Dynamic Stray Current Interference Testing And Mitigation Design For A 90-Inch Water Main

Authors: Rogelio de las Casas, Ron Turner, Kristi Roe; EN Engineering

This paper discusses two sections of pipeline installed in a circular rib and lag tunnel. These tunnels are geographically the closest points between the electric railroad and the 90-inch water transmission pipeline.

Abstract

A large number of pipelines are routed around or through the Chicago metropolitan region of Illinois. Pipeline operators are faced with operational and maintenance challenges that include the mitigation of static and dynamic stray current interference. This interference is generated by DC current sources which can include foreign pipelines and DC electric rail systems. In the Chicago area, the Chicago Transit Authority (CTA) railway system is one of the sources of dynamic DC stray current that can affect pipeline operators.

Preliminary testing conducted on a local 90-inch water transmission pipeline was observed to indicate the presence of dynamic stray current interference. Based on this preliminary testing, more advanced testing was initiated. Ultimately this activity lead to design services to address and mitigate the DC stray current found on this water transmission pipeline.

Field testing and analysis, calculations and the final mitigation design are presented in this paper.

Introduction

When testing on a local 90-inch water transmission pipeline indicates the presence of dynamic stray current interference, additional confirmatory testing and design services were initiated. The focus of this work is to assess the level of stray current interference and after field testing recommend a design to help mitigate the effects of the stray dynamic DC current.

Pipeline Characteristics

The water transmission pipeline consists of approximately 9 miles of 90-inch diameter Pre-Stressed Concrete Cylinder Pipe (PCCP). The pipeline runs in the vicinity and adjacent to the CTA electric rail system. The pipeline is directly buried for the majority of the distance; however, there are two (2) sections where the pipeline is located in a tunnel. These sections are located at a point where the 90-inch pipeline is routed closest to the CTA electrical rails.

Running approximately parallel to the 90-inch pipeline, but with a separation of approximately ½ a mile, is a 72-inch steel water transmission pipeline. The 72-inch line has an existing DC stray current system in place.

DC Interference Considerations And Testing

Existing Electrical Shielding

As described above, there are two (2) sections of 90-inch water transmission pipeline which have been installed in a circular rib and lag tunnel. These tunnels are geographically the closest physical point between the CTA electric railroad and the 90-inch water transmission pipeline. The 90-inch water main as installed is not provided with any designed protection from the action of DC stray current interference.

If the tunnels act to electrically isolate the 90-inch water transmission pipeline and there is no electrolyte, such as water or soil between the external pipe surface and internal tunnel surface (tunnel annulus), then stray current cannot be discharged from the pipe surface to ground within these two (2) tunnel locations. If isolated, these tunnels act to increase the electrical path resistance for the DC stray current and may act to eliminate the stray current from being discharged from the water transmission pipeline at a point which is closest to the DC electric rail system. These tunnels may also act to move the point of electrical interference to a point upstream or downstream of this location.

As installed there is no possible means to directly measure pipe-to-soil potentials or perform any other tests related to interference at the tunneled locations. As such, it is unknown whether there is water or soil in the tunnel annulus. If the tunnel is not acting to completely shield the pipeline; it is possible that the 90-inch water main may be experiencing interference due to its close proximity to the DC rail system.

Testing Outside of the Tunnel

Since the section of the 90-inch water transmission pipeline contained within the two (2) tunnels and closest to the DC rail system could not be directly tested, a section of main was selected for more advanced testing based on a review of the pipeline route and engineering experience. The test section selected is the first pipeline section east of the second tunnel which begins at stationing (156+38) and heads east. The testing performed on this section of the 90-inch water transmission is as follows:

Graphing of the Beta curves. This test included measurement of the pipe-to-rail open circuit potential Eo, and the pipe-to-soil potential Vg. These two parameters were measured during the same period of time and the values were plotted together in an x-y graph, where the Vg is the y axis and Eo is the x axis.

Determination of Beta values. The slope of the best fit line formed by the data gathered during the step above is known as the Beta value and was used to interpret the level of DC stray current at that point. This value helped calculate the bond characteristics, such as the maximum bond resistance and the maximum allowable current flowing through the bond cable.

Determination of Vg in the case of no interference. This value is the value of Vg when the pipe-to-rail open circuit potential Eo is equal to zero. This was determined as the intercept of each beta curve with the y axis.

