Corrosion of Steel Piles in Some Waste Fills

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On the basis of studies conducted about 30 years ago, steel piles having a significant portion of their length driven below fresh groundwater tables showed only minor losses of metal due to corrosion. Previous investigators attributed the lack of corrosion to global cathodic self-protection of driven piles. Recent construction in Hartford, Connecticut, uncovered piles installed more than 30 years ago. Some showed losses of cross-sectional area greater than 50 percent. These piles were driven through layers of waste materials called miscellaneous fill. The results of an investigation into this unusual corrosion loss are presented. The cause of the corrosion is traced to a macro cell developed between contiguous layers in the miscellaneous fill that overrides the global protection normally found at most pile installations in fresh water. Electrical characteristics of the macro cell are presented. Techniques for detecting areas that might develop these macro cells are outlined, and methods of protecting piles from their effects are discussed.

Previous research indicated that steel piles driven with more than about half of their length below the groundwater table experienced only nominal amounts of corrosion with negligible loss of metal (1–5). Romanoff (1,2) of the National Bureau of Standards concluded that the large area of steel pile below the groundwater table is anodic and develops a weak cathodic protection for the upper portion exposed to oxygen in the fill (2). As a result, designers usually avoided the expense of protective coatings for steel piles and were justified in doing so in most cases (6). Reconstruction of the I-91 to I-84 interchange in Hartford, Connecticut, however, revealed certain fill conditions that caused steel H piles to lose large amounts of cross-sectional area to corrosion during the 30 years since their installation. The research reported here identifies the conditions that led to this unusual corrosion loss and tests to show the aggressiveness of certain fills.

DISCOVERY OF THE LOSS

The design of the new I-84 to I-91 interchange in Hartford required the enlargement of some existing pier foundations. The construction of these enlarged foundations required excavating beneath the original pile caps, cleaning the exposed portion of the original HP 12 × 53 mild steel piles by sand blasting, driving some new piles to carry the additional load, and forming and placing concrete for a new pile cap to include the old and new piles.

Excavation below the original pile cap at Pier 12 under the I-91 southbound lane uncovered severe corrosion of the piles

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approximately 1 to 1.2 m below the bottom of the cap. The average loss of cross-sectional area was 55 percent. The greatest loss was 65 percent, the least was 35 percent. An example of the corrosion loss is shown in Figure 1. Some pitting of the metal had occurred, but the most striking feature about the damage was the loss of metal from the flange. In several cases, corrosion had removed the steel from a triangular-shaped area in the flange, as shown in Figure 1. The base of the loss triangle was at the location of the original flange edge. The flange metal that remained was thinner than the original section, forming a knife edge around the rim of the remaining metal. The "height" of the triangle as measured from the line of the original flange edge was 60 mm for the case shown in Figure 1. The pattern of corrosion suggested a current flow that exited the piles at a localized elevation of the flange. The surface of the webs contained pits, but the metal loss on the webs was substantially less than on the flanges. This pattern appeared again as construction exposed the piles beneath other piers. All corrosion losses occurred above the groundwater table.

The corrosion loss at Pier 12 occurred in a layer of fill having 94 percent of its particles smaller than the No. 200 sieve. The layers above and below the corrosion loss contained a high percentage of ash and cinder particles. These piles had been driven through a repository of waste materials commonly called miscellaneous fill.

The design of the original pier used a maximum fiber stress of 6 ksi for these piles. The remaining cross sections of the piles were adequate to carry the existing loads. The pier was never in danger of failure.

This interchange is in downtown Hartford, where traffic is heavy and construction could not be delayed. The consultant responsible for design retained a corrosion specialist who recommended coating the new piles with coal tar and attaching sacrificial zinc anodes. This is a treatment often used for pipelines that are completely buried in disturbed soils (7–9). These solutions, usually considered conservative for steel piles (1,2), allowed construction to continue. Measurements indicated no evidence of stray current. The existing piles were reinforced by welding structural shapes to the remaining steel in the piles, and sacrificial anodes were attached. Pouring the new pile cap encased the piles to a depth about 1.5 m below the elevation at which the loss occurred. The research described herein addressed the reasons for the unusual corrosion loss.

