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ANALYSIS OF MONITORING TECHNIQUES FOR PRESTRESSED CONCRETE CYLINDER PIPE

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ABSTRACT

Concrete pressure pipe (CPP) is used in water and waste water systems that serve virtually every city in North America. Various techniques are used to evaluate the corrosion state of a buried pipeline. The two most commonly used are the pipe-to-soil (P/S) and cell-to-cell potential techniques. However, only a few references exist relating to the use of these monitoring procedures for CPP.

Various corrosion engineering firms have confidence in one or the other technique without being able to provide the rationale for their preference. Both techniques have recently been challenged as being insufficiently reliable for CPP.

This project consisted of setting up simulated corrosion cells on a 48" (1.22 m) diameter prestressed concrete cylinder pipe (PCCP) line and allowing five corrosion engineering firms the opportunity to use their monitoring techniques to locate corroding sites.

This project evaluated existing corrosion monitoring techniques based on measuring electrical potentials on PCCP. It was found that bonded and unbonded prestressed concrete cylinder pipe can be monitored for corrosion depending on the intensity of corrosion and the location of the corrosion site on the pipe circumference.

Keywords: Corrosion monitoring, potential survey, prestressed concrete cylinder pipe, water pipelines, soil moisture contents, test methods

INTRODUCTION

Concrete pressure pipe is used in the water and waste water systems that serve virtually every city in North America. It is primarily used for distribution of water for industrial, agricultural, and residential use. It is manufactured in sizes from 12" (0.30 m) to up to 21' (6.40 m) in diameter with pressure ratings up to 500 psi (3.45 MPa). Approximately 18,000 mi. (29,000 km) of PCCP are installed in North America.[1]

Various techniques based on potential measurements are used to evaluate the corrosion state of a CPP line. The two most commonly used are the pipe-to-soil (P/S) and cell-to-cell potential techniques. However, only a few references exist which relate the use of these monitoring procedures for CPP.[2,3,4]

The P/S potential technique requires that all steel elements within the pipe and between each pipe section be electrically continuous (or bonded). Most CPP lines installed in the Western United States in the last 15 years have been adequately bonded. In the Eastern United States most pipelines are not bonded. The P/S potential technique is used in the oil and gas pipeline industry, primarily on organically coated steel pipe, to determine the potential of the pipeline under cathodic protection.[5]

In the P/S potential technique, a thin insulated copper wire is electrically connected to the pipeline and to the positive terminal of a high input impedance voltmeter. A reference cell, typically a copper-copper sulfate reference electrode (CSE), is connected to the negative terminal. The terminal connections may be switched depending on the preference of the engineer. The reference cell is placed on the ground directly above the pipeline or off to the side repeatedly at a selected interval and the potential measured along the length of the pipeline. Potentials on mortar-coated steel ranging from +50 mV to -300 mV are believed to indicate a passive, noncorroding state. Potentials more negative than -300 mV are believed to indicate that the pipeline is corroding, is under cathodic protection, or is being subjected to stray current pickup. Potentials more positive than +50 mV are believed to indicate stray current discharge. However, soil resistivity, moisture, and groundwater level may affect potential readings. In any case, the P/S potential technique has not always given results which adequately or accurately explained the condition of a CPP.[6]

The cell-to-cell potential technique does not require that the pipeline be electrically continuous. In this technique, the potential between two reference cells placed on the soil is measured. The distance between the two reference cells, depending on the corrosion engineer, may be less than 3' (1 m). The fixed cell-to-moving cell (FC/MC) method requires one cell to be placed at a fixed location, normally over the centerline of the pipe, and the other cell moved along the length of the pipeline at selected intervals either directly over the pipeline or offset from the pipe from 6 to 20' (1.8 to 6.1 m).

The moving cell-to-moving cell (MC/MC) potential technique typically consists of spacing the cells from 3 to 20' (0.9 to 6.1 m) apart, placing one cell over the centerline of the pipeline and the other offset from the line by the chosen distance. The distance appears to be dependent on the engineer. Both cells are moved simultaneously along the length of the pipeline. The cell-to-cell techniques may also include soil resistivity measurements to aid in interpreting the cell-to-cell measurements. The reliability of the cell-to-cell potential technique has also been challenged.

Various corrosion engineering consultants have confidence in one of the two techniques without being able to provide the rationale for their preference. The objective of this project was to evaluate existing corrosion monitoring techniques based on measuring electrical potentials on CPP and, if necessary, to refine existing practices or develop new monitoring techniques based upon potential measurements.

TEST SETUP

The project consisted of setting up simulated corrosion cells on PCCP, installing the pipeline, and allowing corrosion engineers to use their potential monitoring techniques to locate the simulated corrosion sites.

Approximately 240' (73 m) of 48" (1.22 m) diameter by 24' (7.3 m) long PCCP were manufactured and installed. A plan view of the installation is shown in Figure 1. The pipe was manufactured with two 1" (2.54 cm) wide shorting straps, 180° apart to reduce the electrical attenuation along a pipe section. The straps were not attached to the cylinder. Provisions were made to engage or disengage this connection remotely after pipe installation. The steel joints were specially manufactured with oversized bells, epoxy coated, and installed with oversized gaskets to ensure electrical discontinuity between adjacent pipe sections.

Two of the pipe sections were coated with a 26-mil (660-micron) thick supplemental coal tar epoxy (CTE) coating (pipe nos. 8 and 9) and two of the sections were encapsulated in an 8-mil (200-micron) thick polyethylene (PE) wrap (pipe nos. 10 and 11). Pinholes and holidays were present in both coating systems. Six sections (pipe nos. 2 to 7) had no additional supplemental protection beyond the highly alkaline cement slurry and mortar coating.

Inert anodes were placed on the concrete core between the prestressing wire to simulate corrosion activity. The mortar coating removed in this process was repaired. The anodes were placed 90° apart at the top, bottom, and springlines (east and west) of the midpoint of each pipe section as shown in Figure 2. A lead wire was connected to each anode and brought up to a common junction box. The anodes were activated by connecting them to the positive terminal of an adjustable power supply and by connecting the pipe to the negative terminal. A gas-powered generator was used to power the power supply.

The pipe sections were installed with 6' (1.8 m) of cover in an arid environment in Palmdale, California. Mortared night caps were provided at each end with two access manholes. The site was selected to be representative of arid environments where electrical monitoring techniques are thought to be the least reliable.

The native soil at the site is a sandy gravel with 60% of the soil retained on a No. 4 sieve. That passing the No. 4 is a clean, well-graded sand. Soil-box resistivity ranged from 100,000 to 200,000 ohm·cm dry and 16,000 to 30,500 ohm·cm saturated. The pH of the soil samples ranged from 7.8 to 8.2. Water-soluble chloride and sulfate contents were less than 10 mg/kg which indicates that the soil is non-corrosive to CPP. The pipeline was backfilled with sand from an adjacent aggregate pit which had similar chemical properties. The Wenner four-point soil resistivity values of the backfilled area at 3, 5, and 10' (1, 1.5, and 3.0 m) spacings ranged from 13,400 to 63,200 ohm·cm when wet or dry.

Provisions were made to allow easy electrical connection or disconnection between adjacent pipe sections and between the prestressing wire and steel cylinder of each pipe to simulate bonded and unbonded pipelines. This was done by connecting insulated 4/0 copper cables to the prestressing wire and cylinder and bringing them to the surface above each joint and providing a test station at each joint.

