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Corrosion Rates On Underground Steel Test Piles At Turcot Yard, Montreal, Canada—Part 1

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Corrosion Rates On Underground Steel Test Piles At Turcot Yard, Montreal, Canada—Part 1

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Contents

Corrosion Rates on Underground Steel Test Piles at Turcot Yard, Montreal, Canada—Part I

W. J. Schwerdtfeger and Melvin Romanoff*

In 1966, isolated steel H-piles allocated for underground corrosion tests were installed in three locations at the Turcot Yard Interchange of the Transcanadian Highway at Montreal. The reason for the installation was to furnish answers to some questions concerning the corrosion characteristics of piles, 12 in-74 lb/ft (30.5 cm-110 kg/m), which are identical with the piles supporting the concrete piers under the highway. Polarization measurements have been made once every year since installation.

This paper describes the determination of corrosion rates based on the polarization measurements made up to the time of removal of the first group of piles in 1969. The piles, placed underground at three locations, differ mainly in that at one site all the piles are bare, at the second site the upper ends of the piles are coated with an epoxy paint and at the third site the upper ends are encased in concrete. Physical measurements made on the cleaned piles after removal are correlated with corrosion rates calculated from the polarization measurements. Also, penetration rates on the piling based on the polarization data are compared with average penetration rates (based on actual weight losses) on relatively small pipe specimens. The pipe specimens were removed from 28 underground sites having a range of soil resistivities comparable to those of the three piling sites.

Using one of the polarization techniques applied to the individual test piles, polarization measurements were also carried out on 32 interconnected piles supporting one of the concrete piers. The calculated average corrosion rate of the 32 piles was found to compare favorably with that of the separate test piles in the same area.

Key words: Average penetration rate; H-piles; instantaneous corrosion rate; linear polarization; pit depth; polarization curve.

* Deceased

1. Introduction

Several thousand 12-in, 74 lb/ft (30.5 cm, 110 kg/m) steel H-piles of German fabrication were driven to bedrock during the construction of the Transcanadian Highway at the Turcot Yard Interchange, Montreal 1966. Because of the corrosive nature of some of the fill (soil and cinders) used at Turcot Yard, some engineers were of the opinion that cathodic protection should be used on the underground piling supporting the massive concrete piers under the highway. However, in view of a paper by Romanoff [1][1] published by the National Bureau of Standards (NBS) in 1962, a difference of opinion prevailed regarding the necessity for cathodic protection. Accordingly, during construction of the highway, steps were taken to provide access for cathodic protection by interconnecting the piles constituting a concrete pier, should protection be deemed advisable pending further investigation. In the meantime, a cooperative project was undertaken by NBS and National Boring and Sounding, Inc. Montreal (responsible for the underground structures). The project was sponsored by the Province of Quebec and the American Iron and Steel Institute (AISI). It was agreed that NBS would design a test program and that National Boring and Sounding, Inc. would install piles and remove some of them after 3,6,12,25 and 50 years of exposure for inspection and physical measurements. Three sites were selected in the Turcot Yard area where piles, identical to those used to support the concrete piers, were driven to bedrock. At one of the sites the piles were left unprotected (bare), at the second site the upper part of the piling exposed to the fill soil was protected with an organic coating and at the third site concrete covered the upper end. It was decided to make yearly polarization measurements over a period of several years in order to calculate average rates of corrosion on the bare surfaces of the piling and then to compare the calculated data with physical measurements made on removed piles following removal of corrosion products. The first piles were removed from each of the three sites in 1969 after 3 years of exposure and the intervening measurements and results are described in this paper.

This project fits nicely into the overall NBS program on piling corrosion sponsored by the AISI. It is the first major attempt to evaluate the significance of instantaneous corrosion rates measured by polarization techniques on underground piling in situ.

2. Description of the Test Sites

Seven test piles were installed during September 1966 at each of the three sites, designated as A, B, and C, located in the Turcot Yard area, Montreal during the construction of the Transcanadian highway interchange. The piles[2] were steel H-piles, 12 in x 12 in x 74 lb/ft (30.5 cm x 30.5 cm x 110 kg/m),

[1] Figures in brackets indicate the literature reference at the end of this paper.

[2] Chemical composition, weight percent—C, 0.11-.14; Mn, 0.52-.63; P, 0.054-.067; S, 0.026-.038; Si, 0.04-.08.

the same size and from the same source as the H-piles driven to support the piers of the highway.

At each site, six piles were driven to bedrock, approximately 30 ft (9.2 m), one of the six being in the center of a circle of piles having a radius of about 6 ft (1.8 m). Five of the driven piles were equally spaced on the circumference of the circle. The seventh pile was buried horizontally, 10 ft (3.1 m) outside and tangentially to the circle of driven piles, in a back-filled trench previously excavated to a depth of about 7 ft (2.1 m). The upper 7 ft (2.1 m) of the driven piles were also exposed to back-filled soil. The excavated depth of 7 ft (2.1 m) corresponds to the depth of the concrete footings enclosing the upper ends of the steel piles under the piers of the actual highway structure. The horizontal pile was included at each site for the purpose of comparing the pattern of corrosion on the steel surface exposed to disturbed soil and fill (previously excavated) with the corrosion on the surface exposed to undisturbed soil (natural soil). The driven piles, of course, were exposed to undisturbed soil below the excavated areas.