Significant cross-sectional losses occurred at several other pile groups within the project. An example of the losses at Pier 7 are shown in Figure 2. The damage in Figure 2 includes loss of metal from the flange edge and some holes corroded through the flanges. Measurements taken on the remaining
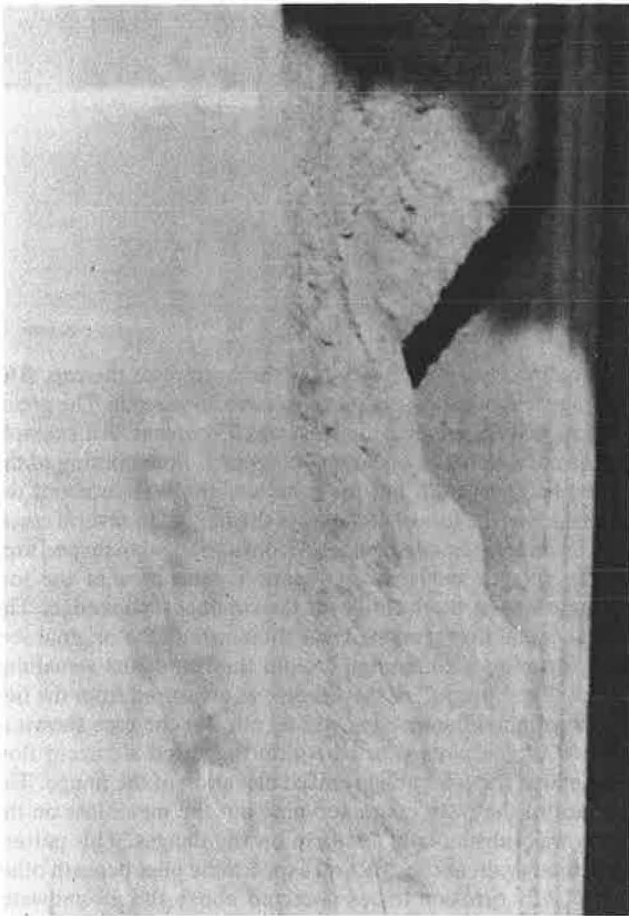
FIGURE 1 Typical corrosion loss, Pier 12, I-91 southbound, Hartford, Connecticut.
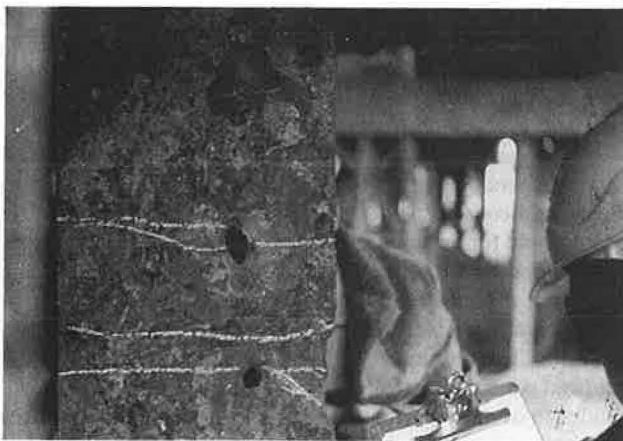

FIGURE 2 Corrosion loss at Pile 5, Pier 7, I-91 southbound, Hartford, Connecticut.

thickness of the piles under Pier 7 indicated losses of cross-sectional area up to 32 percent.

The piles under the existing west wing wall at Abutment 2 had to be removed because they were in the way of the proposed construction. During extraction with an air-activated pile hammer, several of the piles did not have enough cross section left to allow them to be pulled out of the ground. Damage to the piles under the west wing wall of Abutment 2 is shown in Figure 3, which shows that there was considerable loss on piles that could be removed. As will be shown, this unusual corrosion had to do with the fill surrounding the upper portion of the piles.

