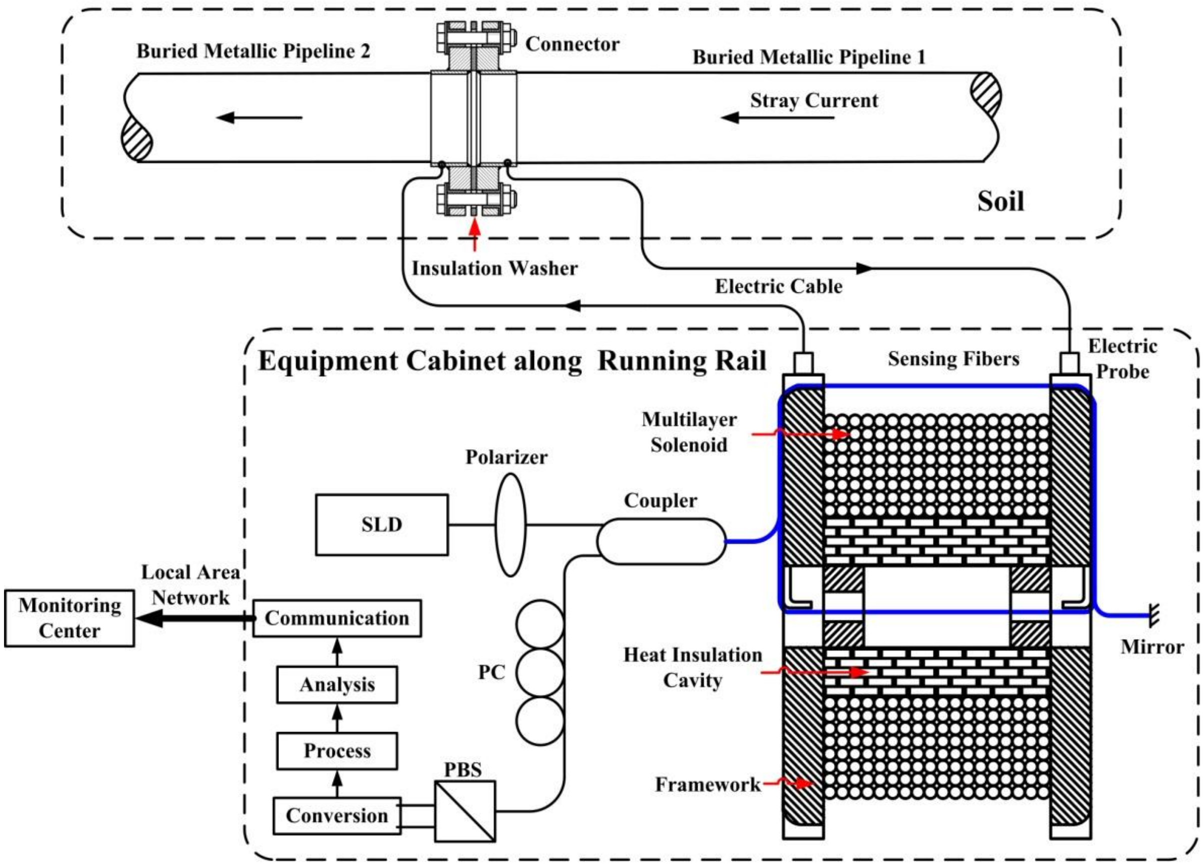

Figure 2. An optical fiber sensing system to measure stray current.

To permit the flow of the stray current on the buried metallic pipeline to the multilayer solenoid, a connector with an insulation washer is installed between two buried metallic pipelines. Moreover, the one end of the electric cable is welded in the flange of the connector and the other one end is welded in the electric probe of the solenoid. With the help of the insulation washer, the stray current in buried metallic pipeline 1 firstly flows into the solenoid, then is measured by the optical structure and finally flows into buried metallic pipeline 2. The measured stray current dataset will be sent to the monitoring center by the local area network in the transit system.