The piles at the three sites were arranged in the same way with the following exceptions. At site C, concrete encasements were poured over the upper 7 ft (2.1 m) of the six driven piles and over one end of the horizontal pile, again for a distance of about 7 ft (2.1 m). The concrete encasement was rectangular in cross section with at least 6 in (15.2 cm) of concrete covering the steel at all points. All piles at site A were exposed entirely bare. At site B, an organic coating was used on the upper ends of the piles to cover about the same area of steel encased by concrete at site C. Before applying the coating, the area to be coated was cleaned with a motor-driven rotary steel wire brush. The brushing operation was immediately followed by applying a hand-brushed coat of epoxy primer. The next day, a brush coat of C-200 coal-tar epoxy coating was applied over the primer coat. After driving the piles and before the concreteing and coating operations just described, the driven piles were cutoff at the top ends 2 ft (0.61 m) below the ground line. Identification numbers were welded on each pile about 12 in (0.3 m) below the top. Prior to driving, identification numbers were also welded about 24 in (0.6 m) from the bottom ends. A 1.375 in (3.5 cm) steel reinforcing rod was welded to the top of each driven pile and terminated about 12 in (0.3 m) below the ground line. On the horizontal piles, reinforcing rods were also positioned vertically and welded to the center of the pile. The rods served as points of electrical contact for carrying out the polarization measurements. To keep the soil out of direct contact with the rods when not in use, the rods were covered with removable molded concrete caps which protruded above the ground line. Figure 1 shows the concrete encased piles (upper ends) at site C before back-filling and figures 2 and 3 are views after back-filling.

Figure 1. *Site C—View (before backfilling) showing the 6 driven piles encased by concrete at the upper ends.*
Reinforcing rods shown protruding above the concrete are for the electrical connection.

Figure 2. *Site C—View (after backfilling) showing concrete caps covering the reinforcing rods.*
Location of the horizontal pile is indicated by arrow in the background.

Tables 1 and 2 show soil types at sites A and B, respectively, and also soil resistivity and pH as measured in July 1966. The resistivities of excavated soil areas were measured in situ with Shepard canes [2]. At depths of 8 ft (2.4 m) and deeper, soil samples were shipped to the NBS laboratory in sealed nonmetallic containers. Resistivities were measured in the laboratory using a standard soil cup and a Wheatstone bridge. Resistivities are corrected to 60° F. All pH measurements were from soil samples in sealed containers. Table 3 shows mainly a chemical analyses of soil samples from all three sites made by a Canadian laboratory in accordance with NBS Circular 579, table 6 [2].

FIGURE 3. *Site C—Showing surrounding highway structures.*

TABLE 1. *Soil characteristics based on soil borings at site A Turcot Yard, Montreal, Canada*

Sample	Depth ft	Soil types	Resistivity, ohm-cm at 60° F	pH
A	3 – 4.5	Fill—sand, brown silt cinders.	2030	7.8
B	5 – 6.5	Fill—brown silt, black shale, trace of clay.	2130	7.6
—	6.5– 8	Boulder.	—	—
C	8 – 9.5	Black shale, gravel, sand.	—	—
D	9.5–10	Peat.	1170	7.0
—	10 –10.5	Peat.	—	—
E	10.5–11.5	Marle.	1630	7.4
F	11.5–13	Marle.	1880	7.3
G	13 –13.9	Gray Clay.	1470	7.2
—	13.9–14.5	Sand, silt, gravel.	—	—
H	15 –15.9	Sand, silt, gravel.	4570	8.2
—	15.9	Boulder obstruction.	—	—

TABLE 2. *Soil characteristics based on soil borings at site B Turcot Yard, Montreal, Canada*

Sample	Depth, ft	Soil types	Resistivity, ohm-cm at 60° F	pH
A	2 – 3.5	Fill—cinders, clinkers.	510	7.2
B	3.5– 5	Fill—cinders, clinkers, silt, gravel, trace of brown sand.	400	7.2
C	5 – 6.5	Fill—cinders, sand, gravel, trace of clay.	1020	7.5
D	7 – 8.5	Fill—cinders, sand, silt, gravel.	1220	6.9
E	8.5–10	Peat.	—	—
F	10 –11.5	Peat.		
—	11.5–12	Marle.	460	6.8
G	12 –13.5	Marle.	660	7.3
H	13.5–14.5	Gray clay.	1120	7.1
—	14.5–15	Silt, sand, gravel to boulders.	—	—
K	15 –16.5	Silt, sand, gravel to boulders.	4570	7.8
—	16.5–18	Gravel.	—	—
	18 –20	Silt, gray sand.	—	—
L	20 –21.5	Silt, gray sand.	4830	7.7
—	22	Silt.	—	—

3. Corrosion Rates Based on Polarization Measurements

3.1. Measurement Techniques

The polarization techniques used for measuring instantaneous rates of corrosion on the piling under discussion are based for the most part on a considerable amount of earlier laboratory and field work on relatively small specimens [3,4,5,6]. Weight losses calculated from these earlier polarization measurements have shown by comparison with actual weight losses on the same specimens that agreement is remarkably good. Reference [6] also describes polarization measurements made on underground piling and although, in the case of the piling, weight loss verification was not possible, the corrosion rates as measured by the polarization method seemed very reasonable, especially so upon inspection of and pit depth measurements on one of the piles after extraction from the soil.