Not all the piles had large corrosion losses. For example, at Abutment 2 only the piles under the wing wall had significant corrosion loss. Under the portion of the abutment carrying the roadway, the piles were in excellent condition. Pier 10, about 200 ft south of Pier 12, required a similar enlargement scheme, and the excavation occurred at about the same time as Pier 12. The piles at Pier 10 showed minor losses, although the layering appeared similar. The boring logs for both sites indicated miscellaneous fill above the natural deposits of varved clay and sands. Tests indicated negligible sulphur and pH range between 7.6 and 9.4. The layers below Pier 12, near the corrosion loss, had resistivities below 1,000 ohm-cm (10). The resistivities of the layers below Pier 10 were larger than 1,000 ohm-cm. A few samples were taken for laboratory tests, and a strategy was developed to investigate the metal loss.

Most of the other pile groups had small losses of cross section, usually as surface pits. For example, the piles at Pier 8, surrounded throughout most of their length with natural clay, had only a few minor pits.
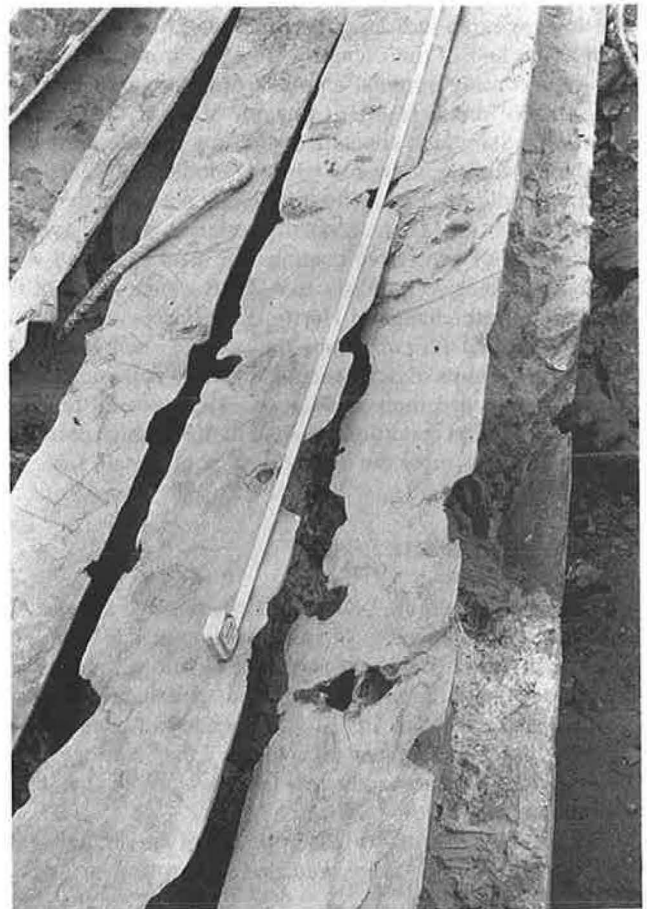

FIGURE 3 Piles extracted from beneath Abutment 2, I-91 southbound, Hartford, Connecticut.

PREVIOUS RESEARCH ON CORROSION IN SOILS

Corrosion of iron and steel has been the subject of many research studies (*11–15*). These investigations have found that steel corrodes in the atmosphere, sea water, or disturbed soil at rates requiring protection to remain serviceable. The study by the National Bureau of Standards (NBS), as the National Institute of Standards and Technology was then known, on metals buried in disturbed soils extended over a 30-year period and indicated that the corrosion of metals in disturbed soils correlates with specific properties of the soil-water system, such as soil resistivity, pH, and chloride and sulfide content (*11*). Results of a recently published study indicate that the most important conditions are electrical resistivity of the soil-water system and the presence or absence of oxygen (*12*).

Subsequent research by NBS addressed driven steel piles (*1,2*). These investigations examined steel piling, both H and sheet piling, installed in soils for periods up to 40 years. The results indicated minor damage from corrosion. As part of the study, investigators measured the loss of material from cross sections of the piles. The cross-sectional areas had reductions of only a few percent. The losses did not correlate with any of the conditions such as pH, and chloride and sulfate concentrations were observed to promote corrosion loss in buried metals (*2,11*). In fact, the prediction of metal loss based on techniques from the NBS study on buried metals were conservative for steel piles in that they predicted much more metal loss than actually occurred (*1,2*).

