Int. J. Electrochem. Sci., 16 **(2021)** Article ID: 210547, doi: 10.20964/2021.05.59

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

Study of Impressed Current Cathodic Protection (ICCP) on the Steel Pipeline under DC Stray Current Interference

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Received: 6 January 2021 / *Accepted:* 16 March 2021 / *Published:* 31 March 2021

In this work, a detection method of stray direct current on buried pipelines and a determination method for anodic/cathodic regions on pipelines is proposed. To compensate for the current interference, a current requirement test is adopted to provide a reference for an additional impressed current cathodic protection system. When the buried pipeline is severely disturbed, the implemented impressed current cathodic protection system, which is based on the results of the requirement test, negatively shifts the instant-off potential of the pipeline by at least 350 mV during the measurement period. This shift meets the cathodic protection criteria, suggesting that the impressed current cathodic protection system can effectively suppress stray subway current-induced corrosion.

Keywords: Impressed current cathodic protection; Current requirement test; DC stray current; Drainage; Instant-off potential

1. INTRODUCTION

In the southeastern coastal area of China, the well−developed high−tension electricity network and electrified mass transit strikingly flourish in the local economy; however, the rail transit traction systems and high-voltage transmission lines generate stray DC that inevitably causes the corrosion of adjacent metallic pipelines [1]. These underground pipelines include gas pipelines, oil pipelines, water pipelines, and heating pipelines, all of which form a complex network downtown. Some pipelines lay parallelly for a dozen miles or cross metro tracks; thus, some of the DC current of the metro circuit may flow through the pipelines and result in severe metallic pipeline corrosion accidents [2]. The metro mass transit is powered by DC current, and the track serves as one part of the circuit when running; therefore, stray DC will be generated due to the electric connection between the track and ground [3-6].

The corrosion issue caused by stray current was noticed within ten years of the first DC-powered rail line in Virginia of the United States in 1888. Since then, the control of stray current has been a critical issue [7]. In China, the water pipelines in the tunnel of the first-stage project of the Beijing metro leaked in the 1970s due to corrosion perforation, which was attributed to stray DC [8]. In another case, the DN300 gas pipelines under the Century Avenue of Shanghai leaked 10 times before 2008, which was also ascribed to the stray DC generated by its accompanied metro No. 2 line [9]. Stray DC can promote serious corrosion of its adjacent metallic structures because the location where DC current flows out always acts as an anode area associated with a considerable corrosion rate. Therefore, the prevention of corrosion induced by stray DC remains incomplete and needs to be solved for many underground systems.

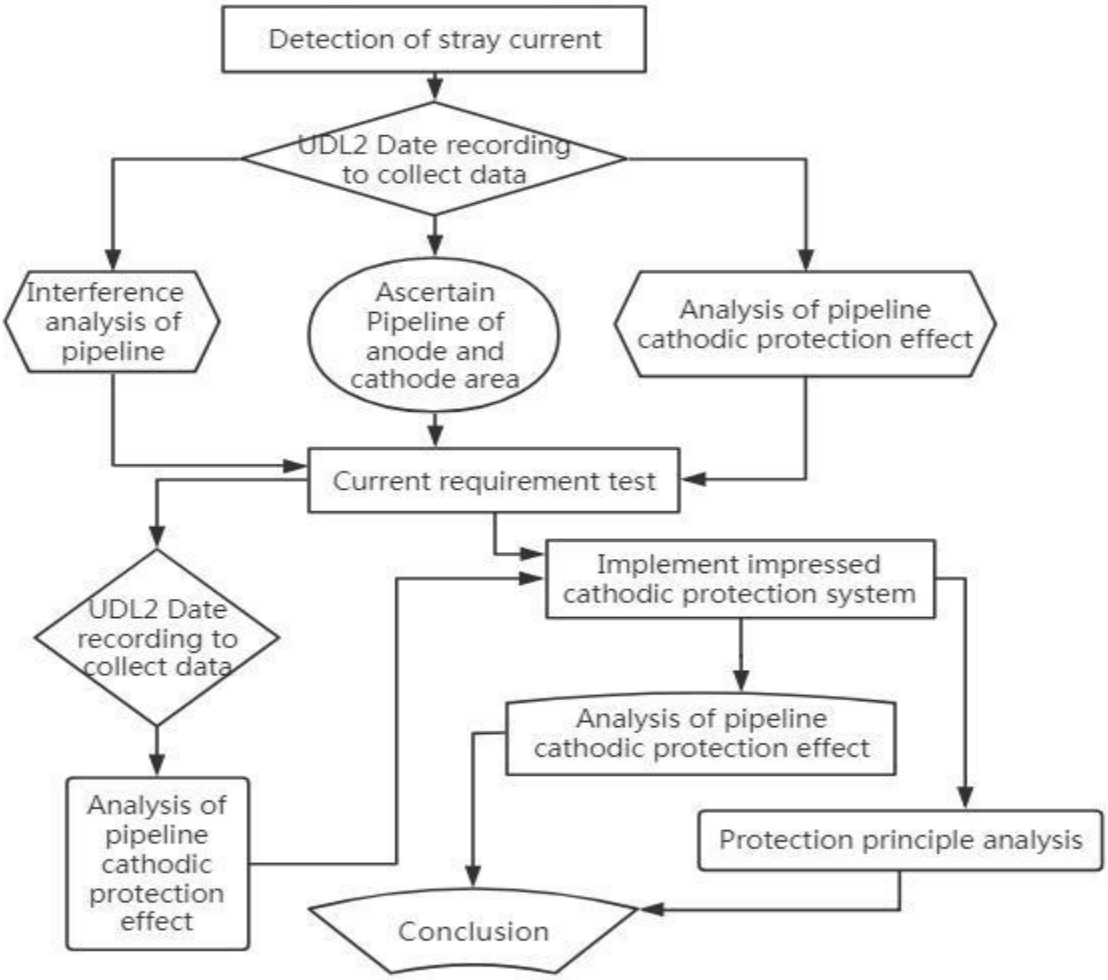

Figure 1. Implementation process of the analysis of an impressed current cathodic protection (ICCP) system.

Only passive defense techniques are currently available for alleviating the corrosion of metallic pipelines adjacent to metro mass transit, including grounding drainage, direct drainage, polarity drainage, and impressed drainage, which have been summarized in the file of BS EN 50162:2004 [10].