TABLE 3. *Chemical and physical properties of the soil at the test sites, Turcot Yard, Montreal Canada*

Sample identification	Particle size, percent by weight		Moisture percent by weight	pH	Resistivity, Ohm-cm at 60° F	Composition of water extract, milligram equivalents per 100 grams of soil*					
	Over 2mm	Under 2mm				Ca	Mg	Na+K as Na	HCO_3	Cl	SO_4
Site A Sample A	23	77	14.3	7.2	775	8.39	0.48	0.88	0.51	0.18	9.06
Sample B	43	57	9.1	7.5	1050	9.79	1.34	1.05	0.73	0.08	11.35
Sample C	71	29	11.8	8.0	Insufficient Sample	11.79	1.53	2.39	1.73	0.18	13.80
Sample D	—	100	61.0	7.2	Insufficient Sample	5.44	0.46	1.03	1.53	0.47	4.93
Sample E	—	100	59.8	7.4	2000	3.49	0.35	2.47	3.30	0.49	2.52
Sample F	—	100	57.3	7.4	2200	3.24	0.23	2.29	3.62	0.23	1.91
Sample G	—	100	45.5	7.3	Insufficient Sample	4.99	0.58	0.57	0.91	0.69	4.54
Sample H	37	63	9.6	7.8	3250	2.30	0.32	0.23	0.67	0.10	2.08
Site B Sample A	62	38	22.4	7.7	2500	4.09	0.37	0.10	0.91	0.18	3.47
Sample B	57	43	17.5	7.7	2550	4.44	0.24	0.18	1.15	0.17	3.54
Sample C	49	51	15.0	7.5	2850	3.69	0.23	0.21	1.35	0.14	2.64
Sample D	46	54	23.5	5.9	Insufficient Sample	12.17	0.74	1.31	0.78	0.34	13.10
Sample E	—	100	58.1	6.1	Insufficient Sample	4.04	0.37	1.72	0.14	0.86	5.13
Sample F	—	100	74.3	6.6	400	3.84	0.53	7.69	0.53	7.08	4.45
Sample G	—	100	62.0	7.3	1150	3.04	0.41	5.34	3.80	3.72	1.27
Sample H	—	100	42.4	7.5	1675	3.09	0.39	0.94	1.00	1.15	2.27
Sample K	75	25	9.7	8.1	6675	2.59	0.35	0.33	2.09	0.22	0.96
Sample L	—	100	18.0	7.8	5875	0.90	0.10	0.16	0.61	0.07	0.48
Sample M	15	85	16.9	8.0	5875	1.31	0.14	0.00	0.62	0.08	0.75
Sample N	55	45	6.7	7.8	3350	2.74	0.24	0.20	1.28	0.09	1.81
Site C Sample A	46	54	19.1	5.2	1750	4.55	0.32	0.23	0.07	0.16	4.87
Sample B	—	100	80.0	7.4	1200	6.49	1.11	2.41	4.90	0.80	4.31
Sample C	—	100	61.8	7.3	2550	3.14	0.37	3.31	4.45	0.19	2.18
Sample D	59	41	9.5	7.6	5550	2.04	0.32	0.14	1.46	0.11	0.93
Sample E	69	31	5.4	8.1	5550	2.04	0.20	0.90	1.72	0.13	1.29
Sample F	62	38	4.9	8.0	2700	3.89	0.50	0.17	1.33	0.11	3.12
Sample G	19	81	11.5	7.9	2550	2.54	0.42	0.32	0.61	0.05	2.62
Sample H	5	95	14.3	7.9	4750	1.10	0.16	0.11	0.57	0.05	0.75

*The analysis was carried out on the portion of soil with particle size less than 2 millimeters in diameter and all values are calculated on anhydrous basis.

Two polarization techniques were used in making measurements on the piling discussed in this paper. A preliminary measurement, polarization rate ($\Delta V/\Delta I$), more commonly known as the polarization resistance or linear polarization method, based to a large extent on experience, was used in order to estimate the magnitude of the current increments applied in determining the polarization curves. Corrosion rates were calculated primarily from changes-in-slope, known as breaks [4], in the cathodic and anodic polarization curves. Corrosion currents were also calculated from the $\Delta V/\Delta I$ data by a method described elsewhere [4].

The use of a bridge circuit for the elimination of IR (voltage drop through the soil) is invariably a necessity when making polarization measurements in soils without interrupting the polarizing current, unless the IR is an insignificant part of the measured potential change. Here the Holler bridge circuit [7] was used. Such a bridge circuit designed chiefly for measurements on piling has already been described [6]. As a word of caution, it should be mentioned that the arm of the bridge used for balancing out the IR requires variable resistors capable of carrying the polarizing current. However, the physical size of these resistors does not present a problem. For the piles in Montreal, the value of the total balancing resistance was less than 2 Ω. Voltage loss across the balancing resistors is not prohibitive because the value of resistance required is an inverse function of the area of metal in contact with the soil. It was found that two 12 V storage batteries connected in series provided ample current for the polarization measurements. Electrical apparatus used in Montreal is shown at one of the test sites (fig. 4).