In this optical fiber sensing system, the SLD is produced by EXFO Co. Ltd., model FLS-2200. The extinction ratio of the polarizer is not less than 25 dB. The sensing fibers are produced by Oxford Electronics Co. Ltd., model LB 1550-125. The modulation angle of PC is about 45 deg, which is applied to obtain the maximum sensitivity of optical fiber sensing system. Moreover, it is noted that the connector should match the size of buried metallic pipeline. Furthermore, the axial number of turns per unit length in the multilayer solenoid is about 639.7 /m while the vertical number is about 545.2 /m. The number over the magnetic field and the sensing fibers is about 3. In addition, the reflectivity of the mirror is greater than 95%.

3. RESULTS AND DISCUSSION

3.1 Imperfect long-term accuracy of polarization potential measurement method

For analyzing the imperfect long-term accuracy of polarization potential measurement method, the polarization potential measurement results in 2004 and 2010 are obtained from a real transit system, which are shown in Figure 3 and 4, respectively. The measurement time is about 10 h and every data point is the average value of positive deviation in half an hour. The reference electrode is $Cu/CuSO_4$ electrode.

In Figure 3(a), the maximum and minimum values of positive deviation are 131 mV and 39 mV, respectively. And in Figure 3(b), the maximum and minimum are 26 mV and 12 mV, respectively. Thus, according to Table 1, the non-corrosive probability of buried metallic pipeline is more than 90% in the presence of stray current. In addition, the stray current corrosion status of buried metallic pipeline is also not serious referring to the China standard CJJ49-1992 [10] and the European standard EN 50122-2 [11]. Moreover, the results in Figure 3 are obtained at the time when the buried metallic pipeline and the $Cu/CuSO_4$ electrode are just installed. Obviously, the buried metallic pipeline is still in good condition. Thus, the measurement results in Figure 3 are accurate.

In Figure 4(a), the maximum and minimum deviations are 286 mV and 229 mV, respectively. And in Figure 4(b), the two deviations are 243 mV and 172 mV, respectively. Since the measurement results in Figure 4 are mainly between 200 mV and 350 mV, the stray current corrosion status should be uncertain based on Table 1. Moreover, the stray current corrosion has not occurred in the buried metallic pipeline based on the China and European standard. However, the results in Figure 4 are obtained when the buried metallic pipeline needs to be replaced, which dues to the actual corrosion failure. Thus, the measurement results in Figure 4 are not accurate.

Compared the measurement results in Figure 3 with results in Figure 4, the accuracy of the polarization potential measurement method is reduced from 2004 to 2010. It indicates that the long-term accuracy of this method is imperfect, which verifies the analysis results in Section 2.1.