Nonetheless, these methods have some defects in practice. For instance, direct drainage can promote potential danger for metro operation because it demands an electric connection between the track and the disturbed pipeline to guide the stray DC returning to the electric loop of the metro. Ground and polarity drainages are widely adopted by using sacrificial or belt anodes, but the effective protection distances of both methods are generally less than 150 m [11]. In the case of a high-intensity stray current, the drainage effect is quite limited and may be less than 50 m. In view of this, ICCP is an effective way to overcome the limitation of the abovementioned techniques. It has been reported that the effective distance can reach 14 km via the impressed current method [12].

In Dongguan city of Guangdong Province in China, one of the gas pipelines is located across the metro No. 2 line. The stray DC derived from the power supply system of the metro may affect the pipe−to−ground potential, promoting stray current corrosion of the pipeline. In this work, the interference of stray DC on a gas pipeline was evaluated, and an ICCP system was proposed in view of the results of the current requirement test and installed underground. Systematic and specific considerations in the design and protection results are reported, aiming to provide a practical reference for corrosion protection engineers to resolve stray DC issues. The implementation process is shown in Figure 1.

2. EXPERIMENTAL

2.1. Measurement of stray current interference

The cathodic protection (CP) effect evaluation aims to test the potential (versus a reference electrode) of a preburied steel coupon electrically connected to cathodic protected pipelines. The steel coupon has an identical grade to that of the pipelines. Moreover, a reference electrode is guided to the vicinity of the steel coupon via a plastic pipe throughout the ground and underground [13-15]. Nonetheless, when a CP system operates on a specific pipe, a high voltage drop (IR drop) accounts for a considerable portion of the measured structure-to-ground potential. In this case, a polarization probe (PP) is adopted to evaluate the CP effect by collecting the instant-off potentials of the pipe in this work [16]. PP is a combination of a reference electrode and steel coupon (see Figure 2). The reference electrode and steel coupon are both mounted in PP, in which two identical steel coupons are used to study the electric properties of the coating defects on pipelines as well as the self-corrosion state. The shortened distance between the reference electrode and steel pipe compared to the traditional CP effect evaluation can mitigate the IR drop in the signal circuit [17]. The specific structure of the PP and the connection diagram of the potential collector are presented in Figure 2.

In Figure 2, the stray current testing system in this work is composed of a PP (NCS PP2000, Qingdao NCS Testing Protection Technology Co., Ltd. China), a potential collector (UDL2, Mobiltex Data Co., Ltd. Canada), and the pipeline with stray current interference, respectively. The UDL2 potential collector can automatically record the on and instant-off potentials of structure-to-ground by connecting its blue terminal to the pipeline, red terminal to the Cu/CuSO4 reference electrode, and black terminal to the steel coupon with an exposed surface of 6.5 cm2. The grade of the steel coupon in this work is Q345, which is in harmony with that of the pipe. The specific testing procedures are listed as below:

(i) Burying the PP in the vicinity of the test station, backfilling the soil, and watering and tamping the soil.

(ii) Connecting the UDL2 with the pipe, the reference electrode and the steel coupon in PP. The UDL2 was placed in the test post on ground.

(iii) Collecting the potentials of the pipe in the presence of a pre-existing CP system using a ten-second ON and one-second OFF cycle.

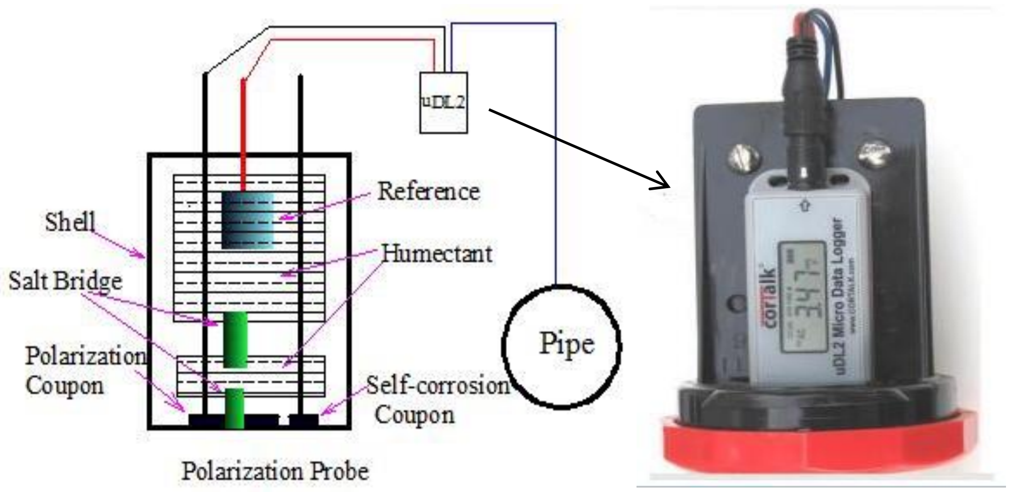

Figure 2. Schematic of the stray current testing system.

2.2. Cathodic protection criteria with stray current interference

In BS EN12954:2019 [18], under soil and water conditions, the protection potential should be more negative than −0.85 V (IR free versus the saturated Cu/CuSO4 reference electrode, CSE). Under aerated conditions, $T < 40$ °C and $100\ \Omega\cdot m < \rho < 1000\ \Omega\cdot m$ in solid water, the protection potential should be more negative than −0.75 V (IR free, versus CSE).

In AS2832.1-2015[19]: The protection criteria for structures subject to traction current effects varies with the structure polarization time. Structures with sound coating characteristics, or those that have otherwise been proven to be polarized and depolarized rapidly in response to stray current, shall comply with the following criteria:

i) The potential should not be 5% more positive than the protection criterion of the test period.

ii) The potential should not be more positive than the protection criterion plus 50 mV, i.e., −800 mV for ferrous structures with more than 2% of the test period.

iii) The potential should not be more positive than the protection criterion plus 100 mV, i.e., −750 mV for ferrous structures with more than 1% of the test period.

iv) The potential should not be more positive than the protection criterion plus 850 mV, i.e., 0 mV for ferrous structures with more than 0.2% of the test period.

2.3. Current requirement test

The current requirement test is generally adopted for pipelines with indescribable stray current. The complexity of the buried pipe system associated with the absence of previous construction data of the pipeline makes the current requirement test necessary because an appropriate ICCP design cannot be achieved in this regard. The current requirement test refers to using a temporary ICCP system at the construction site to provide cathodic current to the present pipeline and targeting to obtain the magnitude of impressed current, which can cathodically polarize the pipeline to meet the potential principle of the cathodic protection standard. The tentative results can supply a reference for further CP design.

