The Effect of Steel Segment's shielding against Stray Current from DC Railway Systems

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Abstract: It is generally known that at the intersection between underground pipes and railway trucks, stray currents originating from the leak currents from DC electric railways cause galvanic corrosion. The Bureau of Waterworks Tokyo, Metropolitan Government (hereinafter the Tokyo Waterworks) frequently has difficulty with the open-cut method when laying new pipes under trunk roads and railway tracks in urban areas, so new non-cutting construction methods such as the tunneling shield method are frequently used, which has led to concerns about galvanic corrosion of underground pipes at railroad intersections. However, there have been almost no academic studies on corrosion caused by stray currents with regard to how conditions such as the material, burial depth, and soil resistance of segments used in the tunneling shield method affect pipes inside the shielding. This paper successfully clarifies that "the stray electric current flowing into and out of the inner pipe is almost completely suppressed" by the electric field effect by the shielding made of steel segments, and the result is verified based on actual measurements in the field.

Keywords: shielding effect; steel segment; stray current

1. Introduction

At present, the renewal of aging public infrastructure is becoming an important public concern. According to the estimates made by the Corrosion and Loss Investigation Committee upon request by the national government, the massive economic loss is caused by corrosion; one of the factors is aged deterioration It also mentions the importance of risk management and asset management in the future based on scientific knowledge.

Corrosion of underground pipes including water pipelines can be broadly categorized into galvanic corrosion and natural corrosion. Galvanic corrosion is defined as "the phenomenon in which a metallic object corrodes due to electrolysis when current flows out of metal buried underground" (The Ministry of Land, Infrastructure, Transport and Tourism). In Japan, where direct current electric railways are common, direct current corrosion caused by stray currents from the rail (return rail) when electric current from the overhead line travels through the rails and returns to the transformer (direct current stray current corrosion) is simply referred to as “galvanic corrosion”, and it is believed to be caused by current leaking through sleepers and track beds because insulation between the rail and the ground is not perfect. In order to prevent this galvanic corrosion, companies involved such as electric railways, waterworks, gas, electric power, and telecommunications companies are required to take effective countermeasures by means of mutual understanding and cooperation.

The Tokyo Waterworks is actively promoting the renewal of aging water pipelines and the duplexing and networking of water pipelines, but in many cases it is too difficult to lay new pipelines with the open-cut construction method under trunk roads and railway tracks in urban areas, so new non-cutting construction methods such as the tunneling shield construction method are frequently used. It is known that buried water pipelines which cross railway tracks in particular are affected by galvanic corrosion due to stray currents caused by currents leaking from DC electric railways. The Tokyo Waterworks has taken measures against corrosion in accordance with the individual circumstances based on the results of surveys on galvanic corrosion, but there are still concerns about the effect of galvanic corrosion of underground water pipelines built with the tunneling shield method at where they cross under railways. Yet, there have been almost no academic studies on stray-current corrosion with regard to how conditions such as the material of the segments, burial depths, and soil resistances affect pipes inside the shield. The Tokyo Waterworks conducted collaborative research with the Tokyo Institute of Technology and Yokohama National University to reveal the mechanism of corrosion in such cases and establish more appropriate anti-corrosion measures.

This study using model analysis and simulation successfully clarified that, in the shield construction part consisting of steel segments, the stray electric current flowing into and out of the inner pipe is almost completely suppressed by the electric field effect by the steel segments, and the result was verified based on actual measurements in the field (construction sites using the shield construction method with steel segments).