Only a few studies on corrosion of steel piles driven in fresh water locations have been conducted since the NBS study (*3*). The results of these studies confirmed the conclusions of Romanoff (*2*). The electrochemical models that emerged from these studies are valid for conditions at many sites. In the case of buried steel, the metal is entirely in the fill, and the availability of oxygen promotes corrosion. For driven steel piles, the large portion below the groundwater table gives cathodic protection to the portion in the homogenous fill (*2*). Obviously, something in the site conditions at the intersection of I-84 and I-91 at Hartford disrupted this pattern.

Research on pipelines noted a tendency for corrosion to occur where soil regions with different characteristics were in contact with metal (*16*). The corrosion characteristics of this situation, called a macro cell, have been reported (*17*).

MISCELLANEOUS FILL

Land in cities has always been valuable. Low areas were often filled to make them more desirable. The filling was usually done with cheap waste materials, which were applied over time and gave the site a subsurface profile having thin layers. The layers may consist of construction debris and rubble, waste soil from excavations, and cinders and ash. Usually the process excluded organic materials, but layers containing organics are sometimes seen.

The sites containing these materials are difficult to describe or quantify with the few words that fit on a boring log. Therefore, drillers in Connecticut came to refer to these materials as miscellaneous fills. The profiles in miscellaneous fills vary from location to location at the same site. Any large structure built on these locations is usually supported on a deep foundation, so few details about these fills were requested. As the excavations in Hartford show, there are conditions existing in these miscellaneous fills that can aggressively attack driven steel piles.

INVESTIGATION OF THE MECHANISM OF CORROSION IN THE WASTE FILL

Role of the Macro Cell in Corrosion

Corrosion is an electrochemical process requiring a difference in electrical potential between points on a metal surface (*18*). The potential difference can be caused by differences in grain orientation, inclusions, imperfections, and other conditions on the surface of the metal (*13*). It can also be caused by inhomogeneities in the electrolyte, including differences in aeration, temperature, and local depletion or accumulation of chemicals in the soil (*13*). The potential difference causes a flow of current. If the electrical resistance of the soil-water system is low enough, the flow of current can cause a significant loss of metal. The flow of current takes place in two forms. Inside the metal the current is envisaged as the movement of electrons. In the soil the current is carried by ions moving through the pore water. The most interesting phenomenon occurs at the interface of the steel and the pore water. At the cathode, hydrogen gas forms. At the anode, the passage of current is accompanied by the dissociation of ferrous or ferric ions from the main member, causing loss of metal.

The electrochemical conditions that support corrosion led to the hypothesis of a macro cell in the miscellaneous fill counteracting the global cathodic protection of the piles set up by the groundwater table. This investigation studied the possibility of a macro cell formed by contiguous layers causing the observed losses of metal.

Possible Causes of the Electrical Potential Difference

In a miscellaneous fill, many conditions capable of developing a difference of electrical potential between contiguous layers can exist. Contiguous layers of cinders and clay, for instance, may contain different amounts of oxygen, forming what is known as an oxygen concentration or aeration cell. There may be different species of chemical constituents present in each contiguous layer producing a similar potential difference. Electrical properties of organisms playing a part in corrosion have also have been reported (*19,20*). A difference in electrical potential between various layers of earth materials, called self-potential, has been observed by geologists and used for the past 100 years to measure the thickness of layers in a borehole (*21*). A large self-potential is about 0.5 V, but values as large as 1.3 V have been reported (*22*). None of the mechanisms advanced to explain the cause of these differences in electrical potential is adequate (*23,24*). However, the method continues to be used satisfactorily despite the uncertainties (*25*).