The temporary ICCP system associated with the potential testing system constitutes the current requirement test. The temporary ICCP system comprises an anode bed (DN40 × 1000 mm, 30 pcs), a cathodic cable, a current rectifier (NCSRC01, Qingdao NCS Testing Protection Technology Co., Ltd. China), a slide rheostat (SF041, Shanghai Hanbiao Electronic Technology Co., Ltd. China), and some jumper wires connecting different pipelines to be protected. The potential testing system includes a test station, a PP, a digital multimeter (FLUKE289C, Fluke Corporation, USA), and a UDL2 potential collector. The connection diagram of the current requirement test is depicted in Figure 3, and the procedure of the current requirement test is listed as follows.

(i) Thirty pcs of steel tubes (DN40 × 1000 mm) were knocked into the wet zone approximately 50 m away from the pipeline that was affected by stray current. These steel tubes, serving as anode beds, were electrically connected to each other in parallel. The anode bed was electrically connected to the slide rheostat and further connected to the positive terminal in the current rectifier. The ground resistance of the anode bed in this work was approximately 2.2 Ω.

(ii) The negative terminal of the current rectifier was connected to the pipelines via the amphenol connector in the test post, powering the rectifier and then cathodically polarizing the pipelines.

(iii) The on and instant-off potentials of the structure were collected by the UDL2 instrument with a three-second ON and one-second OFF cycle after 30 min of polarization.

(iv) The output current of the rectifier was adjusted as soon as the instant-off potential of the pipeline revealed by the UDL2 instrument was beyond the required potential scope.

(v) The adjusted current was kept running for more than 24 h to ensure the desirable instant-off potential of the pipe.

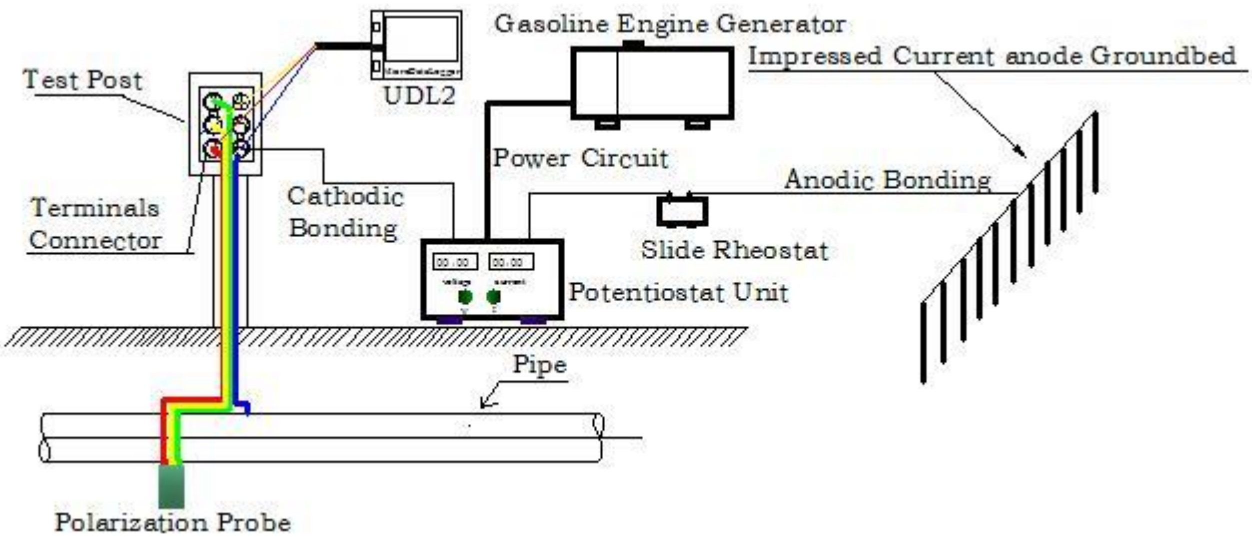

Figure 3. Connection diagram of the current requirement test.

The current magnitude of the current requirement test initially adopted 5 A. The output current was increased to 8 A, 12 A and 15 A step by step if the potentials varied insignificantly. The current was maintained at 15 A for 4 h because the potentials of the pipe to ground met the criteria in Section 2.2.

2.4. On and instant-off potentials

For buried steel pipelines disturbed by stray subway current, the stray current flows into the pipelines thorough the defects of anticorrosive coatings, where the pipeline potential deviates negatively and the pipeline is cathodically protected; thus, these defects are regarded as cathodic regions. The stray current in the pipeline subsequently flows out from the defects of the pipeline close to the subway, where pipeline is severely corroded, and these defects are regarded as anodic regions [20,21]. The anodic regions are the most dangerous part in the pipeline because they are the very sites where corrosion initiates on the pipeline. Nonetheless, the anodic regions are alterable with the states of subway operation [22-23].

When the pipeline is cathodically protected regardless of the stray current, the relationship between the on and instant-off potentials can be expressed as:

$$U_{on} = U_{off} + I_0 R \tag{1}$$

where U_{on} is the on potential, U_{off} is the instant-off potential, I_0 is the output current of the rectifier, and R is the loop resistance; thus, I_0R signifies the IR voltage drop of the measurement loop.

In the presence of stray current interference,

$$U_{on\text{-}stray} = U_{off\text{-}stray} + (I_0 + I_{stray})R \tag{2}$$

where $U_{on\text{-}stray}$ and $U_{off\text{-}stray}$ are the on potential and instant-off potentials of the pipeline in the presence of stray current interference, respectively. $I_{stray}R$ is the IR voltage drop derived from the stray current interference.

The instant-off potential of the cathodically polarized pipeline is related to the IR voltage drop of the measurement loop. The instant-off potential is formulated as,

$$U_{\text{off-stray}} = (I_0 + I_{\text{stray}})R_p \quad (3)$$

where R_p is the polarization resistance, which can be deemed a constant in a short time. Consequently, the variation in the instant-off potential ($U_{\text{off-stray}}$) is determined by the flow direction of I_{stray}. In the case of no interference, the instant-off potential of the pipeline equals U_{off}. As soon as the metro operates, the resultant stray current at the anodic region flows in the opposite direction compared with that at the cathodic region, resulting in the instant-off potential of the anodic region shifting positively. In addition, the magnitude of the potential deviation relates to the interference degree of the stray current.