Permanent copper-copper sulfate reference cells and soil moisture cells were installed. The lead wires were brought to a common junction box.

A plastic sprinkler system was installed along the length of the pipeline to simulate wet conditions. The sprinklers were on 15 minutes every 2 hours during the six weeks of testing.

Five corrosion engineering firms familiar with corrosion monitoring were selected to review the proposed test and provide comments and suggestions, to visit the pipeline site, and to monitor the pipeline. They have experience in monitoring techniques for organically coated steel pipelines but varying levels of experience and divergent opinions on how those techniques should be applied to CPP. The consultants represented firms ranging from small, local companies to large, multinational corporations.

Each engineering firm conducted their monitoring tests without other firms in attendance. Each firm was allowed two days to complete the testing. All testing was accomplished in a six week period. Five test scenarios for the bonded pipe condition and five test scenarios for the unbonded condition were selected by the author. The first scenario consisted of a baseline potential survey without any of the simulated corrosion sites activated. The other scenarios consisted of sites being activated at current levels given in Table 1. The corrosion rates using the surface area of one pipe section, 10% of the area of a pipe section, and an 8' (2.4 m) diameter area around the simulated corrosion site were calculated using Faraday's Law. They are reasonably low to moderate corrosion rates for corroding steel.

The location and current level of the sites were not known to the consultants. The application of current to the anode changed the potential of the steel at that location simulating corrosion. The consultants were expected to locate the shift in potential using their monitoring techniques. The scenarios were the same for the five firms although the sequence was changed.

TEST RESULTS AND DISCUSSION

Bonded Pipeline

For the bonded pipeline condition, all consultants used the pipe-to-soil (P/S) potential technique over the centerline (over-the-line) of the pipeline. Three also used the P/S potential technique with an 8' or 10' (2.4 m or 3.0 m) offset from the centerline of the pipeline on both sides of the pipeline. The other two used the moving cell-to-moving cell (MC/MC) potential technique, sometimes referred to as side drains, where one cell is placed over the centerline of the pipe and the other cell is placed perpendicular to the pipe at selected distances. Both cells are moved together along the length of the pipeline. In this study, the two consultants used side drain distances of 8' and/or 10' (2.4 and/or 6.1 m). The MC/MC technique was performed on both sides of the pipeline. Potentials were taken every 1' to 5' (0.3 to 1.5 m) along the length of the pipeline.

The over-the-line P/S potential survey curves by the five firms in which the simulated corrosion site was located in pipe no. 5 at an intensity of 100 mA (scenario no. 2) are shown in Figure 3. The peaks indicate the location of the corrosion site. A shift of 60 mV to 100 mV occurred at pipe no. 5. Although only the over-the-line P/S potential data are shown, the consultants were able to locate the site using all of the potential techniques discussed.

The P/S potential survey curves for scenario no. 4 in which the corrosion site was located under a coal tar epoxy (CTE) supplemental coating at the top of pipe no. 8 are shown in Figure 4. The corrosion intensity was 100 mA, identical to the previous survey. A shift of 40 mV to 60 mV occurred at pipe no. 8. This indicates that coal tar epoxy coated pipe can be monitored for corrosion. Similar results were obtained using all of the techniques.

An extraneous peak is present on two of the curves in Figure 4. This was due to residual polarization present from the prior scenario run. The two consultants who performed this survey were able to quickly go from one scenario to another which did not allow for adequate depolarization. Approximately 30 minutes was required for complete depolarization to occur.

The P/S potential survey curves for scenario no. 5 in which the corrosion site was located at the east springline of pipe no. 3 at a corrosion intensity of 170 mA are shown in Figure 5. The three extraneous peaks were due to prior tests as stated earlier. Four of the consultants were able to locate the site of corrosion using the over-the-line P/S potential technique although it appears that the distance counter used by one consultant was slightly off. A 20-mV peak was seen in the over-the-line P/S data from firm no. 2 but could not be differentiated from other peaks in the same curve. However, firm no. 2 found the site using the east 10' (3.0 m) offset P/S potential technique.

Unbonded Pipeline

For the unbonded pipeline condition, two of the consultants used the fixed cell-to-moving cell (FC/MC) technique where one cell was fixed at the centerline of the pipe at one end and the other cell was moved along the length of the pipeline over its centerline and at a 10' (3.0 m) offset from its centerline on both sides of the pipeline. One of these two also used the over-the-line P/S potential technique. Two of the consultants used the moving cell-to-moving cell (MC/MC) technique with side drains of 8' and/or 20' (2.4 and/or 6.1 m). The remaining one used the P/S potential technique exclusively.

The potential survey curves of the unbonded pipeline by the five firms in which the simulated corrosion site was located in pipe no. 6 at an intensity of 100 mA (scenario no. 7) are shown in Figure 6. Two over-the-line FC/MC, two MC/MC with 8' (2.4 m) side drains on the east or west side of the pipeline, and two over-the-line P/S potential surveys are shown. The peaks indicate the presence of the corrosion site. The consultants were able to locate the site of corrosion using all of the techniques including P/S, FC/MC, and MC/MC. The P/S technique was successful, even though the pipeline was not bonded, because the potential of the pipe was constant and allowed the pipe to act as a reference cell.

The MC/MC potential technique using two different side drain distances of 8' and 20' (2.4 m and 6.1 m) was used by firm no. 5. The potential survey curves are shown in Figure 7. The greater shift in potential using the 20' (6.1 m) distance indicates that it is able to provide greater sensitivity in finding corrosion sites than using the 8' (2.4 m) side drain. The potentials using the

20' (6.1 m) side drain on the west side is more erratic due to lower moisture content in the soil since the prevailing wind from the west blew the water from the sprinkler system toward the east.

The potential survey curves of the unbonded pipeline for scenario no. 8 in which the corrosion site was located under a coal tar epoxy (CTE) supplemental coating at the top of pipe no. 8 are shown in Figure 8. The corrosion intensity was 100 mA, identical to the previous survey. A shift of approximately 20 mV to 30 mV occurred at pipe no. 8 using the FC/MC and MC/MC potential techniques. This indicates that coal tar epoxy coated PCCP can be monitored for corrosion using these monitoring techniques. The extraneous peaks were due to prior tests as stated earlier. The MC/MC curve using the west 20' (6.1 m) side drain was erratic due to the low moisture content of the soil since the prevailing wind from the west blew the water from the sprinkler system toward the east. The over-the-line P/S potential techniques provided the least definitive test results for this scenario.

The curves of the unbonded pipeline for scenario no. 9 in which the corrosion site was on the west springline of pipe no. 3 are shown in Figure 9. The corrosion intensity was 130 mA. A 20-mV peak was found using the FC/MC technique with a west 10' (3.0 m) offset method. Peaks were not evident using the other methods as in previous tests. It appears that the location and intensity of the corrosion site affect the sensitivity of the techniques. One data point at 70 mV on pipe no. 8 is due to improper contact of the reference cell to the ground and does not indicate corrosion.

Sensitivity of Potential Monitoring Techniques

The potential shifts obtained from the over-the-line P/S, FC/MC, and MC/MC techniques for the bonded and unbonded pipeline where the top anode was activated at 100 mA (scenarios 2 and 7, respectively) are given in Table 2. The potential shift is the difference between the highest potential measured and the approximate baseline potential at the adjacent pipe sections.