Several approaches to reproduce a macro cell in the laboratory were tried. The simplest demonstration used remolded varved clay and cinders from the vicinity of Pier 12. This setup is shown in Figure 4. A layer of cinders 76 mm thick was
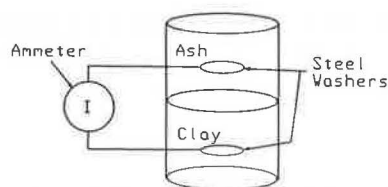
FIGURE 4 Laboratory demonstration of the macro cell using materials from a miscellaneous fill.
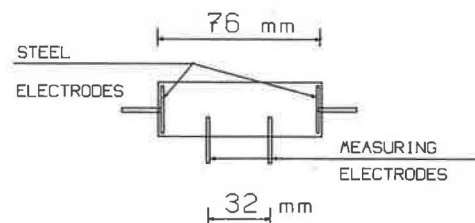

FIGURE 5 Test cell for measuring resistivity and contact potential.

FIGURE 6 Plot of resistivity versus water content for materials sampled from Pier 7.

placed in an acrylic cylinder 150 mm in diameter over a clay layer of similar thickness. One steel washer was buried in each layer. Connecting the lead wires from the washers to an ammeter completed the circuit. The circuit was interrupted periodically and the open circuit potential measured. The electrical potential was measured at 0.3 V and remained approximately constant. The current began at 1.1 mA and decreased to about 0.6 mA. The sample became dry on two occasions, and the current stopped. Upon rewetting with tap water the flow of current resumed. This demonstrated that contiguous soil layers can develop a macro cell capable of producing enough electricity to cause the observed losses. It also showed that periodic drying and wetting, which may occur in the field, does not destroy the cell.

Measurement of Soil Resistivity

The resistivity of the soil is an important property in the study of corrosion. The amount of metal lost is directly proportional to the amount of current passed, and the soil resistivity is important in the control of current flow. The resistivity of soil, cinders, and other particulates of interest must be measured.

The resistivity of soil is illustrated with the device used to measure it in the laboratory. This device is shown in Figure 5 and is similar to devices used by other agencies (10,26). The soil at the desired water content is placed in a container made of acrylic plastic. All electrodes are made of steel and polished with fine emery paper before each measurement. A known alternating current is passed through the soil, and the potential drop is measured between the pin electrodes placed in the sides of the container. The resistivity of the soil is computed from the following equation:

$$R = \frac{dV}{I} = p\,\frac{L}{A} \tag{1}$$

where

R = the resistance of the soil (ohms),
p = soil resistivity (ohm-cm),
dV = measured potential difference (volts),
L = length of soil (cm) across which dV is measured, and
A = cross-sectional area (cm²) carrying the current I.

Typical values of resistivities measured for samples taken from beside Pile 5 of Pier 7 are shown in Figure 6. As can be seen from Figure 6, the soil resistivity is sensitive to water content of the material. At low water contents, the resistivity of the soils is relatively high. As water is added, the resistivity drops quickly, then remains fairly constant. The low resistivity values of all three of these soils are below 1,000 ohm-cm.
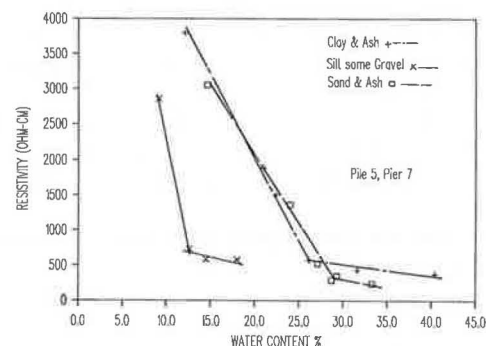
This low resistivity region is of interest. The samples were mixed with distilled water and lightly compacted into the device shown in Figure 5. To ensure that all measurements were made in the low resistivity region, enough water was added so that free water was observed on the surface of the soil sample. The resistivities reported here are all from the low region and are referred to as approximate minimum resistivities. Resistivities of soil samples taken from Pier 7 are given in Table 1 as well as the open circuit potentials developed between contiguous layers. Note from Table 1 that the loss of pile occurred where the approximate minimum resistivities were well below 1,000 ohm-cm and the measured potential was 0.34 V.