3. RESULTS AND DISCUSSION

3.1. Analysis of stray current interference on pipelines

A sketch map of the gas pipeline associated with subway line No. 2 in Dongguan city of Guangdong Province is presented in Figure 4. The DN300 gas pipeline with a wall thickness of 11 mm is 15.13 km in length. The pipeline is protected against soil corrosion by a 3PE coating associated with sacrificial magnesium anodes. Eleven test posts were distributed along the pipeline.

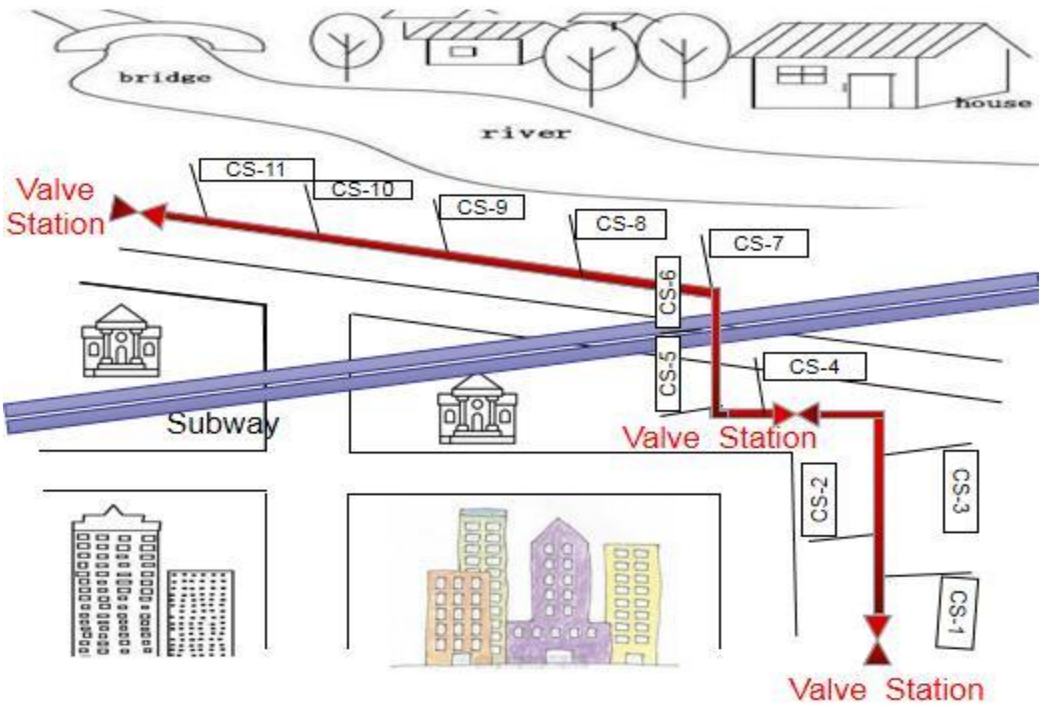

Figure 4. Comparative distribution of gas pipeline and subway lines No. 2, CS-1 to CS-11 signify the numbers of the test posts along the pipeline.

Figure 5a presents the minimum and maximum potentials obtained at each test post of the pipeline in the absence and presence of stray DC interference within 24 h. It is obvious that the stray DC strikingly affects the on and instant-off potentials of the pipeline. In Figure 5a, the fluctuation scope of the on potentials of the pipeline in the absence of DC interference (0:00-6:00 AM) is much smaller than that in the presence of DC interference (6:00 AM-12:00 PM), e.g., the potentials of pipeline revealed by CS-7 signify the most serious interference caused by stray DC, of which the minimum and maximum on potentials are −9.239 and 5.084 V, respectively; in contrast, the minimum and maximum instant-off potentials are −1.101 and −0.088 V, respectively. The highest potential fluctuation of CS-7 can be attributed to its location, which is the closest to the metro line among these test posts. The potential fluctuation decreases with an increasing distance of the test posts away from the subway line, indicating that the stray DC undoubtedly influences the potentials of the pipeline. It has been reported that buried gas pipelines located in the neighboring area of rail transit in Shanghai have pipe-to-soil potentials that fluctuate dramatically. The positive shift in the average potential is approximately 40 mV, and the instantaneous maximum positive shift of the potential reaches 200 mV [24], the results were consistent with that in this work. Nonetheless, the potential fluctuation of CS-4 in the absence and presence of stray DC are the lowest among these test posts, which can be ascribed to the presence of an adjacent value station, by which the stray DC can be drained by its grounding system.

In Figure 5b, the fluctuation scope of the instant-off potentials is much smaller than that of the on potentials in Figure 5a for each test station. The decayed fluctuation range can be due to the IR drop in the current loop that has been eliminated by the method mentioned in Section 2.1 using the UDL2 and PP.

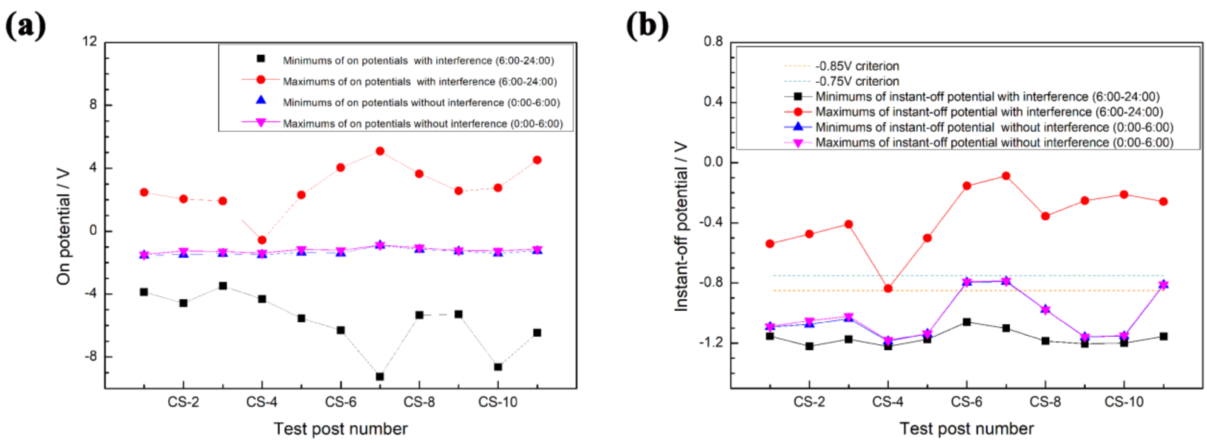

Figure 5. Extremes of the on (a) and instant-off (b) potentials of the pipeline monitored within 24 h of the absence and presence of stray DC interference. CS-1 to CS-11 signify the numbers of the test posts along the pipeline.