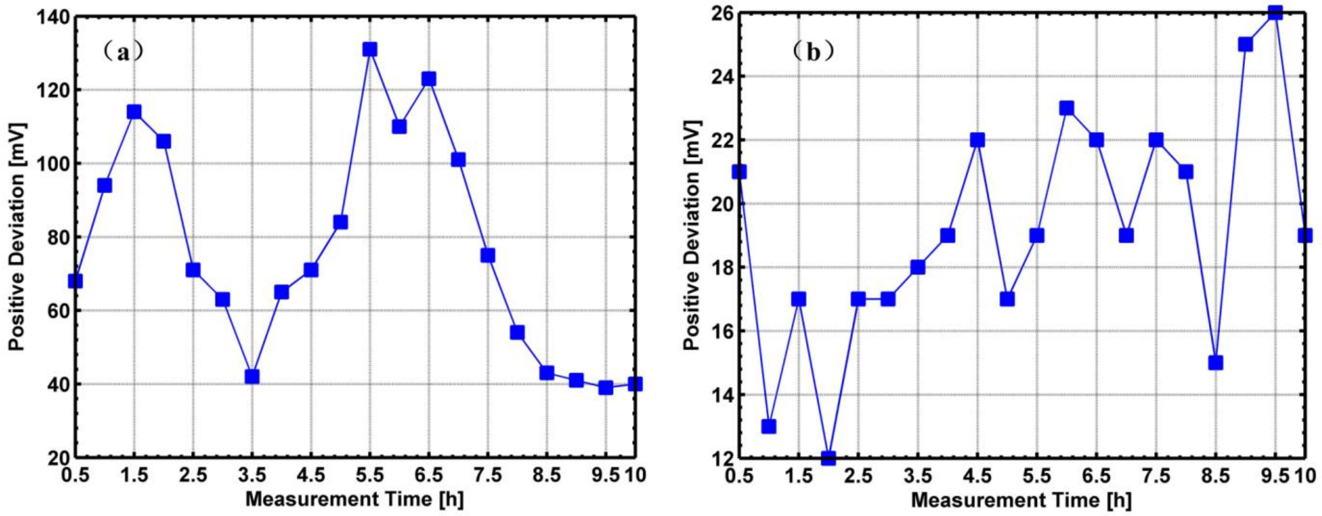

Figure 3. Polarization potential measurement results in 2004.

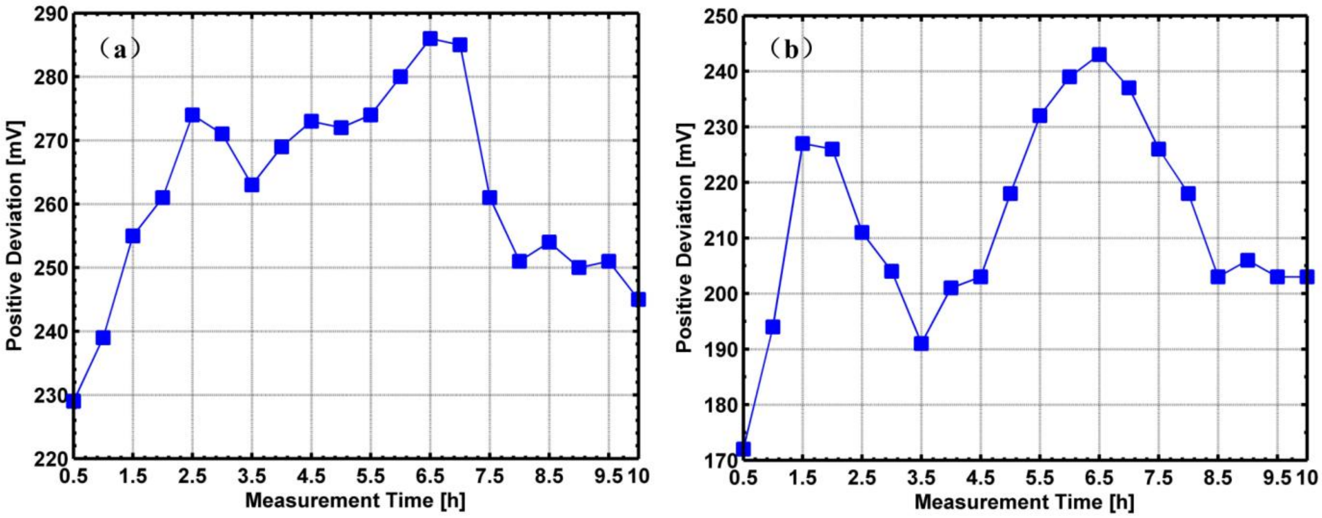

Figure 4. Polarization potential measurement results in 2010.

3.2 Measurement performance of stray current measurement method

Since the stray current is a random current and its magnitude is small, the optical fiber sensing system in Figure 2 needs to have properties of both quick response ability and high accuracy. Thus, the transient response test and the accuracy test should be conducted.

The experiment has been conducted on the transient response to the step signals. The step signals include step-down signal and step-up signal, which are produced by a function signal generator and a power amplifier [19]. It is noted that the sampling frequency is 4096 Hz. The transient response results of optical fiber sensing system are illustrated in the Figure 5. In Figure 5(a), the step-down signal drops from 2.0 A to 0.0 A. Three signals have been sampled on the falling edge, which indicates the response time is about 0.73 ms. Moreover, in Figure 5(b), the step-up signal rises from 0.0 A to 2.0 A. Two signals have been sampled on the rising edge, which indicates the response time is 0.49 ms.