2. Research Method

In this research, we constructed a mathematical model on the behavior of the corrosion in question and verified the basic corrosion mechanism with a beaker scale experiment. After that, we made continuous measurements on the rail-to-ground and pipe-to-ground electric potentials, which

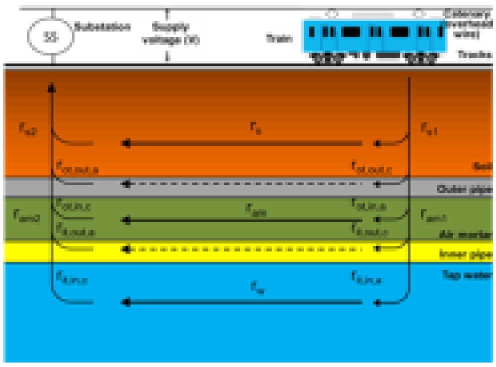

Figure 1 Flow of stray electric current

were the indicators of the effects of stray-current corrosion, at the points where the actual shielded pipe cross under railway tracks.

(1) Constructing a theoretical formula (mathematical model)

An image of stray electric current flowing into the water pipes laid by the shield construction method is shown in Figure 1. When a stray electric current flows into the shield, it is believed to take multiple routes as shown in Figure 1. When this happens, stray electric currents flow in and out through low resistance routes.

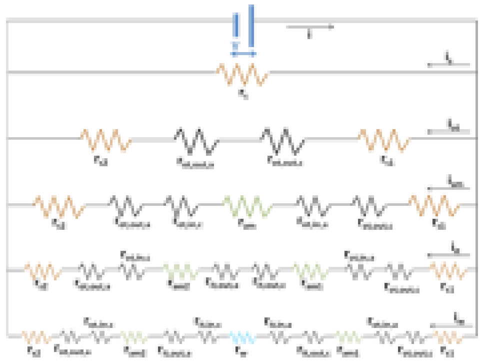

Figure 2 Electric Equivalent Circuit

Here, the resistance components are the soil resistance r_s, the air mortar r_{am}, the resistance of tap water r_w, and the interfacial polarization resistance of the pipes*.

*Interfacial Polarization Resistance:

Although the amount of metal corrosion can be calculated by finding the corrosion current, the current at the metal interface is an electrochemical reaction involving ions and depends on the properties of metal and composition of the electrolytes (earth, mortar). Therefore, in the experiment the interfacial polarization resistance was calculated from the properties found by continuous measurement of electric potential and electric current with a combination of metal pieces in soil assumed to be in the actual environment.

Assuming a supply voltage of V [V] that generates the stray current, an equivalent circuit is shown in Figure 2.

The stray current i [A]is expressed by theoretical expression (A) from Ohm's Law.

[Stray Current Theoretical Formula] (A)

$$\boldsymbol{i} = \frac{\boldsymbol{V}}{\boldsymbol{R}} = \boldsymbol{i}_{\mathbf{s}} + \boldsymbol{i}_{\mathbf{ot}} + \boldsymbol{i}_{\mathbf{am}} + \boldsymbol{i}_{\mathbf{it}} + \boldsymbol{i}_{\mathbf{w}}$$

$$= \frac{V}{r_s} + \frac{V}{r_{s1} + r_{ot,out,c} + r_{ot,out,a} + r_{s2}} + \frac{V}{r_{s1} + r_{ot,out,c} + r_{ot,in,a} + r_{am} + r_{ot,in,c} + r_{ot,out,a} + r_{s2}} + \cdots$$

$$+ \frac{V}{r_{s1} + r_{ot,out,c} + r_{ot,in,a} + r_{am1} + r_{it,out,c} + r_{it,out,a} + r_{am2} + r_{ot,in,c} + r_{ot,out,a} + r_{s2}}$$

$$+ \frac{V}{r_{s1} + r_{ot,out,c} + r_{ot,in,a} + r_{am1} + r_{it,out,c} + r_{it,in,a} + r_w + r_{it,in,c} + r_{it,out,a} + r_{am2} + r_{ot,in,c} + r_{ot,out,a} + r_{s2}}$$

i : all stray current | i_s : stray current flowing to the ground
i_{ot} : stray current flowing to outer pipe | i_{am} : stray current flowing to air mortar
i_{it} : stray current flowing to inner pipe | i_w : stray current flowing to tap water
i_{it} : stray current flowing to inner pipe | i_w : stray current flowing to tap water
r_{am} , r_{am1}, r_{am2}: air mortar resistance | r_w : tap water resistance