Maximum Eo value: After the point of maximum exposure was determined, the value of Eo, Vg and the Beta value were determined over a 24 hour period of time. By doing this, the variables of the worst case scenario were determined. These values were used to calculate the bond characteristics; which were the maximum current allowed through the bond, the maximum bond cable resistance and the bond cable gauge.

Test Results

Graphing Beta Curves

To obtain the values for the worst case scenario, the 72” main was disconnected from the existing reverse current drainage switch. The existing negative connection to the rail was used as the point of connection to measure the open circuit potential Eo, between the electrical rail and the 90” pipeline. The rail was connected to the negative lead of the data logger and the 90” pipe was connected to the positive lead of the data logger.

The data logger was used in a two channel mode, where one channel was used to measure the Eo value, and the other channel was used to measure the pipe-to-soil potential Vg, with respect to a saturated $Cu/CuSO_4$ reference cell. Both values were recorded simultaneously and they were plotted on an x-y graph to obtain the best fit line equation that corresponds to each set of data.

A set of data was taken at Test Station A and at 100 foot intervals along the pipeline to the east of the test station, which is located at the eastern end of the tunnel. The Eo and Vg data was recorded once every second for a total of ten minutes at each location. A total of 14 sets of data were obtained and the graphs were plotted with the pipe-to-rail open circuit potential Eo on the x axis and the pipe-to-soil potential Vg on the y axis. Figure 1 below shows an example of one of the Beta Curves.

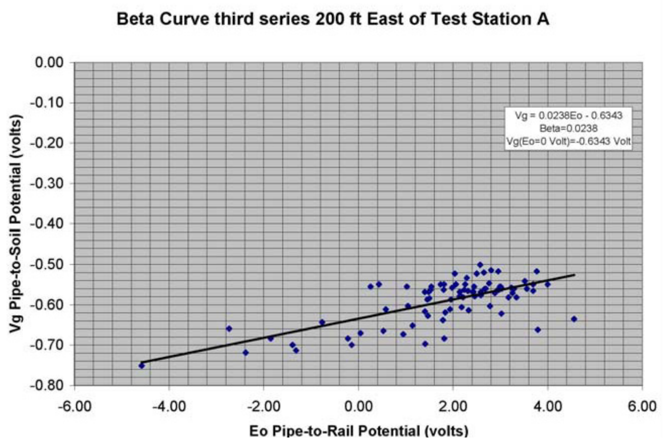

Figure 1 – Representative Beta Curve

Potential when stray current source turned off

The structure-to-soil potential, Vgo, is the pipe-to-soil potential when stray current affecting the pipe is turned off. Vgo cannot be determined because the rail system current source cannot be turned off. Even at night, when the rail system operates at a lower electrical load, there is still current flowing on the pipe.

Vgo can only be determined when Eo is zero in the equation of the best fit line for the data points related to Eo and Vg. The equation of the best fit line is as follows:

$$Vg=\beta*Eo+Vgo \qquad (1)$$

Where:

Eo = the open circuit potential between the pipe and the rail, measured in volts. For the measurement, the railroad is connected to the negative terminal of a high resistance multimeter and the pipe is connected to the positive terminal.

Vg = the pipe-to-soil potential, measured in volts with respect to a $Cu/CuSO_4$ reference electrode at the same time that Eo is measured.

ß= the slope of the line, the best fit line, for the scatter plot representing the relationship between Eo and Vg.

Vgo = the pipe-to-soil potential in volts, when the source of interference is turned off. This can only be measured when Eo= zero.

Figure 2[1] below shows how the connections were made for the Beta tests. Points A, B and C represent different points where the structure-to-soil potentials were obtained while the open circuit potential was measured at a fixed location. In this case, the fixed location was at Test Station C. This test station is the closest test point to the railroad.