Thus, the response time is less than 0.73 ms in the experiment. It indicates that the optical fiber sensing system presents the preferable transient response performance.

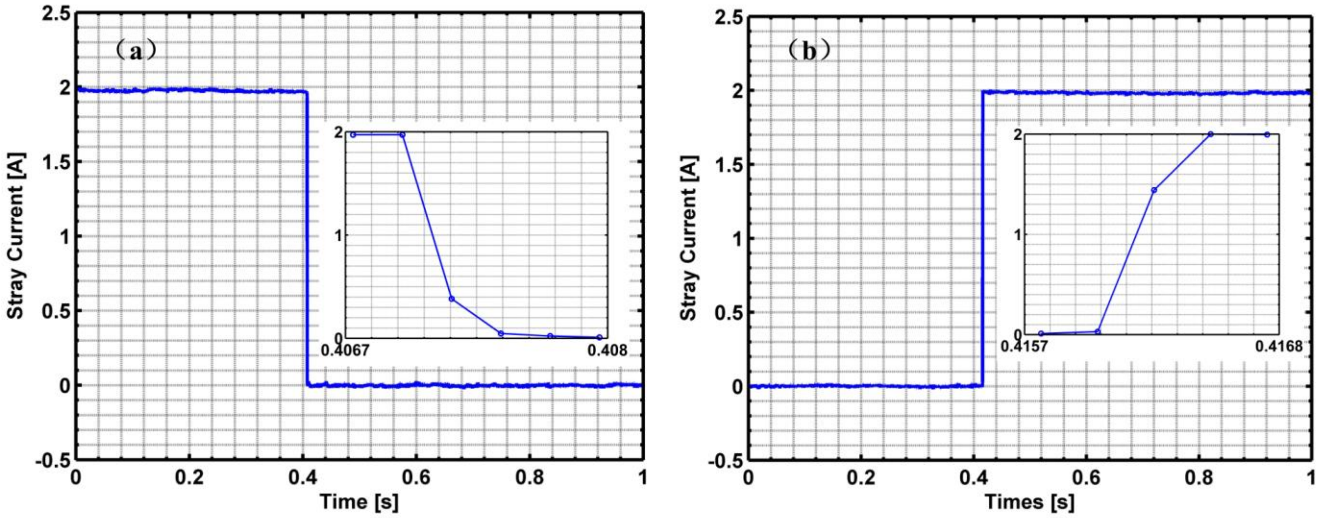

Figure 5. Transit response test results: (a) step-down signal; (b) step-up signal.

Furthermore, the accuracy test of optical fiber sensing system has been conducted. And the test results are shown in Figure 6. We can find that the relative error is not greater than 0.4% when the measured stray current is about 4 A and 8A. Moreover, the relative error is not more than 0.35% at 12 A. In addition, if the measured stray current is about 16 A or 20 A, the relative error will be smaller than 0.3%. Obviously, it means that the optical fiber sensing system can accurately measure the stray current on buried metallic pipeline.