$r_{ot,out,c}$: outer pipe outside cathode interfacial polarization resistance
$r_{ot,out,a}$: outer pipe outside anode interfacial polarization resistance
$r_{ot,in,c}$: outer pipe inside cathode interfacial polarization resistance
$r_{ot,in,a}$: outer pipe inside anode interfacial polarization resistance
$r_{it,out,c}$: inner pipe outside cathode interfacial polarization resistance
$r_{it,out,a}$: inner pipe outside anode interfacial polarization resistance

***Interfacial Polarization Resistance**

$r_{it,in,c}$: inner pipe inside cathode interfacial polarization resistance
$r_{it,in,a}$: inner pipe inside anode interfacial polarization resistance

(2) Verification of the theoretical formula of the stray current through beaker scale experiment

To verify theoretical formula (A), we constructed five layers consisting of soil, outer pipe (steel), air mortar, inner pipe (steel), and tap water, to simulate the corrosion environment and piping conditions using solutions and panels. Then we generated a stray current by applying voltage and verified that our theoretical formula (A) and measured values in the experiment match the theoretical values through precise measurement. (Figure 3)

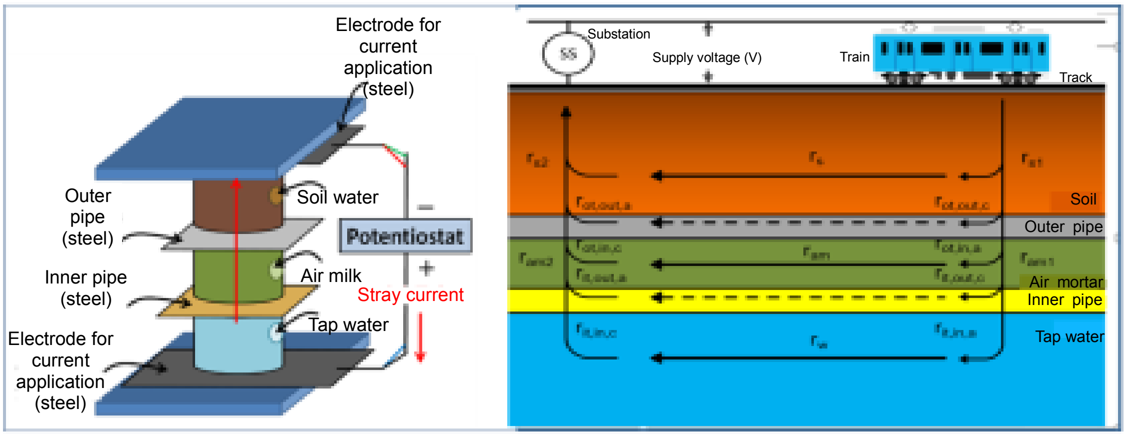

Figure 3 Beaker Scale Experiment

We conducted the experiment using the experimental cell shown on the left side of Figure 4. By combining many acrylic cylindrical containers and sandwich electrodes between them, it is possible to simulate stray electric current flowing inside water pipes. The cylindrical containers have holes for pouring in the solution, and are filled with solution through these holes. Experimental cells were set up by sandwiching these acrylic cylindrical containers and electrodes between two acrylic panels and fixing them in place with screws. There are four possible cases shown in Figure 1 for the routes through which stray current flows out of water pipes.

Each case was simulated with an experimental cell. (Figure 4)

・Case (i): Current flows into the outer pipe then flows out to the soil

・Case (ii): Current flows into the air mortar, then flows out to the soil via the outer pipe

・Case (iii): Current flows into the inner pipe, then flows out to the soil via the air mortar and outer pipe

・Case (iv): Current flows into the tap water then flows out to the soil via the inner pipe, air mortar, and outer pipe