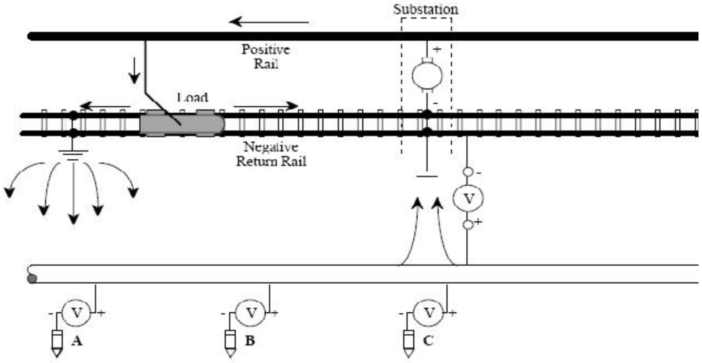

Figure 2 - Example Beta Test locations

Vgo was calculated for each Beta plot. The structure-to-soil potential measurements tended to become more electro-negative as the readings were taken progressively further east of Test Station C. This tendency might be a consequence of the pipeline receiving increased current as potential readings are recorded at greater distances from the location of maximum current discharge near the rail substation.

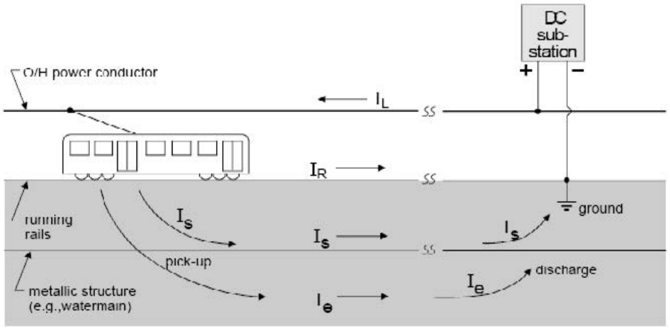

Figure 3 – DC Stray Current

See Figure 3[2] for a graphical explanation of how current moves in a DC stray current circuit.

The points where the current is being picked up from the soil to the main will have more electro-negative potentials and the points where the current discharges from the main to the soil will have less electro-negative pipe-to-soil potentials.

Figure 4 shows the Vgo, the tendency of values more negative as the readings are taken progressively further east of Test Station C is observed.

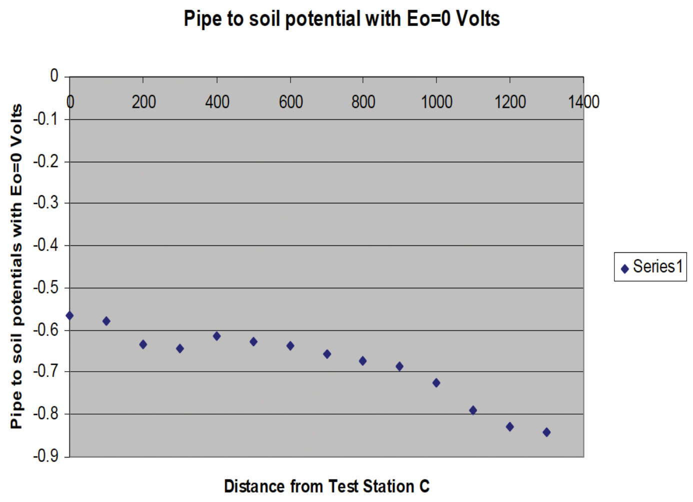

Figure 4 – Pipe to soil potential with Eo=0 Volts.

Beta Value Determination

The value of Beta (ß) is defined as the slope of the line represented by Equation 1. This value expresses how the magnitude of the structure-to-soil potential, Vg, changes with respect to changes in the pipe-to-rail open circuit potential Eo. In general, the larger the value of Beta (the steeper the slope), the greater the pick-up or discharge of current will be. The polarity of the Beta value depends on the point of connection for the voltmeter measuring the pipe-to-rail potential. In this case, because this connection was made closest to the railroad substation (close to discharge point), the value of Beta will always be positive.

Open Circuit Potential Between Main and Rail

The pipe-to-rail open circuit potential is the difference in potential between the pipe and the rail. It is the driving force that initiates current movement through the soil between the pipe and the rail. The test connections made to determine this value are shown in Figure 2, where the pipe is connected to the positive lead of a high resistance voltmeter and the rail is connected to the negative lead of the voltmeter. When current is discharging from the pipe to the soil, the voltage readings will be positive and when current is being picked up on the pipe from the soil the voltage readings will be negative.