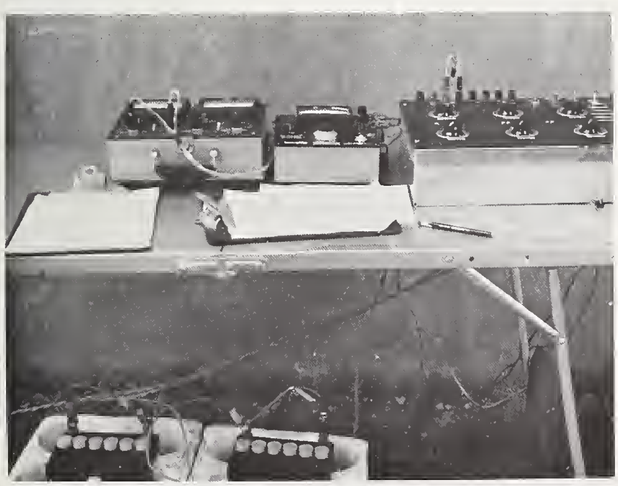

FIGURE 4. *Electrical apparatus as set up for polarization measurements.*

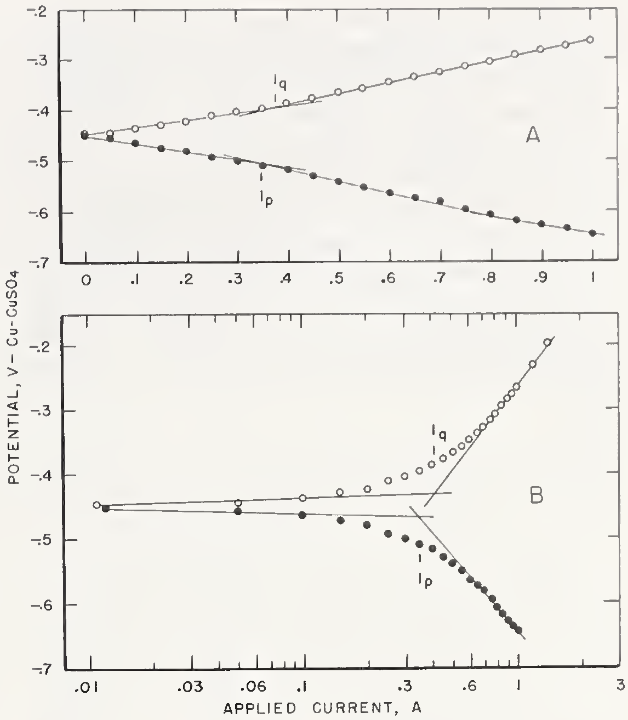

FIGURE 5. *Cathodic and anodic polarization curves obtained on H-pile No. 1, site B, after exposure for 34 months.*
A and B are the same data plotted respectively on rectangular and semilogarithmic coordinates.

3.2. Results on Test Piles at Sites A, B, and C

A set of polarization curves obtained on pile 1, site B just prior to extracting the pile for inspection is shown in figure 5. These curves are typical of all obtained on the several piles, except for the actual and relative values of I_p and I_q which indicate the values of polarizing current at which breaks in the curves occur. In calculating corrosion rates, it was assumed that corrosion occurred only on bare steel surfaces exposed to the soil and fill. Thus, at sites B and C the area considered in calculations excludes that respectively under the organic coating and under the concrete. Therefore, at site B, where upon inspection corrosion was found under the coating, the corrosion rates after 3 years of exposure were actually less than those stated later in the tables. This is so because the polarization measurements reflect the total corrosion including that in areas where the coating had deteriorated. The bare areas originally measured for the purpose of making calculations, later small deviations notwithstanding, are tabulated in table 4. Instantaneous corrosion current densities, based on these areas and calculated from measurements made at approximately yearly intervals are tabulated in table 5. A remote copper-copper sulfate reference electrode was used in making the measurements shown in table 5. The reference electrode was positioned in a moist location on the soil surface about 50 ft (15.2 m) away from the pile under observation. All polarization data were obtained by applying approximately equal increments of continuous current for one minute intervals and then reading the pile potential at the end of each interval. Usually, cathodic polarization curves were obtained first and followed the next day by the anodic curve. In the field, polarization data were immediately plotted on rectangular coordinates in order to verify the occurence of a break in the curve, before commencing measurements on the next pile.

TABLE 4. *Area of uncoated steel exposed to soil and fill at the test sites*

Pile No.	Area of bare surface, ft [2]		
	Site A	Site B	Site C
1	157	[1] 149	[1] 141
2	130	125	150
3	131	145	155
4	133	145	152
5	[1] 142	140	148
6	131	149	149
7	152	[2] 149	161

NOTE: Area is equal to approximately 6.1 ft ^{2} per linear ft of H pile 12 BP (12 in.×12 in.), 74 lb/ft.

[1] Pulled July 1969.

[2] Horizontal pile—removed July 1969.

Average penetration rates of metal on all bare surfaces exposed to the soil or fill as calculated from yearly instantaneous corrosion currents (based on semilog curves, table 5), are shown in table 6. Values are rounded to the nearest decimal place. Where values are missing, no attempt was made to obtain data.

3.3. Corrosion Rate of Composite Piling Under Pier A-10 Near Site B

During July 1969 an attempt was made to measure the instantaneous corrosion rate of the interconnected piling under pier A-10 indicated by arrow in figure 6. One of the underground test piles at the site in the foreground of the photograph, about 100 ft (30.5 m) away from the pier, was used as an auxiliary electrode for passing current through the soil to the composite piling under the pier. Because of the limited current carrying capacity of resistors in the bridge circuit, the corrosion rate measuring technique was confined to the $\triangle V/\triangle I$ method. The composite piling under pier A-10 consists of 32 piles of about the same size as the test piles and each pile presumably having about the same bare area exposed to the soil down to bedrock. With the bridge balanced and current applied cathodically, the average corrosion current per pile was calculated to be 121 mA. After removing the polarizing current and waiting some time for reasonable stabilization of the piling potential, current was applied so as to make the piling anodic. The average corrosion current under these conditions was now calculated to be 102 mA per pile. The average area of bare piling for those with upper portions encased in concrete is about 149 ft^2 (13.9 m^2) based on table 4. By averaging the corrosion currents calculated from cathodic and anodic polarization curves and using an area of 149 ft^2 (13.9 m^2), the corrosion of the piling under pier A-10, based on current density, is calculated to be around 0.75 mA/ft^2(81μA/dm^2). This compares reasonably with the corrosion data calculated for the test piles (table 5). The corrosion rate (surface penetration) based on this current density is equivalent to about 0.38 mpy (10 μm per year). This is comparable with the penetration rates calculated for the test piles (table 6).