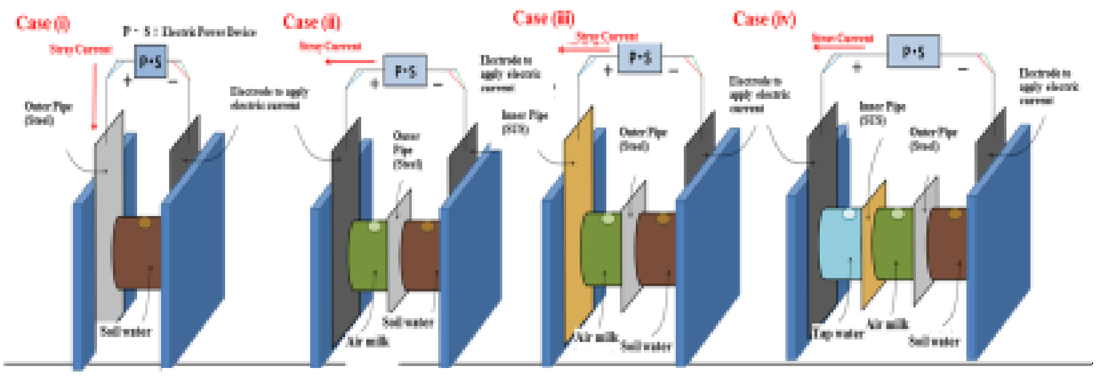

Figure 4 Experiment Circuit diagram simulating each case

Only 1 type of steel piping was usd as piping material, and an electrode for applying electric current was necessary to conduct the experiment, so we used steel (SS400) for the electrode. Steel pipes were simulated with steel plates (SS400).

In the experimental cells used to simulate each case, we measured how much electric current was generated when the same voltage was applied, then calculated the inflow ratio. Figure 4 only shows the outflow of stray current, but in the experiment we also verified a situation in which stray current flows into water pipes by reversing the polarity of the power supply and running the current.

(3) Numerical Analysis Simulation

We also conducted a numerical analysis simulation with the boundary element method (BEM) regarding the effect of stray current in pipelines built with the shield construction method. As shown in Figure 5, we simulated a pipeline built with the shield construction method to simulate a scenario with φ3000 mm steel segments for the outer pipe, φ2000 mm cast iron pipes for the inner pipes, and a soil resistivity of 70 (Ω/m).

External voltage simulating a stray current was 0.6 V.

(4) Field survey in water pipes crossing under a railway

In order to verify the model formula, beaker test and numerical analysis results, we carried out verification with

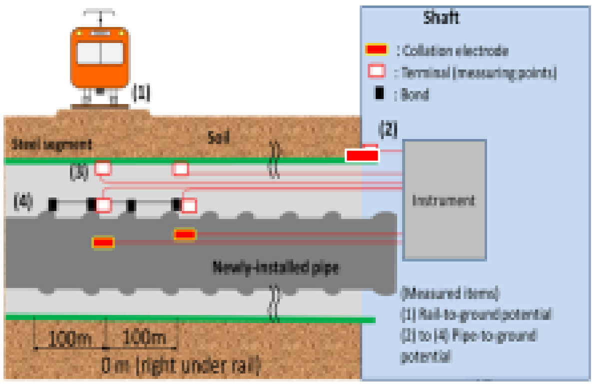

Figure 5 Measurement system from the actual field survey

We evaluated the effect by conducting continuous measurements for 8 days with the measurement system shown in table1 in the raw water connection pipelines crossing under railway tracks.

3 Research Results & Details Studied

(1) Verification of the theoretical formula with beaker scale experiment

Measurement results from the beaker scale experiment for the theoretical formula are shown in Figure 7.