It is apparent that the greatest potential shifts and, hence, sensitivity occurred with the over-the-line P/S and FC/MC techniques and the MC/MC technique with 20' (6.1 m) side drains when the pipeline is bonded. As the side drain distance in the MC/MC technique increased, the potential shift and, hence, sensitivity increased as shown in Figure 10. This would indicate that the optimum side drain spacing for the MC/MC technique is at least twice the distance from the ground surface to the pipe bottom. However, since only one pipeline diameter and depth were investigated, the optimum side drain spacing cannot be determined from the data collected in this project.

The sensitivity of the techniques for the unbonded pipeline decreased approximately 43% to 49% compared to the bonded pipeline.

Additional Scenario Results

Potential curves for scenario nos. 3 and 10 were not shown since the anode currents were greater than those given in this paper, the shifts were substantially greater, and the corrosion sites were located without difficulty. Baseline potentials were also not shown since they were similar to the curves shown in Figures 3 to 9 but without the peaks.

Locating Corrosion on Pipe Bottom

During system checkout, corrosion sites at the bottom of the pipeline were not found when the anode was activated at 100 mA. Consequently, this scenario was not tested by the consultants. Although a substantial shift in potential occurred when measured with a permanent reference cell located 2' (0.6 m) under the bottom anode, no shift in P/S potentials occurred at ground level within 10' (3 m) of the pipe centerline. Additional testing will be undertaken to determine whether side drains or offsets of greater distance can locate the corrosion sites on the bottom of the pipeline.

Potential Surveys in Various Soil Moistures

The effect of soil moisture level on the usefulness of potential surveys was determined. After the corrosion consultants performed their surveys in the wet soil environment, the sprinkler system was turned off and potentials were measured periodically during the summer season with the top anode on pipe no. 5 activated at 30 mA during the survey. The daily maximum temperature ranged in the 90's during the summer (drying) season. No rain occurred during this period. The surveys was performed with the reference cell(s) placed directly on the dry soil and with approximately 8 oz (225 ml) of tapwater poured on the ground with the cell placed on the moistened soil. The moisture content of the soil was determined using moisture probes placed in the soil during backfilling. The probes were placed 1', 3', and 5' (0.3, 1, 1.5 m) from the soil surface above the pipeline and 1' (0.3 m) from both springlines and the pipe bottom at the mid-point of each pipe section.

The over-the-line P/S potential survey curves taken with the reference cell placed directly on the dry soil for potentials taken up to 16 weeks during the drying season are given in Figure 11. The soil moisture content 1' (0.3 m) below the soil surface, 5' (1.5 m) above the activated anode, on pipe no. 5 during the 16 weeks of the test are shown in the figure. The moisture content at other points around pipe no. 5 during the 16 weeks are shown in Table 3. The soil moisture content at the 1' (0.3 m) level decreased substantially from 11.7% to 2.6% during the 16 weeks.

Without moistening the soil, erratic potential readings were obtained even after only 1 week of drying. Although the potential shifts at pipe no. 5 are evident, they could not be distinguished between the other peaks present in the figure.

The over-the-line P/S potential survey curves taken with the reference cell placed on the ground which was moistened with the 8 oz (225 ml) of tapwater during the 16 weeks are given in Figure 12. Stable potentials were obtained and the corrosion site was located during the first 4 weeks of drying. At 8, 12, and 16 weeks, a second peak near the joint between pipe 8 and 9 became evident. It is unknown if this was due to corrosion occurring at the joint or if this is an anomality due to the dryness of the soil.

The results indicate that drying conditions down to 4.3% moisture produced similar monitoring conditions as long as a small quantity of water was poured on the ground at the reference cell contact point.

Polyethylene-Wrapped Pipe

Corrosion sites were not found under the polyethylene wrapped PCCP sections during the initial system checkout so were not tested by the consultants. It appears that the polyethylene wrap prevented water from entering the mortar. Such effect may be beneficial on a pipeline in service, but for this project the polyethylene wrap resulted in a high-resistance mortar through which sufficient current could not be passed to polarize the pipe.

Permanent Reference Cell Potentials

During testing, the potentials using permanent reference cells placed 2' and 4' (0.6 and 1.2 m) from the top anode showed more negative potentials than the potential measured on the ground. The potentials 2' (0.6 m) from the pipe (4' from the ground surface) were typically 20 to 50 mV more negative than the potentials at the ground surface. This indicates that the actual potential of the corroding steel is more negative than the ground potential measurements and that potentials taken at ground level do not need to be more negative than -300 mV (CSE) before undertaking further investigation.

Monitoring and Cathodic Protection

This project showed that unbonded PCCP lines can be monitored. However, if cathodic protection is recommended in the future based on monitoring and additional investigation and excavation, the pipeline cannot be cathodically protected unless the metallic components between and within the pipe sections are made electrically continuous.

Monitoring should be a first step in the investigation of corrosion on PCCP lines. If shifts in potential are found, further investigation is warranted. Since shifts in potential can be caused by sources other than corrosion, these sources should be investigated prior to undertaking any corrosion control measure. The shift may be due to stray current or corrosion of bare or organically-coated steel appurtenances. Corroding steel trash in the ground may also be picked up by the various techniques resulting in an inaccurate conclusion that the pipeline is corroding. The test site was free of potential sources of extraneous signals.

After these sources have been eliminated as the source of the potential shift, excavation may be warranted to determine the extent of corrosion on the pipeline. In many cases, the corroding areas are inadequately grouted joints which can be repaired. Cathodic protection is rarely required.

Proposed Work

Additional work is being planned. Various offsets will be used to try to find corrosion on the bottom of the pipeline. Tests to determine the current density requirements and resulting polarization potential of the pipeline under cathodic protection are being undertaken.

CONCLUSIONS

- Bonded and unbonded prestressed concrete cylinder pipelines can be monitored for corrosion depending on the intensity of corrosion and the location of the corrosion site on the pipe circumference. The results from potential monitoring techniques can provide useful, but not necessarily definitive, indications of corrosion activity on concrete pressure pipe.

- Pipe-to-soil, fixed cell-to-moving cell, and moving cell-to-moving cell potential techniques are appropriate measuring techniques. A shift in potential from the apparent baseline of the survey indicates that corrosion of steel in concrete may be occurring.

- The potential monitoring techniques are meaningful when conducted in soil with adequate moisture. If the soil surface is not adequately moist or insufficient contact of the reference cell is made to the soil, erratic potentials may be measured.

- Identifying corrosion occurring directly on the bottom of the pipe may be difficult unless that corrosion activity polarizes pipe steel further up the circumference of the pipe. Additional work is planned.

- Coal-tar epoxy coated prestressed concrete cylinder pipe can be monitored for corrosion. Similar results were obtained using all of the potential monitoring techniques.