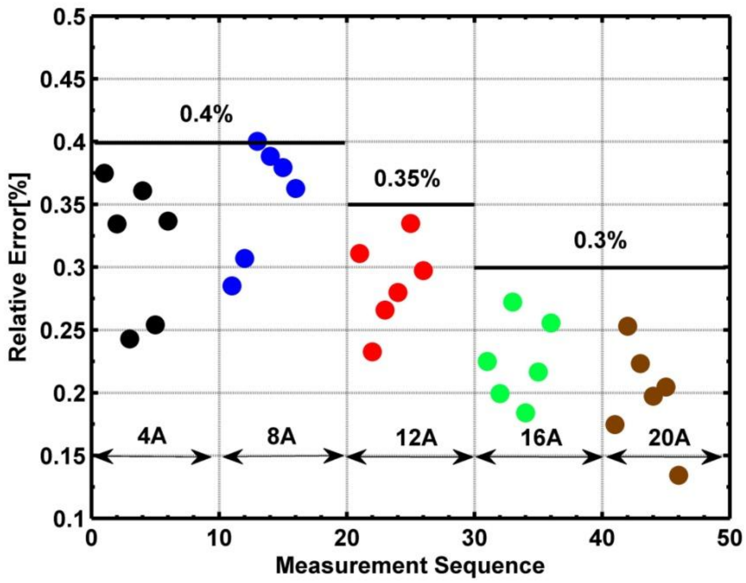

Figure 6. Accuracy test results.

3.3 Stray current corrosion status evaluation

After the stray current has been measured by the optical fiber sensing system, the stray current corrosion status of buried metallic pipeline should be evaluated. It is noted that the buried metallic pipeline in this experiment is steel pipeline and its size is $\varphi 76 \times 10$, which means the outside diameter is 76 mm and the wall thickness is 10 mm. In addition, its density is about 7.85 kg/dm^3 and its cross-section shape is a circular ring. Since the stray current corrosion often occurs in the anode region of buried metallic pipeline, the weight in anode region will be 8.7548 kg if its length is about 1 m [4, 7].

The test results at 20 A are shown in Table 2. And its test numbers are six. It can be found that the average value of the test current is about 19.9558 A. If the corrosion time is about 5 h, the total corrosion amount will be about 0.0268 kg. Moreover, the corrosion amount will be about 0.1287 kg, 3.8618 kg, and 23.1709 kg for one day, one month (30 days) and half a year respectively. According to Table 2, it means that the corrosion perforation will be caused in anode region if the corrosion time is greater than 2 months.

Table 2. Test Results at 20 A

	Test number						Average value
	1	2	3	4	5	6	
Test data (A)	20.0065	19.8971	19.7957	20.0129	20.0345	19.9882	19.9558
t=5 h, ΔFS (kg)	0.0269	0.0267	0.0266	0.0269	0.0269	0.0269	0.0268
t=1 day, ΔFS (kg)	0.1291	0.1283	0.1277	0.1291	0.1292	0.1289	0.1287
t=1 month, ΔFS (kg)	3.8716	3.8505	3.8308	3.8729	3.8771	3.8681	3.8618
t=0.5 year, ΔFS (kg)	23.2298	23.1028	22.9850	23.2372	23.2623	23.2085	23.1709

Moreover, the test results at 4 A are shown in Table 3. And the average value of the test current is about 4.0006 A. If the corrosion time is about 5 h, 1 day, 1 month and 0.5 year, the corresponding corrosion amount will be 0.0054 kg, 0.0258 kg, 0.7742 kg and 4.6452 kg respectively. Thus, for the experimental pipeline, the corrosion perforation will be caused in anode region if the corrosion time is greater than 11 months.

Table 3. Test Results at 4 A

	Test number						Average value
	1	2	3	4	5	6	
Test data (A)	3.9901	4.0197	4.0025	3.9767	4.0228	3.9919	4.0006
t=5 h, ΔFS (kg)	0.0054	0.0054	0.0054	0.0053	0.0054	0.0054	0.0054
t=1 day, ΔFS (kg)	0.0257	0.0259	0.0258	0.0257	0.0259	0.0258	0.0258
t=1 month, ΔFS (kg)	0.7722	0.7779	0.7746	0.7696	0.7785	0.7725	0.7742
t=0.5 year, ΔFS (kg)	4.6330	4.6673	4.6474	4.6174	4.6709	4.6350	4.6452