Measured Item				Case (i)	Case (ii), (iii)	Case (iv)
VoltageApplied	+0.5	Inflow Current	[mA]	+1.6	+0.0379	+0.0272
		Inflow Ratio	[%]	96.1	2.28	1.63
* Direction shown in Figure 5	+1.0	Inflow Current	[mA]	+10.7	+0.1005	+0.0949
		Inflow Ratio	%	98.2	0.922	0.871
VoltageApplied	+0.5	Inflow Current	[mA]	-2.07	+0.00427	-0.0015
		Inflow Ratio	%	99.7	0.206	0.0723
*Opposite direction of direction shown in Figure 5	+1.0	Inflow Current	[mA]	-10.9	-0.0756	-0.00175
		Inflow Ratio	%	99.2	0.688	0.159

Figure7 Measurement results from the beaker scale experiment

Case numbers correspond to the numbers in Figure 5. Regardless of the direction of the stray current, approximately 99% of stray current flowed into the outer pipe, and only about 1% flowed into the inner pipe. This is possibly because steel in the air mortar (high pH steel) forms a passive film, which has high interfacial polarization resistance. From this fact, we found that the danger of corrosion due to stray current flowing into the inner pipe in the shielding was extremely low,as long as the space between the pipe and the segment is filled with air mortar.

Theoretical curve(graph) for the inflow current when stray current flows in each case was drawn according to the theoretical formula in Figure 3. Figure 9 shows the graph of the inflow stray current and the actual measured values as a dot plot. The vertical axis shows supply voltage V[mV] while the horizontal axis shows the inflow current density[$\mathrm{mA/cm^2}$]. This graph shows how much stray current flows in for each case (horizontal axis) when a certain voltage (vertical axis) is applied. The theoretical curve in Figure8 almost perfectly coincides with the plot of actual measurements.

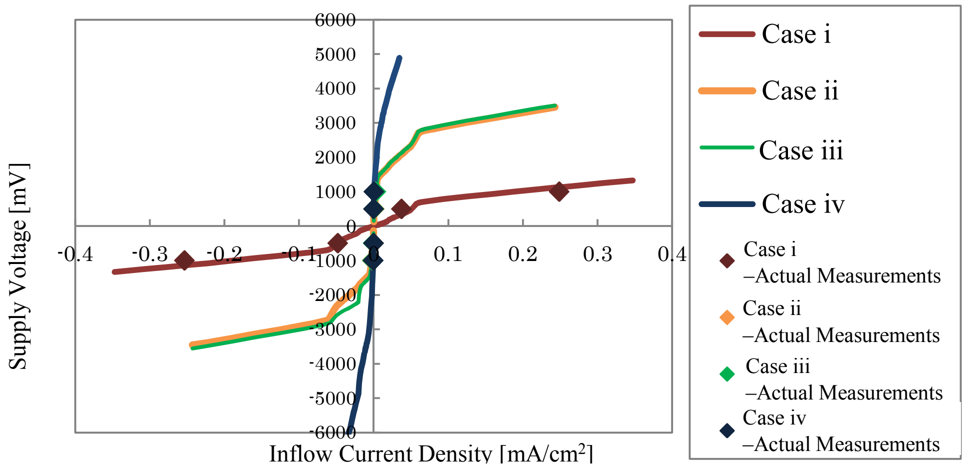

Figure 8 Theoretical line (solid lines) and actual values (plot) of inflow current in these experiment conditions

(2) Numerical Analysis Simulation Results

The following is a description of the simulation results. Color coding represents the magnitude of the corrosion current:red indicating it was large on the side where current flows out of the distribution pipe, and blue indicating it was large on the side where current flows into the distribution pipe. Green indicates that zero electric current. Places where the current flows out of the distribution pipe are at risk of corrosion. If the outflow of the current per unit area of the pipe (current density) is 0.1 (A/m^2), the pipe thins at a rate of 0.11 (mm) per year.

The stray current is set to flow in from the bottom left of Figure 10 and flow out from the top left of Figure 9. We can see from Figure 9 that almost no stray current flows into the inner pipe. From this fact, we also confirmed that the results of the simulation analysis agree almost completely with the model formula and the beaker scale experiment measurement results.