The open circuit potential (Eo) was measured at the nearest accessible pipeline test point to the railroad. This test was performed between Test Station A and the negative of the existing reverse current drainage switch installed on the 72” transmission main. Pipe-to-soil potentials (Vg) were recorded at each of the 14 locations performed during the Beta value test. Following the Beta test, the open circuit potential was recorded over a 24 hour period in order to determine the maximum value of Eo. The maximum value of Eo indicates the maximum amount of current that can flow in the stray current circuit. This value is then used in the bond characteristic calculations.

DC Circuit Characteristic Determination at Maximum Exposure Point

Beta Value During 24 Hour Period. Since Eo and Vg were determined during 24 hours at the closest point to the railroad, the value of Beta at this location can be determined. This value was used together with the Eo value to calculate the bond parameters for design purposes.

Circuit Characteristics With no External Current Source. After all necessary values were determined with no connection between the pipe and the rail, another series of measurements were recorded with a direct connection between the rail and the main installed. Doing this, the parameters such as the average circuit internal resistance and average structure-to-soil potential to current ratio could be determined. These parameters were also used in the equations for bond resistance and current calculation.

These tests simulate a bond connection between the water main and the railroad. A current interrupter and a shunt were connected in series between the wire that is connected to the pipe and the railroad. Measurements of the pipe-to-rail short circuit potential, the current across the shunt and the pipe-to-soil potential were measured and recorded at the same time. This testing provided the following information:

a. Average internal resistance: This is the resistance between the rail and the pipe calculated as the average closed circuit potential divided by the current measured during the test.

b. Average structure-to-soil potential to current ratio: This is the average main-to-soil potential divided by the current through the circuit measured during the test.

Circuit Characteristics With External Current Source. The internal resistance and the average structure-to-soil potential to current ratio were also determined while applying an external current source. The external current source helped to stabilize the circuit reads and helped to obtain more accurate values of these parameters.

Test	Open Circuit potential. Eo (volts) in 24 hours (measured)		Beta value (calc.)	Average Internal resistance Ω (calc.)	Minimum Internal resistance Ω (calc.)	Maximum Internal resistance Ω (calc.)	Average Pipe Volt/amp (calc.)	Minimum Pipe Volt/amp (calc.)	Maximum Pipe Volt/amp (calc.)	Max. positive current A (calc.)	Max. negative current A (calc.)	Maximum Bond resistance Ω (calc.)	Minimum Cable size for bond AWG (calc.)
	More positive	More negative											
With no current applied.	4.33	-5.39	0.014	0.121			0.0023			26.80	33.32	0.04	3/0
	4.33	-5.39	0.014		0.012			0.0008		77.06	95.79	0.04	2/0
	4.33	-5.39	0.014			0.449			0.011	5.42	6.74	0.34	8
With current applied.	4.33	-5.39	0.014	0.080			0.0048			12.68	15.76	0.26	6
	4.33	-5.39	0.014		0.069			0.0031		19.91	24.74	0.15	4
	4.33	-5.39	0.014			0.091			0.007	8.76	10.88	0.40	8

Table 1

Testing Parameters And Results

Table 1 shows the parameters determined during the testing and calculated using the procedures mentioned above. All values listed in Table 1, other than the open circuit potentials (Eo) which was measured in the field, are calculated values.

Design Parameters And Calculations

Design Methodology

The design methodology utilized for this analysis was based on the electrical relationship between the driving force for stray current (the difference in potential between the DC electric rail and the water main) and the change in potential of the pipe due to this driving force. This takes into account that the measured structure-to-soil potential is a combination of its natural potential-to-earth plus the sum of all potential changes caused by the DC sources influencing it.

Design Rationale

Since the pipe-to-rail potential changes with time and can be positive or negative, the calculations were divided into two sets. One set of calculations was performed with the negative pipe-to-rail potentials and the second set of calculations was performed using the positive pipe-to-rail potentials. The set of values that shows the maximum magnitude of current discharge from or pick-up to the pipe was chosen to design the bond.

Data Summary

As seen in Table 1, the bond resistance, the maximum current through the bond and the minimum cable size for six different cases were calculated. The calculations take into account all of the available data and use the parameters that yield the worst case scenario (maximum current) for bond design purposes. The average, minimum and maximum parameter values were derived for each test. A distinction was made between the values obtained when the current was draining from the pipe to the soil (positive current reads) and when the main was picking up current from soil (negative current reads). Doing it this way, all of the current flow scenarios were considered. The primary values used in the bond design are the positive current values. This is the condition when the reverse current drainage switch is closed and allows current to flow through the bond.