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TABLE 1
CORROSION SITE LOCATION, CURRENT LEVEL,
AND CALCULATED CORROSION RATES

Scenario No.	Electrical Continuity	Anode Activated		Current Level (mA)	Corrosion Rate, mils/year		
		Pipe	Location		Pipe	10% Pipe	8' Dia.
1	Bonded	--	--	--	--	--	--
2	Bonded	5	Top	100	0.14	1.4	1.0
3	Bonded	4	All 4	350	0.49	4.9	3.4
4	Bonded	8	Top	100	0.14	1.4	1.0
5	Bonded	3	East	170	0.24	2.4	1.6
6	Unbonded	--	--	--	--	--	--
7	Unbonded	6	Top	100	0.14	1.4	1.0
8	Unbonded	8	Top	100	0.14	1.4	1.0
9	Unbonded	3	West	130	0.18	1.8	1.2
10	Unbonded	5	All 4	450	0.64	6.4	4.3

TABLE 2
EFFECT OF TECHNIQUE TYPE AND ELECTRICAL CONTINUITY
ON SHIFTS IN POTENTIAL

Description	Potential Shift, mV (Firm No.)				
	Pipe-to-Soil (C/L)	Fixed-Cell to Moving-Cell (C/L)	Moving-Cell to Moving-Cell		
			4 ft.	8 ft.	20 ft.
Bonded (Top anode on pipe 5 at 100 mA)	55 (1) 68 (2) 76 (3) 79 (3) 96 (4) 102 (5)	80 (2)	23 (4) 24 (4)	51 (4) 45 (4) 34 (5) 55 (5)	64 (5) 80 (5)
Mean Std. Dev.	79 17	80 0	23 1	46 9	72 11
Unbonded (Top anode on pipe 6 at 100 mA)	43 (2) 43 (3) 49 (3)	38 (1) 43 (2)	--	23 (4) 28 (4) 23 (5) 27 (5)	36 (5) 38 (5)
Mean Std. Dev.	45 3	41 4	-- --	25 3	37 1
Decrease in Sensitivity	43%	49%	--	46%	49%

C/L refers to potentials taken over the centerline of the pipeline.

TABLE 3
SOIL MOISTURE CONTENT AROUND PIPE NO. 5

Moisture Probe Location	Soil Moisture Content, %					
	15 min wet per 2 hrs	1 week dry	4 weeks dry	8 weeks dry	12 weeks dry	16 weeks dry
From ground surface						
1'	11.7	7.0	4.3	3.2	2.8	2.6
3'	5.9	6.1	6.3	6.1	5.4	4.7
5'	12.3	11.8	11.8	11.7	11.4	10.8
East Springline	13.4	12.3	11.4	10.8	10.5	7.8
West Springline	11.8	11.7	11.7	11.4	10.5	7.7
Pipe Bottom	6.3	5.7	5.6	5.6	5.5	5.5

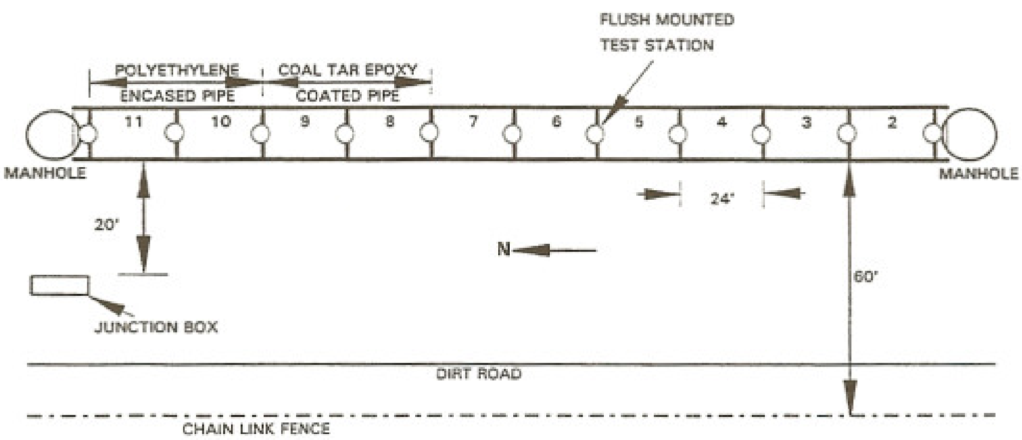

FIGURE 1 - Plan view of buried 48" (1.22 m) diameter PCCP line.

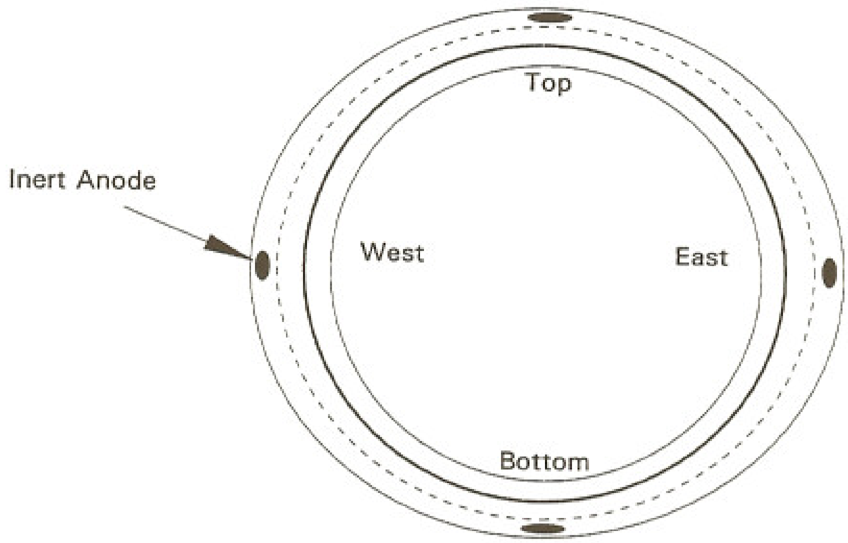

FIGURE 2 - Embedded anodes located at the top, bottom, and springlines of each mid-section.