4. Physical Inspection of Extracted Piling

Before exposing test piles to the underground environment, random flange thickness measurements were made at about 12 in (30.5 cm) intervals along the entire length of each pile on two of the flanges. After 3 years of exposure, one driven pile was extracted from each of the 3 sites and the horizontal pile (buried in a backfilled trench) was removed from site B. Soil was scraped from the piles and rotary motor-driven wire brushes were used to remove loose mill scale and corrosion products. Random flange thickness measurements were repeated on the same flanges as done before exposure. In addition, pit depths were measured where corrosion was significant. Photographs showing mechanical equipment and the driven pile at site C in the process of being extracted are illustrated in figures 7, 8, and 9.

4.1. Site A, Driven Pile No. 5

No significant differences were observed between the original and final random flange thickness measurements. Approximately 23 ft (7 m) of bare pile had been exposed to the soil together with a steel plate, 8.5 in x 8.5 in (21.6 cm x 21.6 cm), welded to an outside flange about 15 ft (4.6 m) from the bottom of the pile. No significant amount of corrosion was

TABLE 5. *C rrosion current densities on piling (test piles) based on p larization data and areas (t ible 4) of bare steel exposed underground*

Site	Pile No.[1]	Instantaneous corrosion current density, mA/ft ²*								
		1967 (10 Mo. Exposure)			1968 (22 Mo. Exposure)			1969 (34 Mo. Exposure)		
		Method A[2]		Method B ΔI/ΔV [3]	Method A[2]		Method B[3] ΔI/ΔV	Method A[2]		Method B [3] ΔI/ΔV
		Semilog coordinates	Rectangular coordinates		Semilog coordinates	Rectangular coordinates		Semilog coordinates	Rectangu ar coordinates	
A	1	1.2	1.1	1.3	0.9	0.8	0.7	1.1	1.0	0.9
	2	1.2	1.0	1.1	1.3	0.9	0.9	1.2	0.8	1.4
	3	1.1	1.0	1.2	0.9	0.9	0.6	1.2	0.8	1.1
	4	—	—	—	—	—	1.1	0.5	0.4	0.4
	5	1.3	1.0	1.5	0.9	0.5	0.7	0.8	0.7	0.4
	7	0.7	0.5	0.8	0.6	0.7	0.3	0.4	0.3	0.3
B	1	1.2	1.4	1.3	1.0	1.1	0.7	1.3	1.2	1.2
	2	1.7	1.7	1.1	1.2	1.4	1.3	1.4	1.0	1.0
	3	1.1	1.0	1.4	1.4	1.1	0.9	1.3	1.0	0.8
	4	—	—	—	—	—	1.1	1.3	1.1	1.2
	5	—	—	—	—	—	0.6	1.1	0.5	0.6
	7	2.9	3.1	1.8	1.9	2.2	2.2	1.5	1.5	0.9
C	1	1.3	1.0	1.3	1.4	1.2	0.8	1.3	0.8	0.8
	2	—	—	—	—	—	0.6	1.2	1.1	0.9
	3	—	—	—	—	—	0.4	1.3	1.0	0.8
	4	1.3	1.2	0.7	1.0	0.5	0.6	1.1	0.5	0.5
	5	—	—	—	—	—	0.6	1.1	0.6	0.9
	7	1.3	1.4	0.9	0.7	0.4	0.6	1.1	0.6	0.7

*To convert mA/ft ² to microamperes per square decimeter ($\mu A/dm^2$) approx., multiply by 107.5

[1] Piles 1, 2, 3, 4, and 5 are driven. Piles 7 are placed horizontally in back-filled trenches. Piles 6 (center of circle of piles) were used for application of polarizing current.

[2] Corrosion current density $=\frac{I_p \cdot I_q}{(I_p+I_q)}\times\frac{1}{\text{Area}}$

[3] Corrosion current density $=\frac{1}{0.0023}\times\frac{\Delta I}{\Delta V}\times\frac{\beta a\beta c}{(\beta a+\beta c)}\times\frac{1}{\text{Area}}$, assuming $\beta a=\beta c=0.1$ V and $\Delta V=10\text{–}20$ mV.

Table 6. *Average penetration rates on piling surfaces (test piles) caused by corrosion calculated from polarization curves*

Site	Pile No.	Average penetration rate, mpy [1]		
		1967 After 10 Mo. exposure	1968 After 22 Mo. exposure	1969 After 34 Mo. exposure
A	1	0.6	0.4	0.5
	2	0.6	0.6	0.6
	3	0.5	0.4	0.6
	4	—	—	0.3
	5	0.6	0.4	[2] 0.4
	7	0.3	0.3	0.2
B	1	0.6	0.5	[2] 0.6
	2	0.8	0.6	0.7
	3	0.5	0.7	0.6
	4	—	—	0.6
	5	—	—	0.5
	7	1.4	0.9	[3] 0.7
C	1	0.6	0.7	[2] 0.6
	2	—	—	0.6
	3	—	—	0.6
	4	0.6	0.5	0.5
	5	—	—	0.5
	7	0.6	0.4	0.5

[1] Average penetration is based on corrosion by Faraday's law, when 1 mA/ft [2] is equivalent to a metallic weight loss of 2.7 mdd (milligrams per sq dm per day) and mpy (mils or thousandths of an inch per year) = mdd×0.183. 1 mil = 0.001 inch = 25 micrometers (μm).

[2] Pulled July 1969.

[3] Horizontally buried—Removed July 1969.

Figure 6. *Site B—arrow points to highway pier A-10 where instantaneous corrosion rate was measured on the composite underground piling supporting the pier.*

Figure 7. *Site C—Rigging used to extract piling.*
View shows pile C1 with concrete broken away for linkage connection to the crane cable. Welded reinforcing rod is also visible.