3.2. Effect evaluation of the subsistent CP

The earth resistivities obtained at each test post are listed in Table 1. The earth resistivities were acquired using the four-probe method, and the distance between the adjacent probes was two meters. The difference in earth resistivities can be ascribed to the variety of soil characteristics because the gas pipeline crosses through farmland, hills, and green belts, as depicted in Figure 4.

Table 1. Earth resistivities along with the gas pipeline route

Test post	CS−1	CS−2	CS−3	CS−4	CS−5	CS−6	CS−7	CS−8	CS−9	CS−10	CS−11
Earth resistivity (Ω m)	26.4	14.4	31.4	85.4	40.2	301.4	389.4	101.7	116.2	74.1	138.2

Note: CS-1 to CS-11 signify the numbers of the test posts along the pipeline.

According to the criteria of BS EN 12954 [18], the cathodic protection potential of pipelines subjected to the stray current effect should not be more positive than −0.85 V (vs. CSE) in the soil with an earth resistivity less than 100 Ω·m, whereas the value is −0.75 V (vs. CSE) in the case of an earth resistivity greater than 100 Ω·m. Two dashed lines signifying −0.85 V and −0.75 V are portrayed in Figure 5b, in which the instant-off potentials revealed by each test post indicate that the pipeline seems to be effectively protected cathodically in the absence of stray DC (0:00-6:00 AM). However, Figure 5b cannot reveal the actual state of the cathodic polarization of the pipeline because it merely illustrates the extrema of the instant-off potentials. It is worth noting that the fluctuations of the on and instant-off potentials in the presence of stray DC (6:00 AM-12:00 PM) validate that most of the pipelines perform as polarity alternating regions due to interference. The alternating area signifies the area where stray DC flows into or alternately flows out; for instance, most of the areas of the pipeline suffer corrosion when the stray current flows out from them. Consequently, the CP system of the pipeline is evidently affected by the DC stray current, and the pipeline is corroded for long running times.

Figure 6 presents the ratios of the instant-off potentials that are more positive than the CP criteria concerning the abovementioned AS2832.1−2015 obtained in the presence of DC interference (6:00 AM-12:00 PM).

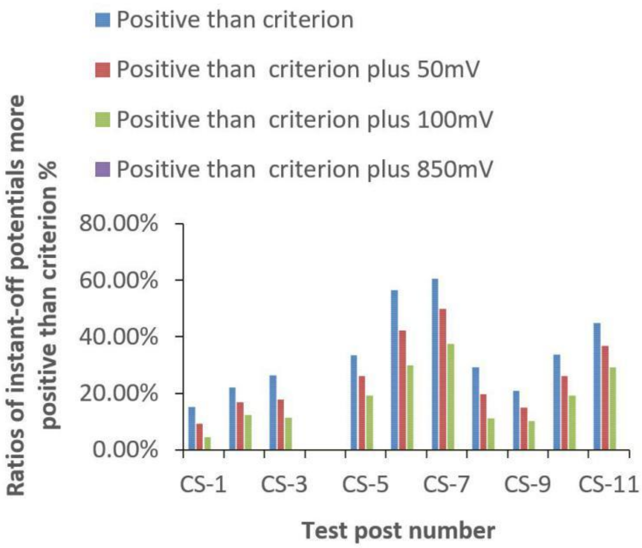

Figure 6. Ratios of the instant-off potentials that fail to meet the cathodic protection criteria obtained at each test post. CS-1 to CS-11 signify the numbers of the test posts along the pipeline.

In Figure 6, the ratios of the instant-off potentials failing to meet the criteria of the CS-6 and CS-7 test posts reach 56.46% and 60.47%, respectively. The subway intersects the pipeline at the CS-7 test station, while the CS-6 test station is located closest to the intersection, both of which validate that most of the time, some portions of the pipeline located in these areas lack cathodic protection compared with others and suffer the most serious corrosion. Within the monitoring period, most of the instant-off potentials obtained from these test posts cannot meet the cathodic protection criteria, indicating that the previous cathodic protection system cannot remedy the effect of stray current. In this case, it can be inferred that the pipeline corrodes for a long time. In the laboratory, under a DC current density of 10 A/m^2, the DC on-potentials of X52 pipe steel with a self-corrosive potential of -0.800 V (vs. CSE) at the anode and cathode can reach approximately −0.400 V and −1.500 V (vs. CSE), respectively; furthermore, in the soil solution and anodic areas, the DC current results in accelerated corrosion of the steel, which presents an essential threat to the integrity of the pipeline [25].

3.3. Determination of the anodic and cathodic regions

When the metro is running, the average value of the instant-off potential ($U_{\text{off-avg}}$) of the pipeline can be determined as:

$$U_{off-avg} = \frac{\sum_{i=1}^{n} U_{off}}{n} \tag{4}$$

where n is the total number of U_{off} within a certain monitoring period.

The $U_{\text{off-avg}}$ derived from each test post is adopted to evaluate the effectiveness of the subsistent CP system, namely, when $U_{\text{off-stray}}$ is more positive than the potential criteria introduced in Section 2.2, the corresponding portion of the pipeline lacks cathodic protection.

The $U_{\text{off-avg}}$ values of these test posts along the pipeline are listed in Table 2, all of which meet the cathodic protection principle mentioned in Section 2.2 concerning the earth resistivities in Table 1. This result shows that the previous CP system can effectively protect the pipeline from corrosion in the absence of interference. Nonetheless, $U_{\text{off-avg}}$ cannot be adopted to determine the effectiveness of the CP system in the presence of stray current interference because the stray current will flow in and out in the very region of the pipeline with the variation in the operating state of the metro. In view of this, we introduce a new parameter $\mathrm{U}_{\text{off-stray-avg}}$, which is the average value of $U_{\text{off-stray}}$ that is more positive than $U_{\text{off-avg}}$ for the potentials derived from a specific test post (Eq. 5). When $U_{\text{off-stray}}$ is more negative than $U_{\text{off-avg}}$, it is believed that the current would flow into the specific region of the pipeline, leading to an enhanced CP. Nonetheless, as soon as $U_{\text{off-stray}} > U_{\text{off-avg}}$ in the presence of stray current interference, the corresponding region of the pipeline must be in the state of current discharge; thus, $U_{\text{off-stray-avg}}$ signifies the average potential state of a specific region of the pipeline. Consequently, the $U_{\text{off-stray-avg}}$ can signify the degree of anodic polarization aroused by stray current to some extent. Combined with the potential criteria introduced in Section 2.2, we can propose a reasonable method to determine the anodic/cathodic regions on pipelines in the presence of DC interference, viz. comparing the value of $U_{\text{off-stray-avg}}$ with the potential criteria introduced in Section 2.2, namely, when $U_{\text{off-stray-avg}} > -0.85$ V ($\rho < 100\ \Omega\cdot$m, CSE), the anodic region is determined, and vice versa.