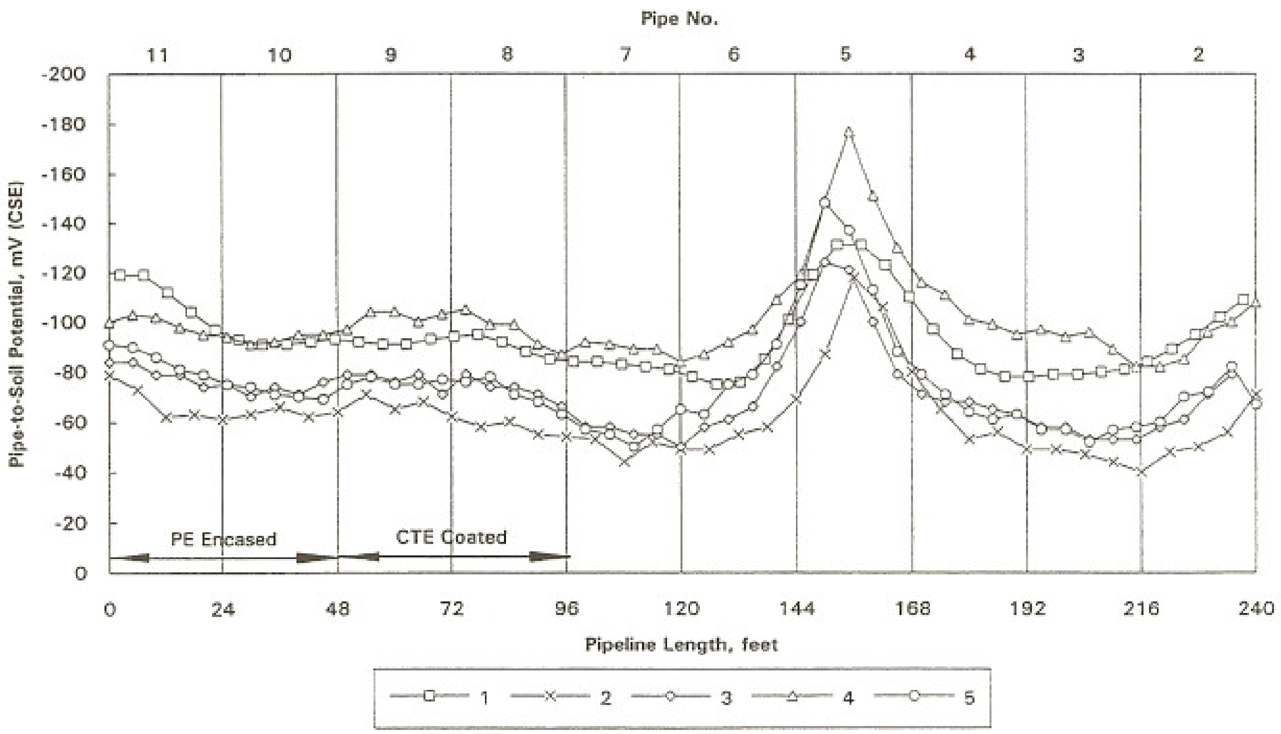

FIGURE 3 - Over-the-line P/S potential of bonded PCCP with top anode in pipe no. 5 at 100 mA (scenario no. 2).

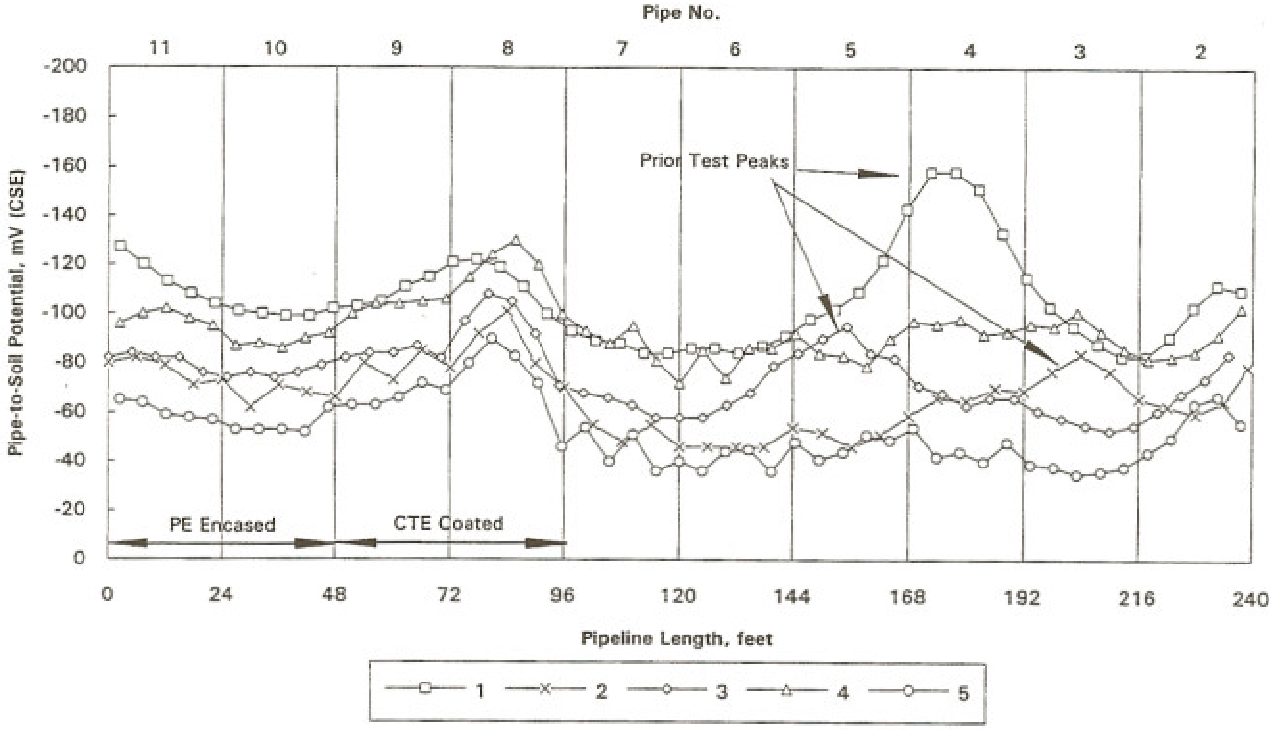

FIGURE 4 - Over-the-line P/S potentials of bonded PCCP with top anode in coal tar epoxy (CTE) coated pipe no. 8 at 100 mA (scenario no. 4).

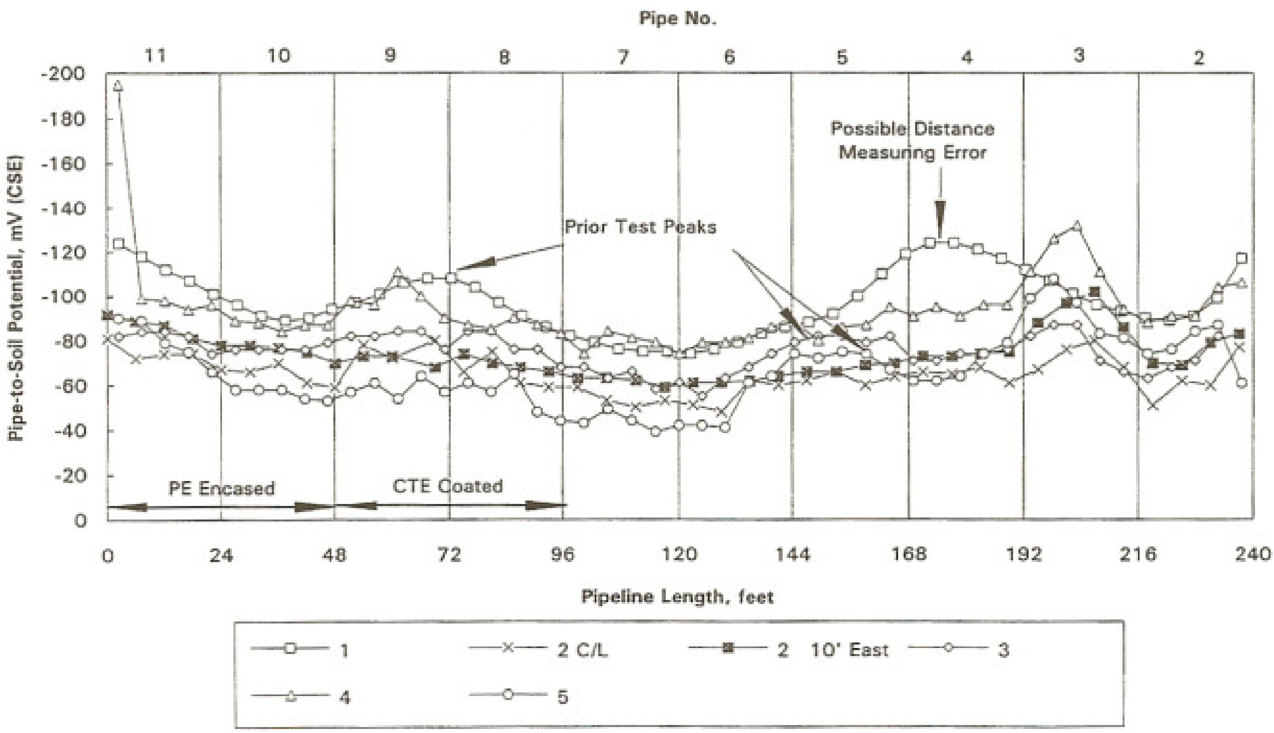

FIGURE 5 - Over-the-line and offset P/S potentials of bonded PCCP with east anode in pipe no. 3 at 170 mA (scenario no. 5).