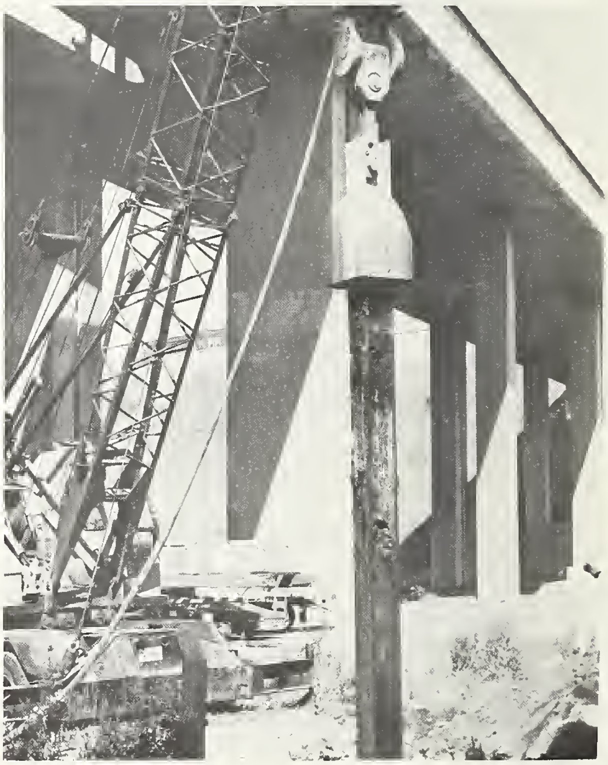

Figure 8. *Site C—pile C1 in the process of being extracted.*

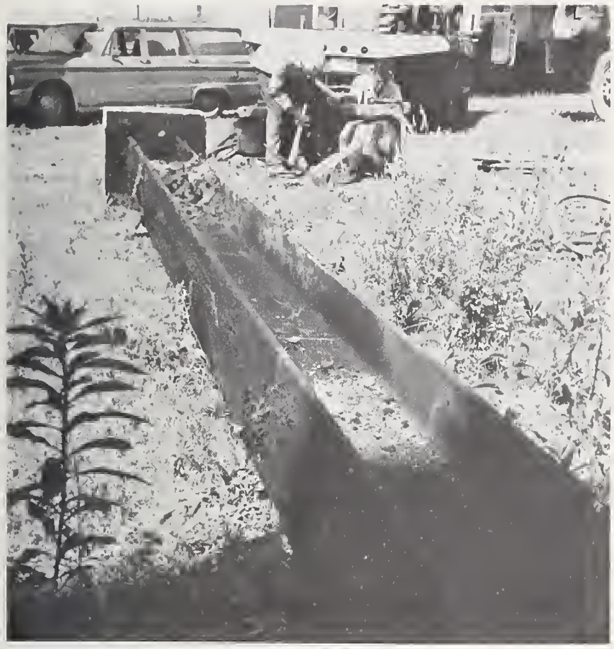

FIGURE 9. *Site C—pile C1 after extraction.*

observed from the bottom of the pile up to 17 ft (5.2 m), including the welded area. About 80 percent of the mill scale was still intact.

On the remaining upper 6 ft (1.8 m), which had been exposed almost wholly to excavated soil and fill, the mill scale had almost entirely disappeared. One outer flange area had a few pits 35 to 40 mils (0.87 to 1.0 mm) deep and many scattered pits 20 to 25 mils (0.50 to 0.62 mm) deep on the upper 3 ft (0.9 m) end of the pile. The other flange showed minor surface attack with little or no significant pitting. The web and inner flange areas on the upper 6 ft (1.8 m) had a calcareous deposit in evidence near the top and some pitting up to 25 mils (0.62 mm) in depth where there was no deposit.

4.2. Site B, Driven Pile No. 1

The differences in measurements of flange thickness made at random before and after exposure were insignificant. This pile also had a plate, similar to the plate previously mentioned, welded to the outside of one of the flanges about 13 ft (4 m) from the bottom end of the pile. The welds appeared unaffected by corrosion.

The entire pile, including the coated area at the upper end, was about 28 ft-4 in (8.6 m) long. The lower 10 ft (3 m) was rusted but showed no pitting beyond the depth of the mill scale, about 50 percent of which was still intact. Between 10 ft (3 m) and 21 ft (6.4 m) from the bottom, the flange areas had several pits up to 30 mils (0.8 mm) and scattered pits 40 to 90 mils (1 to 2.2 mm) in depth. The web area in this range had about 60 percent of the mill scale intact with some calcareous deposition and scattered pitting to a depth of 65 mils (1.6mm).

The area in the range 21 to 24 ft (6.4 to 7.3 m) from the bottom had the most corrosion. This is the area immediately below the coated upper area of the pile. There were several pits ranging from 60 to 100 mils (1.5 to 2.5 mm) deep on the outside of the flanges. The edges of the flanges were most noticeably affected by corrosion. On the inside flange and web areas most of the pits were less than 25 mils (0.62 mm) deep.

The coated area (upper end) of the pile started at 24 ft (7.3 m) from the bottom. This coated area and the bare area in the range 21 to 24 ft (6.4 to 7.3 m) had been exposed to backfilled soil. On the flanges (inside and outside), the coating was about 50 percent removed. There were many pits between 30 and 60 mils (0.75 to 1.5 mm) in depth. The coated web area was less affected by corrosion than were the flange areas, with most of the coating still intact.