$$U_{off-stray-avg} = \frac{\Sigma^{n}{}_{i=1} U_{off-stray}}{n}, (U_{off-stray} > U_{off-avg}) \tag{5}$$

Table 2. Evaluation of the anodic and cathodic areas of pipelines disturbed by stray subway current.

Test post number	$U_{\text{off−avg}}$	$U_{\text{off−stray−avg}}$	Potential criteria (vs. CSE) concerning the earth resistivities in Table 1	Determination
CS−1	−1.091 V	−0.964 V	−0.850 V	Cathodic region
CS−2	−1.068 V	−1.033 V	−0.850 V	Cathodic region
CS−3	−1.031 V	−0.893 V	−0.850 V	Cathodic region
CS−4	−1.182 V	−1.087 V	−0.850 V	Cathodic region
CS−5	−1.135 V	−0.904 V	−0.850 V	Cathodic region
CS−6	−0.794 V	−0.638 V	−0.750 V	Anodic region
CS−7	−0.784 V	−0.611 V	−0.750 V	Anodic region
CS−8	−0.976 V	−0.777 V	−0.750 V	Cathodic region
CS−9	−1.155 V	−0.896 V	−0.750 V	Cathodic region
CS−10	−1.152 V	−0.911 V	−0.850 V	Cathodic region
CS−11	−0.809 V	−0.627 V	−0.750 V	Anodic region

Based on the abovementioned discussion, the calculated and evaluated results are shown in Table 2, from which CS-6, CS-7 and CS-11 are determined to be the anodic regions in the presence of stray current interference. The CS-6 and CS-7 test stations are located closer to the intersection of the pipeline and the metro line than others, and the comparatively low loop resistances there result in the current flowing into the coating defects elsewhere on the pipeline being more apt to flow out at the CS-6 and CS-7 sites, namely, the current discharges there and preferentially corrodes the pipeline.

It is worth noting that CS-11, located at the end of the pipeline, which is comparatively far from the intersection of the pipeline and metro line, is determined to be the anodic region. This result is because CS-11 is located near the river, as depicted in Figure 4, resulting in the comparatively low earth resistance in the deep earth layer (Table 1). Combining the high potential fluctuation of CS-11 in Figure 5a, it can be inferred that the anti-corrosion coating of the pipeline within this region has a large number of defects. In addition, an insulation joint is installed at the end of the pipeline of the CS-11 region, both of which promote the stray current being more apt to flow out from the coating defects and leading to the anodic characteristic of this region. Referring to the polarity of CS-1, which is also located far from the intersection but exhibits cathodic characteristics due to the superior coating performance on the pipeline of the CS-1 region (Figure 5a), the comparatively low difference between the maximum (2.468 V vs. CSE) and minimum potentials (−3.871 V vs. CSE) with interference indicates the desirable coating integrity of the CS-1 region (see Figure 4 and Table S1).

3.4. Current requirement determination

Impressed current cathodic protection commonly used in long-distance pipeline systems can effectively mitigate stray current effects and provide cathodic protection [24]. However, as discussed above, because of cathodic protection system failure, the subsistent CP system cannot effectively protect the whole pipeline against corrosion due to the presence of anodic regions, e.g., CS-6, CS-7 and CS-11. The criteria for selecting the position for the current requirement test should meet the following:

(i) be close to the anodic region of the pipeline;

(ii) be near the pipeline region with the most serious interference, such as the intersections of the subway and the pipeline; and

(iii) be nearby the valve chest of the pipeline, which facilitates the current requirement test and subsequent installation of the ICCP system in the valve chest.

In this case, the region of the test post (CS-11) is the most suitable site for the current requirement test because it meets the above three principles.

Figure 7a shows the extrema and average instant-off potentials of the pipeline with a 15 A temporary cathodic current. Compared with Figure 5b, the maximums of the instant-off potentials deviate negatively in Figure 7a, suggesting that the impressed current weakens the influence of positive potential deviation caused by the stray current. In Figure 7b, the quantities of the instant-off potentials failing to meet the criteria are thoroughly within the limitations that the CP criteria suggests.

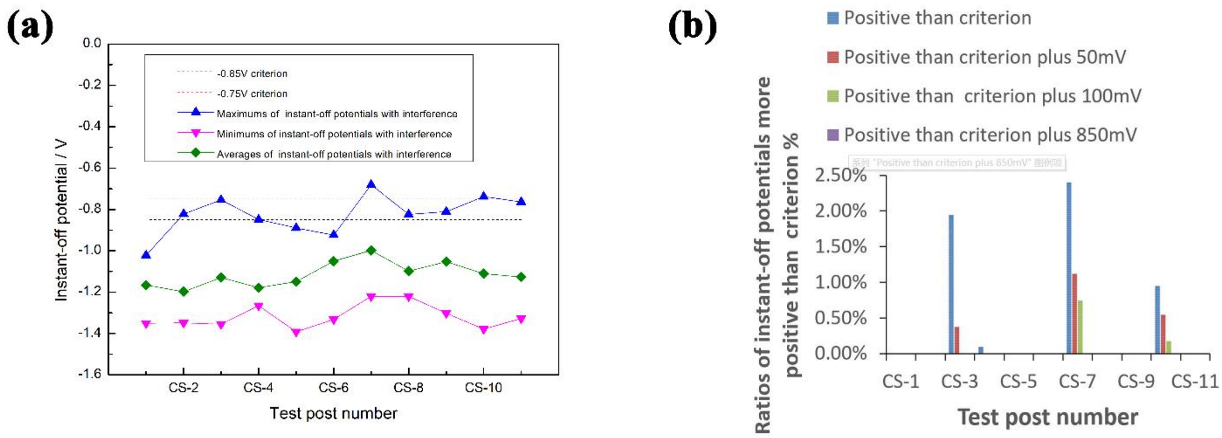

Figure 7. Extremes and averages of the instant-off potentials of the pipeline under 15 A cathodic current with DC interference (a). (b) Ratios of the instant-off potentials that fail to meet the cathodic protection criteria obtained at each test post with 15 A cathodic current. CS-1 to CS-11 signify the numbers of the test posts along the pipeline.