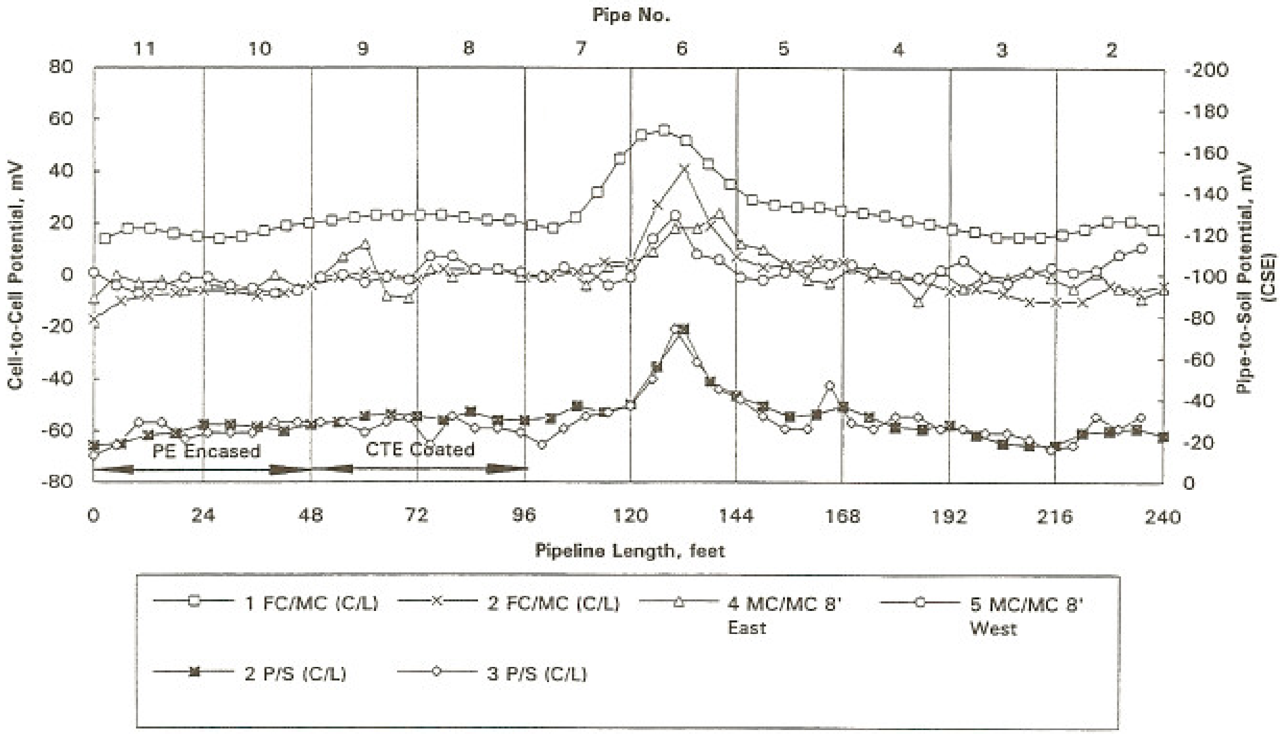

FIGURE 6 - Potentials of unbonded PCCP with top anode in pipe no. 6 at 100 mA (scenario no. 7).

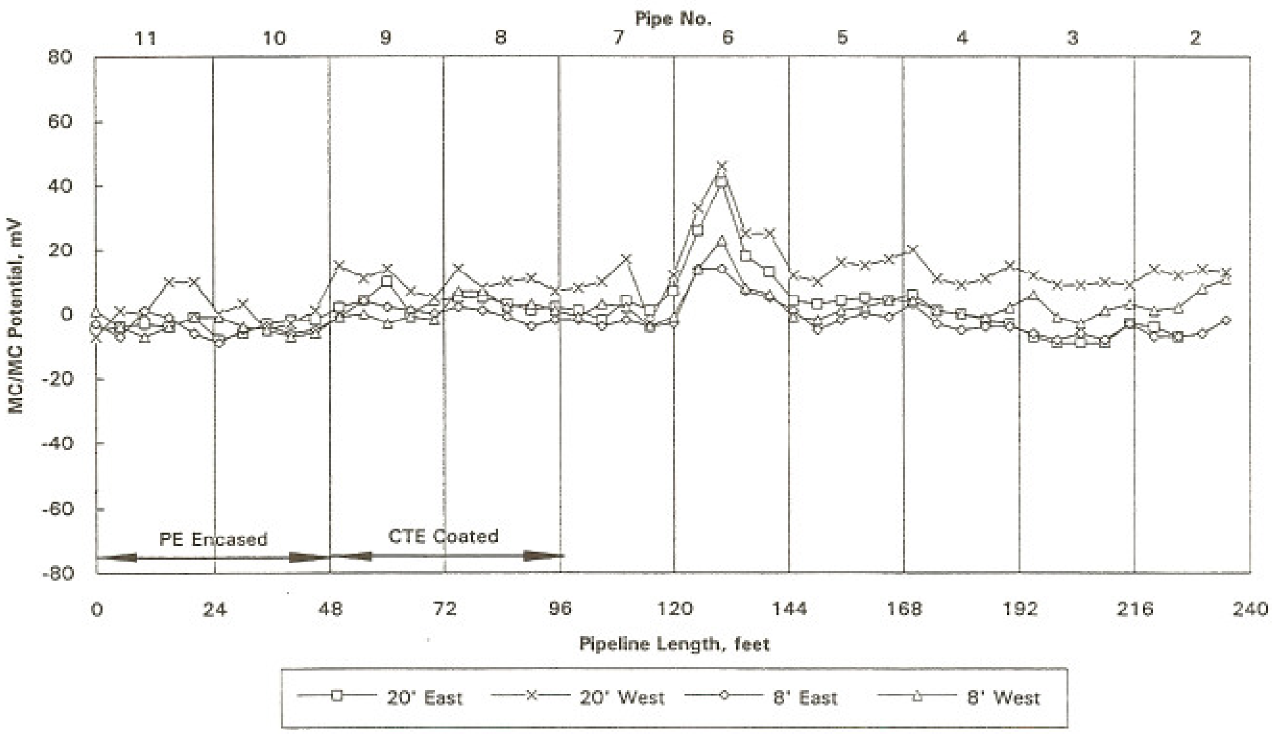

FIGURE 7 - MC/MC potentials of unbonded PCCP with top anode in pipe no. 6 at 100 mA (scenario no. 7) taken at 8 and 20' (2.4 and 6.1 m) side drains by Firm No. 5.