Maximum Bond Current Calculation

The maximum current that can flow through the bond in the case of maximum load in the electric rail circuit was calculated using the following equation:

$$Ib := \beta \cdot \frac{|Eo|}{Rpipe} \tag{2}$$

Where:

Ib = the current through the bond in amperes.

ß = the Beta value for the worst case scenario at the point of maximum exposure, where the accessible pipeline is closest to the railroad (volts/volt)

Eo = the maximum open circuit potential measured over a 24 hour cycle (volts)

Rpipe = the ratio of structure-to-soil potential to current applied (volts/amp)

The maximum calculated current flowing through the bond, from the pipe to the rail was 77 amps.

Bond Resistance Calculation

The bond resistance was determined using the following equation:

$$Rb := Rpipe \cdot \left(\frac{1-\beta}{\beta}\right) - Rint \tag{3}$$

Where:

Rb = the bond resistance (ohms)

Rpipe = the ratio of structure-to-soil potential to current applied (volts/amp)

Rint = is the internal resistance of the circuit

The bond resistance is the maximum resistance that can exist in the bond circuit in order to pass the calculated maximum amount DC interference current. The maximum calculated allowable resistance of the bond was 0.038 ohms.

Bond Cable Size Determination

The equation used to determine the cable size was:

$$Rcb := Rc \cdot Lb \tag{4}$$

Where:

Rcb = cable resistance (ohms)

Rc = cable resistance per 1000 ft. ((ohm/ft)*10-^{3})

Lb = the distance between the test station and the connection to rail (feet)

The cable size was selected based on the current capacity of the cable, the distance between the rail connection and water main connection and the bond resistance. In this case, the minimum cable gauge is 3/0 AWG of stranded copper cable. The length of the directional bore could not be precisely measured due to the obstruction of the electric railroad and therefore the exact required length of cable could not be confirmed. The installation of larger cable (250 MCM) was recommended to ensure the system drains an adequate level of current back to the electric railroad.

Design Specifications And Characteristics

The final design included a reverse current switch as well as corrosion coupon monitoring test stations. Even though the 72-inch main has an existing reverse current switch unit, a separate reverse current switch for the 90-inch was recommended since the timing of pick-up and discharge on the 72-inch main and the 90-inch main may not coincide with one another. The switch will have a remote monitoring unit installed to facilitate switch monitoring and control.

Reverse Current Switch Theory

Reverse current switches are used to prevent DC current from flowing in the wrong direction at DC transit or other DC generating equipment stray current mitigation bonds. The drainage switch equipment has a solid-state circuit that operates an electrical DC contactor. That circuit monitors the voltage differential of the stray current mitigation bond between the structure (water main) and the negative buss (electric rail). When the voltage differential of the structure with respect to the negative buss reaches a positive 150 mV DC (current can move from the main to the soil), the switch will close. This permits the current to flow from the main to the rail through the bond cable instead of draining from the main to soil and back to the railroad. By limiting the amount of current allowed to discharge from the surface of the pipeline, DC stray current corrosion can be mitigated. When the voltage differential between the main and the railroad reaches zero mV DC, the switch will open.

Follow-Up Testing And Analysis

Once the stray current mitigation system is installed, a new series of Beta curves should be obtained in the same locations where the tests were done before the installation. With this new series of Beta curves, a graph with all the Vgo in function of the distance from the connection point to the railroad can be done again (see figure 4 above). If the Vgo values are more negative than -1000 mV[3], a variable resistor should be introduced in series in the electric circuit between the pipe and the railroad to increase the resistance of this circuit and diminish the amount of current being drainage, to keep the potential of the pipeline less negative than -1000 mV.

Updated 2/17

Resources

Authors: *Rogelio de las Casas, Ron Turner, Kristi Roe; EN Engineering*

[1] NACE International CP Interference

[2] NACE International CP Interference

[3] NACE International RP0100-2004

EN Engineering's professionals provide comprehensive and dependable engineering, consulting, design, integrity management, corrosion protection, environmental, and automation services to pipeline companies, utilities, and industrial customers with *excellence from start to finish.*

ENEngineering