3.5. Performance of the ICCP and effect analysis

3.5.1. Calculation the ICCP system

Based on the results of the current requirement test, an additional ICCP system was installed near the valve chest near the No. 11 test post. The ICCP system was composed of a deep anode bed, a rectifier, a junction box, confluence, and connecting cables. The anode body was 40 m long and was installed in an auxiliary anode bed with a depth of 60 m. There were 10 mixed metallic oxide anodes connected in series in the anode body, whose leaving space was filled with coke. A sketch map of the anode body associated with the connection diagram is shown in Figure 8.

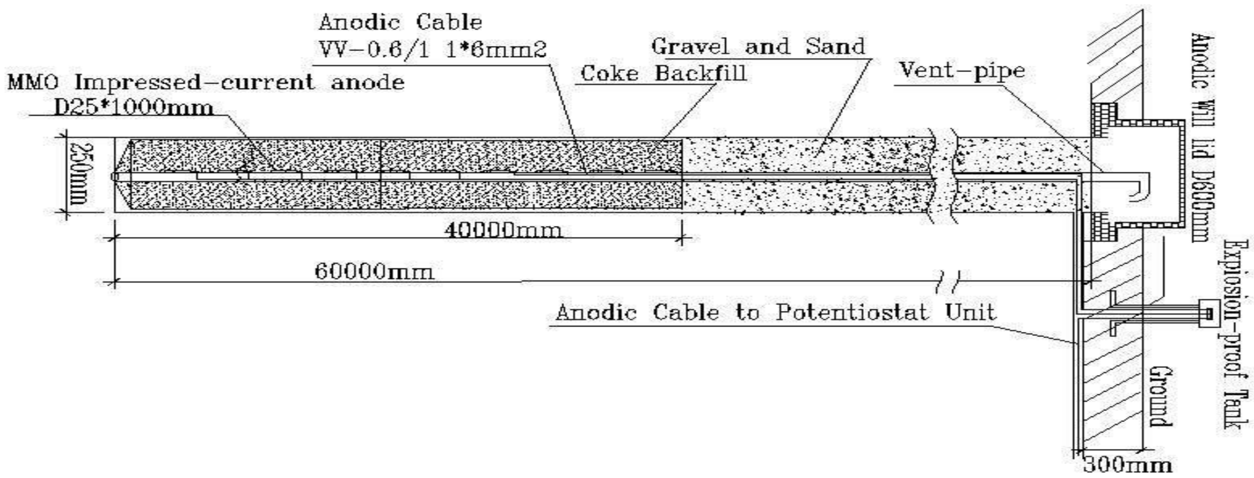

Figure 8. Schematic of the anode body [26].

The computational formula of the ground resistance of a deep auxiliary anode bed can be expressed as

$$R = \frac{\rho}{2\pi L}\ln(\frac{2L}{D}) \tag{6}$$

where R is the ground resistance of the anode body (Ω), ρ is the soil resistivity (75.6 Ω·m, which is the average earth resistivity adjacent to the anode body), L is the length of the anode body (40 m), and D is the diameter of the auxiliary anode length (0.25 m). In this case, the ground resistance of the anode body can be determined ($R \approx 1.74$ Ω). Concerning the degradation of the coating on the pipeline with an increasing operating time, the current (15 A) derived from the current requirement test will not meet the increasing current demand. Consequently, the rated current of the rectifier is estimated to be 40 A, and the corresponding rated voltage is 60 V.

3.5.2. Effect analysis on the impressed current cathodic protection

As soon as the deep anode bed was installed, the performance of the ICCP system was evaluated using the UDL2 instrument, which was connected in the form shown in Figure 2. Three different magnitudes of cathodic current (11 A, 13 A, and 15 A) were impressed on the pipeline for 24 h. Figure 9a depicts the extremes and averages of the instant-off potentials of the pipeline under 15 A cathodic current within 24 h.

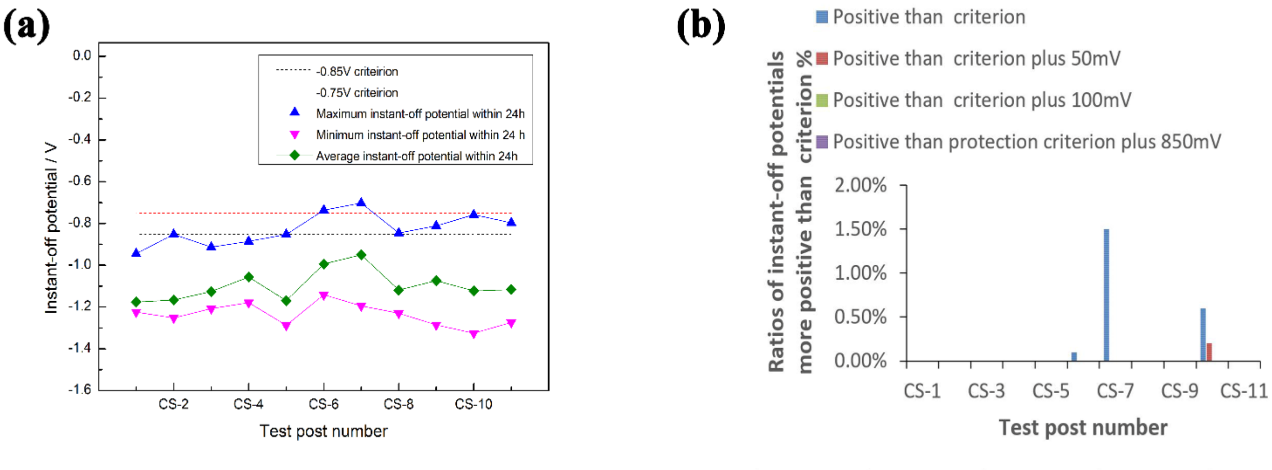

Figure 9. Extremes and averages of the instant-off potentials of the pipeline under 15 A cathodic current within 24 h (a). (b) Ratios of the instant-off potentials that fail to meet the cathodic protection criteria obtained at each test post with 15 A of cathodic current. CS-1 to CS-11 signify the numbers of the test posts along the pipeline.