4.3 Site B, Horizontally Buried Pile No. 7

Differences in random measurements of flange thickness before and after exposure were insignificant. This pile was 31.5 ft (9.6 m) long of which 5.3 ft (1.6 m) at one end was coated. The most noticeable corrosion was on the edges of the flanges along the entire length of the pile. The coating was blistered and peeled off readily. There were many pits in the coated area on the outside of the flanges ranging in depth between 50 and 85 mils (1.3 to 2.1 mm). The entire flange area on the outside was attacked and the mill scale was almost all gone. There were numerous pits in the uncoated area ranging from 20 to 40 mils (0.5 to 1 mm) in depth. Some pits were 100 mils (2.5 mm) deep.

The web and inside flange areas had fairly uniform corrosion with numerous pits between 20 and 30 mils (0.5 and 0.75 mm) in depth and a few 45 mils (1.1 mm) deep.

4.4. Site C, Driven Pile No. 1

This pile was 31 ft (9.5 m) long including the upper end encased in concrete for 4.5 ft (1.4 m). In addition to the use of a motor-driven rotary wire brush for cleaning, an air gun and chisel were used to remove the concrete. Random measurements of flange thickness made before and after exposure revealed no

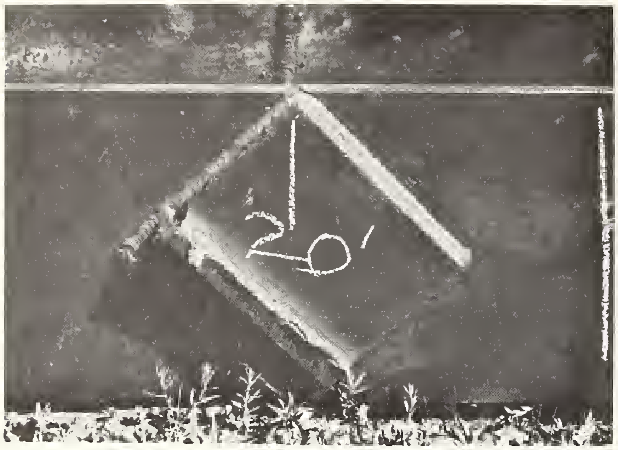

FIGURE 10. *View of pile C1 after extraction and wire brushing, showing the welded plate and surrounding area of the pile.*

significant differences, except perhaps in the bare area immediately outside of the concrete encasement.

The mill scale from the bottom of the pile up to 20 ft (6.1 m) was about 75 percent intact and the little corrosion which occurred was in the form of shallow pitting through the mill scale. The weld at 20 ft (6.1 m) from the bottom and around a steel plate (fig. 10) was unaffected by corrosion. In the area 20 to 24 ft (6.1 to 7.3 m) from the bottom, about 60 percent of the mill scale was gone from the outside of the flanges with some pits up to 25 mils (0.62 mm) deep.

In the area 24 to 26.5 ft (7.3 to 8.1 m) from the bottom, just below where the concrete had been during exposure, corrosion was quite uniform on the outside of the flanges. The average difference in flange thickness based on about 75 measurements made with a micrometer calipers in this area and 75 measurements made in the area previously encased in concrete was about 9 mils (0.23 mm). This 2.5 ft (0.76 m) section of pile is where uniform corrosion was the most noticeable. Some pits in this area were from 30 to 65 mils (0.75 to 1.6 mm) in depth but most of the pits were less than 20 mils (0.5 mm) deep. Corrosion on the inside of the flanges and on the web was in the form of pitting where the mill scale (most of which was still intact) was removed. These pits were no deeper than the thickness of the scale, 10 to 20 mils (0.25 to 0.5 mm).

The upper end of the pile which had been encased in concrete was unaffected by corrosion.

5. Analysis of the Data

Having presented corrosion rates based on polarization measurements and corrosion data obtained on extracted piles based on physical measurements, a comparison of the two types of measurements is in order. The corrosion on this piling might also be compared with the corrosion observed on piling exposed elsewhere and also with the corrosion measured on steel pipe specimens exposed to a variety of soil environments having resistivities of the same order of magnitude as that of the piling soil environments. It must be borne in mind that excessive pitting on underground pipelines cannot be tolerated whereas on piling the important factor pertaining to corrosion is its effect on the load bearing capability of the underground structure.

The average penetration rate on all of the piles (table 6) based on the three sets of polarization measurements made over a period of two years was between 0.5 and 0.6 mils (12 and 15 μm) per year on all bare surfaces exposed to the soil. Thus, it ought not be surprising that the random measurements of flange thickness made before and after 3 years of exposure indicated no significant difference.

At site A, most of the corrosion observed by physical inspection after 3 years of exposure took place on the upper end of the extracted pile. This corrosion pattern was also indicated by polarization measurements made on pile No. 1, site A, after 2 years of exposure in 1968. A boring rig was used to drill a hole about 12 in (30.5 cm) to the side of the pile down to its very bottom. As the drill was lowered, a Cu-$CuSo_4$ reference electrode was alternately placed into the hole at depths of 5,10,15,20 and 22 ft (1.5,3,4.6,6.1 and 6.7 m) below the surface. Based on the $\triangle I/\triangle V$ method used for measuring corrosion current, the corrosion current densities (based on the area, table 4) at the respective depths were calculated to be 1.7, 1.2, 1.4, 0.7 and 0.4 mA/ft^2 (183,129,150, 75 and 43 μA/dm^2). The current densities in table 5 represent an average because the reference electrode was placed in a remote position. Similar measurements made on the same pile with the reference electrode positioned on the earth's surface, showed that the corrosion current was higher when the electrode was close to the pile than when placed at a remote location.

The boring rig was also set up at site B at one pile in the same manner as described for site A except that only corrosion potentials of the pile were read as the reference electrode was alternately placed into the hole. It was observed that the corrosion potentials of the pile varied by as much as 200 mV, the more anodic potentials being at the middle and lower areas of the pile. The more anodic values were attributable to the probably lower concentration of oxygen available in these areas.