4. CONCLUSIONS

This paper focuses on the stray current corrosion evaluation of buried metallic pipeline in an urban rail transit system. The long-term accuracy of the polarization potential measurement is found not to be perfect for the stray current corrosion evaluation of buried metallic pipeline, which is caused by the life cycle, the working condition and the IR drop error of the reference electrode. Moreover, since the stray current corrosion amount is proportional to the stray current of buried metallic pipeline, an optical fiber sensing method is proposed to measure stray current directly. The stray current magnitude of buried metallic pipeline is determined. The design principle and configuration of optical fiber sensing system are demonstrated in detail. In addition, the comparison is conducted between the polarization potential measurement results in 2004 and the results in 2010, which verifies the analysis results of the imperfect long-term accuracy. Furthermore, the transient response test and accuracy test of the optical fiber sensing system are conducted, which indicates that it is suit for the stray current measurement of buried metallic pipeline. Finally, according to the measurement results on the optical fiber sensing method, the stray current corrosion status of the pipeline $\varphi 76\times 10$ are evaluated, which indicates that the corrosion perforation will be caused in anode region if the corrosion time is greater than 2 months and 11 months at 20 A and 4 A, respectively. In the future, the relationship will be created between the start rule of the stray current corrosion prevention system and the stray current measured by the optical fiber sensing system in a real transit system.

ACKNOWLEDGEMENT

The work was supported by Graduate Education Innovation Project of Jiangsu Province of China (CXZZ13_0928), National High Technology Research and Development Program of China (2013AA06A411), and Priority Academic Program Development of Jiangsu Higher Education Institutions of China (PAPD).

References

1. A. L. Cao, Q. J. Zhu, S. T. Zhang and B. R. Hou, *Anti-Corros. Method M.*, 57 (2010) 234.
2. A. W. Peabody, *Control of Pipeline Corrosion*, Chemical Industry Press, Beijing (2001).
3. S. Y. Xu, W. Li, F. F. Xing and Y. Q. Wang, *J. Cent. South Univ.*, 21 (2014) 956.
4. Y. Q. Wang, W. Li, S. Y. Xu and X. F. Yang, *Int. J. Electrochem. Sci.*, 4 (2013) 5314.
5. Q. J. Zhu, A. L. Cao, Z. F. Wang, J. W. Song and S. L. Chen, *Anti-Corros. Method M.*, 58(2011) 234.
6. F. C. R. Hernandez, G. Plascencia and K. Koch, *Eng. Fail. Anal.*, 16(2009) 281.
7. W. Li, *Stray Current Corrosion Prevention in DC Mass Transit Systems*, China University of Mining and Technology Press, Xuzhou (2004).
8. K. Darowicki and K. Zakowski, *Corros. Sci.*, 46(2004) 1061.
9. K. Zakowski and K. Darowicki, *Corros. Rev.*, 19(2001) 55.
10. *Technical Regulations of Stray Current Corrosion Prevention in DC Mass Transit System*, CJJ 49-1992, 1993.
11. *Railway Applications-Fixed Installations-Electrical Safety, Earthing and the Return Circuit Part 2: Provisions Against the Effects of Stray Currents Caused by d.c. Traction Systems*, EN 50122, 2010.
12. *Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete*, ASTM

C 876-91, 1991.
13. I. Cotton, C. Charalambous, P. Aylott and P. Ernst, *IEEE T. Veh. Technol.*, 54 (2005) 722.
14. X. J. Zhou and B. Gao, *J. China Rail. Soc.*, 21 (1999) 99.
15. S. Y. Xu, W. Li and Y. Q. Wang, *IEEE T. Veh. Technol.*, 62 (2013) 3569.
16. C. X. Zhang, C. S. Li, X. X. Wang, L. J. Li, J. Yu and X. J. Feng, *Appl. Optics*, 51 (2012) 3977.
17. S. Y. Xu, W. Li, F. F. Xing and Y. Q. Wang, *Opt. Express*, 22 (2014) 11985.
18. H. Y. Zhang, Y. K. Dong, J. Leeson, L. Chen and X. Y. Bao, *Appl. Optics*, 50(2011) 924.
19. B. Qi and X. R. Yang, *Chinese J. Anal. Chem.*, 35(2007) 196.