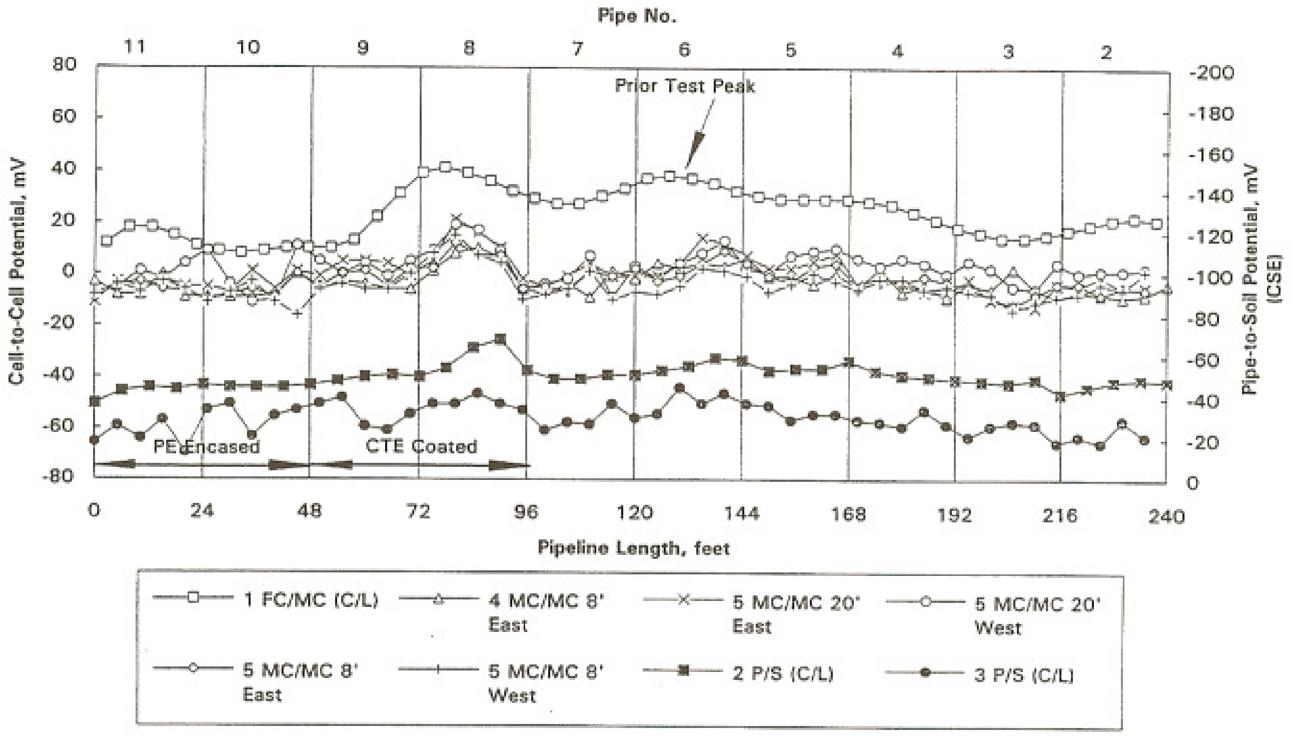

FIGURE 8 - Potentials of unbonded PCCP with top anode in coal tar epoxy coated pipe no. 8 at 100 mA (scenario no. 8).

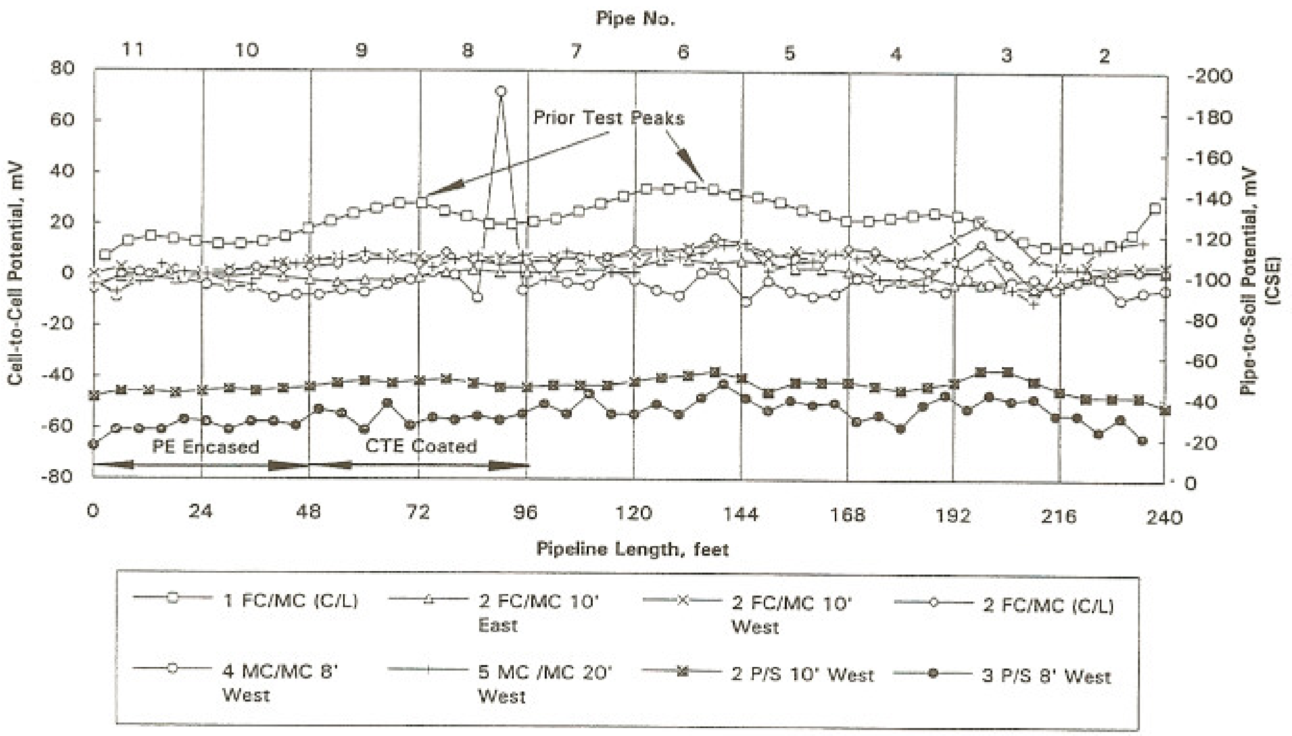

FIGURE 9 - Potentials of unbonded PCCP with west springline anode in pipe no. 3 at 130 mA (scenario no. 9).

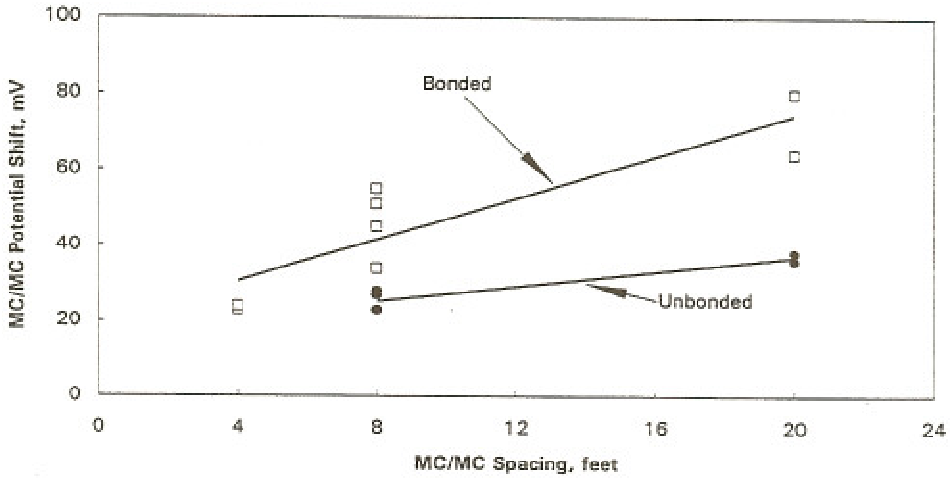

FIGURE 10 - Potential shifts using MC/MC technique in relation to reference cell spacing with top anode activated at 100 mA.