The polarization measurements reveal that the greatest amount of metal loss occurred on horizontal pile No. 7, site B as is shown by the relative magnitude of the corrosion currents (table 5). This was later verified by the corrosion observed upon examining the pile after three years of exposure and by pit depths and their frequency of occurrence. This particular pile was unique in the value of its corrosion potential. From the time that the first polarization measurements were made, one year after exposure, the corrosion potentials of pile No. 7 were always positive with respect to the Cu-$CuSo_4$ electrode, ranging from 0.128 V in 1967 to 0.234 V in 1969 when the pile was removed. The reason for the positive potentials could not be attributed to stray currents in the area because the driven test piles at the same site and piling under a nearby pier footing exhibited normal negative potentials. After some inquiry among persons involved at the time the piles were installed, it was learned that this particular pile was inadvertently completely covered with the primer coat in preparation for application of the coal tar epoxy coating. When it was realized that the coating was to be applied only on one end of the pile, similar to that on the driven piles at the same site, a solvent was used to remove the primer from the area that was supposed to have been left uncoated. Thus, the positive potentials are attributed to the effect of the chemicals.

Based on the instantaneous corrosion rate measurements, the maximum average rate of penetration (table 6), after 34 months of exposure is 0.7 mils/yr. (18 μm/yr). Over a period of 50 years, this rate would account for a reduction in metal thickness of 0.07 in. (1.8 mm) or about 12 percent of the H-pile thickness based on a metal thickness of 0.6 in. (15 mm). At site C, physical measurements made on pile No. 1 revealed a reduction in flange thickness of 9 mils (0.23 mm) over a period of 34 months in the most corroded area, from 0 to 2.5 ft. (0 to 0.78 m) below the concrete encasement. This would account for a reduction in metal thickness of 0.150 in. (3.8 mm) in 50 years, or 25 percent of the metal thickness assuming that corrosion continued at the same undiminished rate. The Corps of Engineers [5] mentioned a 35 percent loss in cross section as an acceptable maximum over a period of 50 years.

While protecting the metal which it covers, concrete does setup a galvanic cell comprising the underlying metal and the metallic area adjacent exposed directly to the soil. The thicker the cover of concrete and the higher the resistivity of concrete becomes with aging the less potent the galvanic effect becomes. On the other hand, a good protective coating in place of the concrete would, theoretically at least, eliminate this galvanic effect. Adverse conclusions should not be reached about coatings because of the relative ineffectiveness of the epoxy coating used at site B. It could be that the coating was not applied in the most effective manner. Assuming no serious loss of bond strength, the use of concrete over a coating at the upper ends of the piles would minimize the galvanic effect caused by bare metal adjacent to the concrete.

One might ask how the corrosion rates based on these few polarization measurements compare with corrosion rates of plain ferrous pipe specimens. Based on actual weight loss-time curves involving hundreds of 1.5 in x 12 in (3.8 cm x 30.5 cm) pipe specimens, the corrosion current densities, after five years of exposure in 28 sites having soil resistivities between 500 and 3000 Ω-cm (similar to sites A, B, and C), averaged 1.6 mA/ft^2 (172 μA/dm^2) and ranged between 0.12 and 6.2 mA/ft^2 (13 and 666 μA/dm^2) [8]. This average corrosion current density of 1.6 mA/ft^2 (172 μA/dm^2) on the pipe specimens, even after 5 years of exposure, is higher than the average corrosion current density of the piling (table 5) after only 34 months of exposure. In soils, there is a general tendency for the corrosion rate of iron or steel to lessen with time and usually to level off after 5 years. Average corrosion current densities as high as 6.2 mA/ft^2 666 μA/dm^2) are rather unlikely on underground piling, even in low resistivity soils.

The corrosion rates and patterns observed on the H-piles described in this paper are similar to what was found on pipe piling exposed to a corrosive underground environment elsewhere [6]. On an extracted pipe pile it was found that most of the corrosion, in terms of depth and number of pits, occurred at the upper end of the pile regardless of the fact that the soil at the upper end had the higher resistivity.

The periodic polarization measurements and extraction of these piles for inspection at the three sites will continue and the results will be published periodically.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

In 1966, isolated steel H-piles allocated for underground corrosion tests were installed in three locations at the Turcot Yard Interchange of the Transcanadian Highway at Montreal. The reason for the installation was to furnish answers to some questions concerning the corrosion characteristics of piles, 12 in-74 lb/ft(30.5 cm-110 kg/m), which are identical with the piles supporting the concrete piers under the highway. Polarization measurements have been made once every year since installation.

This paper describes the determination of corrosion rates based on the polarization measurements made up to the time of removal of the first group of piles in 1969. The piles, placed underground at the three locations, differ mainly in that at one site all the piles are bare, at the second site the upper ends of the piles are coated with an epoxy paint and at the third site the upper ends are encased in concrete. Physical measurements made on the cleaned piles after removal are correlated with corrosion rates calculated from the polarization measurements. Also, penetration rates on the piling based on the polarization data are compared with average penetration rates (based on actual weight losses) on relatively small pipe specimens. The pipe specimens were removed from 28 underground sites having a range of soil resistivities comparable to those of the three piling sites.

Using one of the polarization techniques applied to the individual test piles, polarization measurements were also carried out on 32 interconnected piles supporting one of the concrete piers. The calculated average corrosion rate of the 32 piles was found to compare favorably with that of the separate test piles in the same area.

17. KEY WORDS (Alphabetical order, separated by semicolons)
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