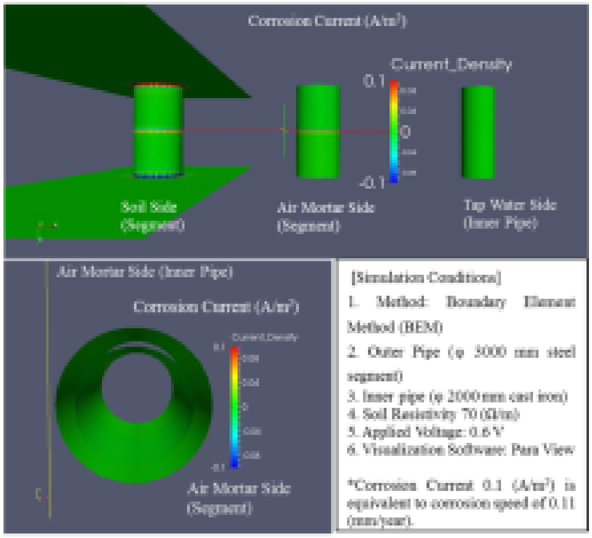

Figure 9 Numerical Simulation Results

(3) Measurements in the actual field

Figure 10 shows a schematic diagram of measurement conditions. Measured items are the rail-to-ground electric potential directly under where the pipe crosses under the railway and the pipe to ground electric potential at measurement points, because it is impossible to directly measure the stray electric current. (It is empirically known that there is no effect if the fluctuation range of pipe to ground electric potential at the measurement point is 50 mV or less with respect to the rail electric potential fluctuation.) Measurement results are shown with a graph at the bottom of Figure 10.

① Because the electric potential in the rail varies greatly and its polarity also fluctuates, it is observed that there is electric current outflow and inflow through the rail.

② While fluctuations in electric potential due to the stray current were observed outside the steel segments, the range of pipe-to-ground electric potential fluctuation was 50 mV or less.

③ Because electric potential fluctuation was not observed inside the steel segments and the inner pipe, it was verified from measurement that the shielding effect in the steel shield prevents stray current from flowing into and out of the internal pipeline.

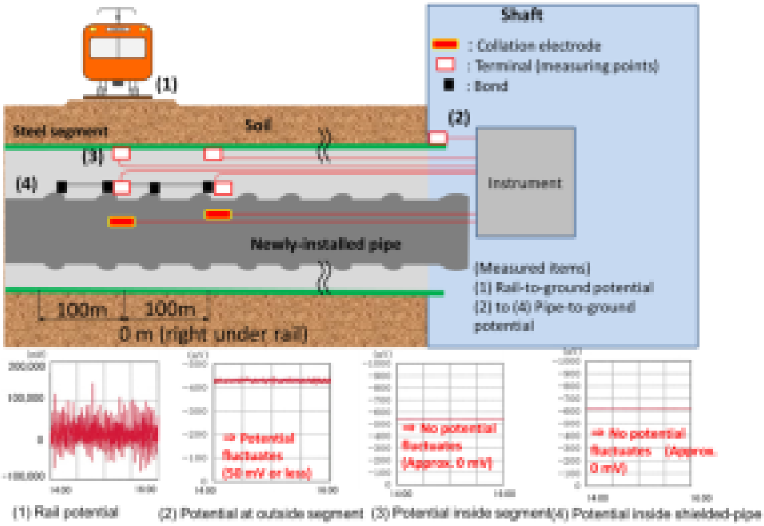

Figure 10 Measurements and results in the field

4. Conclusion

This research confirmed that steel segments are highly effective in electric shielding.These findings revealed that when using steel shields in the future, corrosion measures such as bonding are not necessary regardless of the type of shielded distribution pipes; therefore, we would be able to reduce costs and energy when taking actual measure against corrosion. However, electrochemical behaviors such as macro-cell corrosion still remain largely unexplained, so continued surveys and research are necessary.Moreover, in maintenance and management, the monitoring of the trends in pipe-to-ground potential and the consideration of additional measures in case the effect of stray currents becomes serious would be important.

In the future, we will expand the numerical analysis technique used in this research for qualitative prediction of the corrosion speed and risk assessment in the distribution pipe systems of different shapes and environment.

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