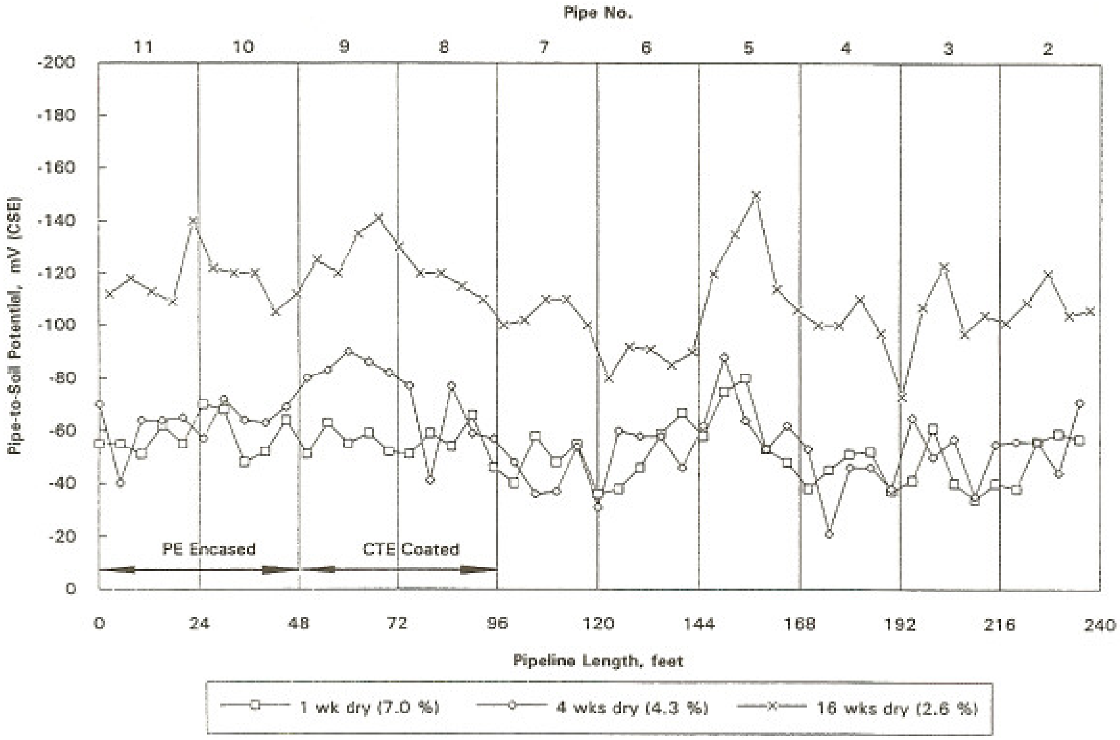

Figure 11 - Potentials of bonded PCCP with top anode in pipe no. 5 at 30 mA at various soil moisture conditions. Potentials were taken without moistening soil at reference cell ground contact.

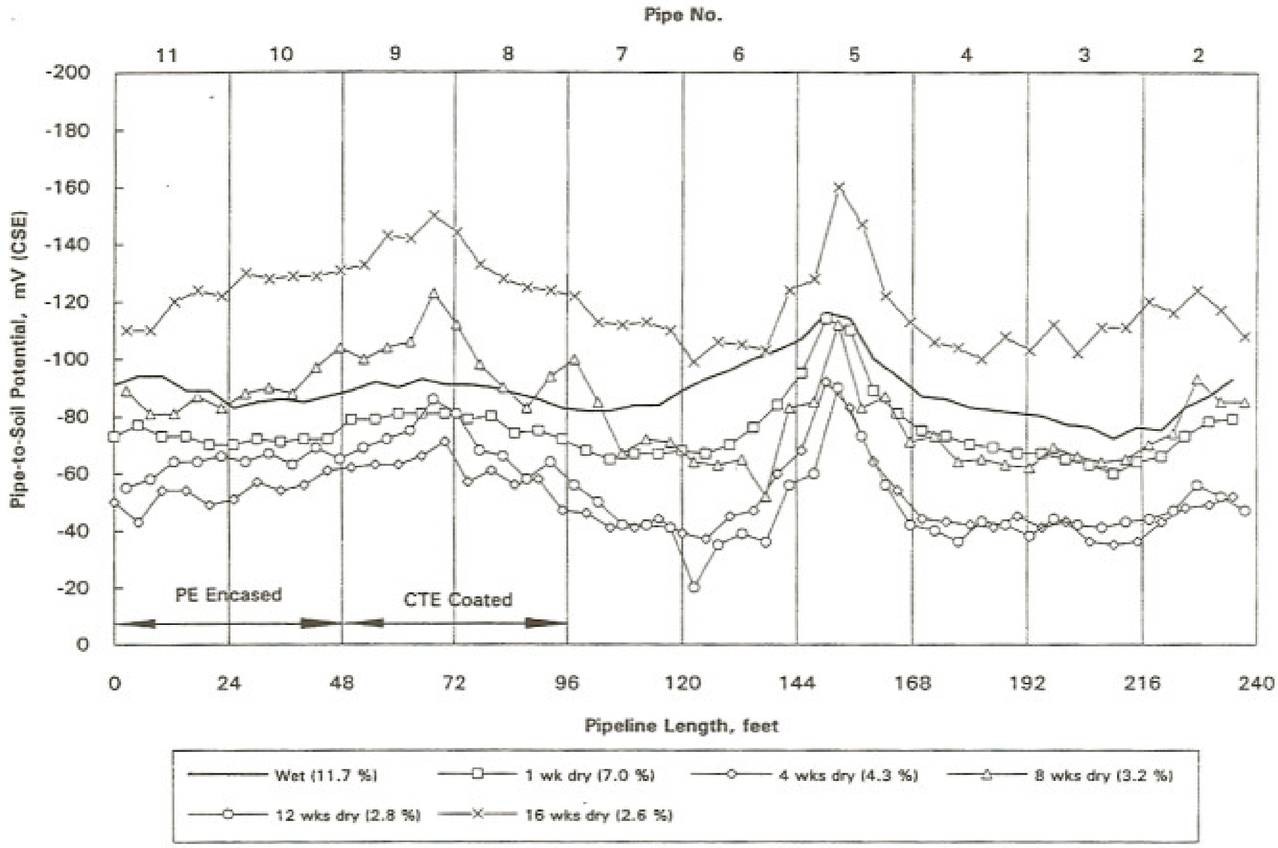

FIGURE 12 - Potential of bonded PCCP with top anode in pipe no. 5 at 30 mA at various soil moisture conditions. Potentials were taken with soil at contact point moistened with 8 oz (225 ml) of tapwater immediately prior to potential measurement.