Compared with the instant-off potentials without the external supplemental ICCP in Figure 5b, the instant-off potentials of the pipeline show striking negative shifts. Comparatively more positive instant-off potentials are also revealed by the CS-6 and CS-7 test posts, which are more positive than −0.75 V; thus, the protective effect is obvious compared with that in Figure 5b. Figure 9b presents the ratios of the instant-off potentials that fail to meet the CP potential criteria; 0.1%, 1.5% and 0.6% of the CS-7, CS-10 and CS-6 test posts, respectively, are observed, all of which are lower than the ratio of 5% as depicted in Section 2.2. This result suggests that the impressed current (15 A) successfully prevents the pipeline from corrosion promoted by stray DC.

Stray DC subway current corrosion is one form of electrochemical corrosion because the driving force of electron transfer is the potential difference between different regions of pipelines in different states [27]. The electrochemical corrosion process of the stray current comprises cathodic and anodic processes simultaneously. The cathodic reaction occurs in the region where current flows into the pipeline associated with the oxygen depolarization process when presented in neutral and alkaline environmental media but is associated with the hydrogen evolution reaction in acidic environments [28,31].

Under neutral or alkaline conditions, the cathodic reaction is

$$\frac{1}{2}O_2 + H_2O + 2e \rightarrow 2OH^- \tag{7}$$

Under acidic conditions, the reaction is

$$2H^+ + 2e \rightarrow H_2 \tag{8}$$

Moreover, the anodic reaction exists in the region where the stray current flows out of the pipeline. The anodic reaction is

$$Fe \rightarrow Fe^{2+} + 2e^- \tag{9}$$

The CP technique can suppress stray DC corrosion and relieve the interference influence of stray current [32] by the compensation of impressed cathodic current. The charge consumption by the interfacial capacitance effect, as well as the extra reactions of other species rather than iron under dynamic DC current corrosion, account a significant part in depressing the metal dissolution when the current flows out of the pipeline [33]. Regarding the previous cathodic region on the pipeline, the impressed cathodic current will further polarize this region with a more negative potential. It is worth mentioning that the cathodic current should not be too high to prevent hydrogen-induced cracking [34, 35].

As shown in Figure 9, the ICCP system doubtlessly relieves stray current corrosion, although it cannot fundamentally solve the interference problem of stray current. Table 3 presents the extremums of the instant-off potentials in the absence and presence of external ICCP systems derived from Figures 5b and 9a, in which the deviations are also listed for fluctuation comparison. As soon as the ICCP system is in operation, the minimums of the instant-off potentials negatively shift slightly, whereas the maximums notably shift. This result validates that the cathodic current will preferentially flow to the electropositive regions of the pipeline and that the flow direction will vary with the variation in the anodic/cathodic region of the pipeline with stray DC interference. In addition, the impressed current drives the cathodic reduction of dissolved oxygen to produce hydroxyl ions, elevating the solution pH. The surface of buried pipelines will cause local alkalization of the solution through the production of OH^- by cathodic reactions [25]. Therefore, a calcium-magnesium deposing layer would be formed in an alkaline environment, resulting in a mitigation of DC stray current corrosion [36].

Table 3. Extremums of the instant-off potential in the absence and presence of external ICCP derived from Figures 5b and 9a, respectively.

Type of test	CS-1	CS-2	CS-3	CS-4	CS-5	CS-6	CS-7	CS-8	CS-9	CS-10	CS-11
Maximums of the instant-off potentials without ICCP, V	−0.539	−0.474	−0.409	−0.837	−0.501	−0.154	−0.088	−0.355	−0.252	−0.211	−0.258
Maximums of the instant-off potentials with ICCP, V	−0.944	−0.852	−0.913	−0.885	−0.852	−0.736	−0.702	−0.8457	−0.811	−0.757	−0.796
Deviations, V	−0.405	−0.378	−0.505	−0.048	−0.351	−0.582	−0.614	−0.490	−0.559	−0.546	−0.538
Minimums of the instant-off potentials with ICCP, V	−1.154	−1.220	−1.175	−1.179	−1.174	−1.060	−1.101	−1.186	−1.204	−1.200	−1.156
Minimums of the instant-off potentials with ICCP, V	−1.224	−1.252	−1.207	−1.222	−1.287	−1.141	−1.194	−1.230	−1.285	−1.325	−1.273
Deviations, V	−0.070	−0.032	−0.032	−0.043	−0.114	−0.081	−0.093	−0.046	−0.081	−0.125	−0.117

4. CONCLUSIONS

In summary, the DC subway stray current causes DC interference of buried pipelines. The maximum fluctuation section of the structure-to-electrolyte voltage in the intersection of the pipeline and subway reaches up to 14 V, and the proportion that the off potential covers above 60% does not meet the cathodic protection rule. As a test method to simulate that the ICCP system suppresses stray current corrosion, the current requirement test has validated the functional effects of the impressed current cathodic protection system, ensuring the reliability of the implementation effect from stray current protection.

By adding the cathodic protection system and applying cathodic current to the pipeline, namely, completely deviating the pipeline potential negatively to the corrosion-free region and generating a settled calcium and magnesium layer on the pipeline surfaces by cathodic polarization, the cathodic/anodic polarization arising from stray current is relieved, the potential fluctuation is reduced, and the current distribution becomes more even [36]. Therefore, the ICCP system of buried pipelines can effectively solve the corrosion problem caused by stray current. Moreover, before impressed current protection is conducted, the current requirement test results can be used to provide a basis for the proper design of ICCPs for metro systems in the future.

The influence of the metro line on the corrosion of the gas pipeline in Dongguan City was evaluated in this work, in view of which the polarity of each test post was determined. After that, an additional ICCP system was installed, and some tentative conclusions are provided below:

(1) The stray DC stemming from the metro evidently affects the corrosion of the gas pipeline, especially at the intersection site.

(2) The pre-existing ICCP system cannot protect the pipeline from corrosion in the presence of DC stray current.

(3) Another ICCP system was added to compensate for the stray current after the current requirement test, and the potentials of the pipeline shift negatively and meet the criteria of CP.

(4) A new method for the determination of anodic/cathodic regions is proposed.

ACKNOWLEDGEMENTS
We acknowledge the financial support from the National Natural Science Foundation of China (Code: 51771057) and Qingdao NCS Testing Protection Technology Co., Ltd. China (NCS Control Code: NJS18019).

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