Measurement of Open Circuit Potential

The appearance of the corrosion damage of the piles indicated that current was being passed between contiguous soil layers and through the piles. Tests indicated that layers near the metal loss had low resistivity. The flow of current also needs a difference of electrical potential. The measurements of potential difference used the same containers as those for resistivity; one-half of the cell was filled with soil or material from one layer and the other half with the material from its contiguous layer. Distilled water was added to both soils until they appeared saturated. The open circuit potential between

TABLE 1 PROPERTIES OF CONTIGUOUS LAYERS SURROUNDING PILE 5,
PIER 7, I-91 SOUTHBOUND

Layer No.	Approx. Layer Thickness	Description	Approx. Minimum Resistivity	Potential Difference	pH	Remarks
	(cm)		(ohm-cm)	(v)		
1	50.8	Coarse Sand, Some Silt	4864		8.4	
				0.012		
2	25.4	Red-Brn Silt, Some Gravel	3846		7.5	
				0.045		
3	15.2	Red-Brn Silt, Some Gravel	578		2.3	
				0.34		
4	45.7	Clay w/Coal And Ashes	377		3.8	Greatest Metal Loss
				0.012		
5	30.5	Sandy Silt Some Ashes	238		7.6	
				0.145		
6	38.1	Brown Clay	1578		6.9	

the end electrodes was measured with a high-resistance voltmeter.

RESULTS AND ANALYSIS

Additional laboratory results are given in Tables 2 and 3. All samples are disturbed. Because the excavations had been open for various lengths of time before the samples could be retrieved, undisturbed moisture contents could not be determined. All the tables indicate soil resistivity close to their minimum values, because this appears to be the best condition for comparing results. Table 1 gives the results for contiguous layers around Pile 5 in Pier 7, the most heavily damaged pile in the group. The thickness of each layer is shown in the second column from the left. The greatest metal loss occurred in Layer 4, where there was low resistivity and high potential difference with Layer 3 above it. The measured pH next to the pile is also given in Table 1. The pH in the vicinity of the metal loss was low but increased with distance from the pile,

rising to about 7.0 approximately 0.6 m from the corroded surface.

Table 2 gives the soil properties beneath the center of Abutment 2. The piles in this section had only minor pitting. The saturated resistivities are high and the potential differences between contiguous layers low except for Layers 5 and 6. No corrosion loss was observed because the layers in this area, being protected from rainfall by the roadway, probably had a resistivity in the field that was greater than the laboratory values reported in Table 2.

Less than 50 m away from the location containing the samples of Table 2 is the wing wall of Abutment 2. The properties of soil from beneath the wing wall of Abutment 2 are given in Table 3. The piles in this area, exposed to both macro cells and deicing salts, experienced severe corrosion. There was no opportunity to see the layering details under the wing wall. The samples for testing were taken from the soil that adhered to the piles at the location of the major corrosion loss and from portions above and below. As can be seen from Table 3, the layers near the metal loss had a low resistivity and a

TABLE 2 PROPERTIES OF CONTIGUOUS LAYERS BENEATH
ROADWAY ABUTMENT 2, I-91 SOUTHBOUND

Layer No.	Approx. Layer Thickness	Description	Approx. Minimum Resistivity	Potential Difference	pH
	(cm)		(ohm-cm)	(v)	
1	22.9	Brown Silty Sand	1385		8.1
				0.016	
2	25.4	Brown Coarse Sand	2881		8.7
				0.093	
3	50.8	Cinders	2458		6.7
				0.012	
4	20.3	Clay	659		8.6
				0.020	
5	17.8	Ashes & Silty Sand	1082		8.2
				0.213	
6	15.2	Gray Clay	739		7.1

TABLE 3 PROPERTIES OF CONTIGUOUS LAYERS IN CORROSION ZONE OF THREE
PILES FROM THE WING WALL AT ABUTMENT 2

Pile No.	Location in Corrosion Zone	Description	Sat. Resistivity (ohm-cm)	Pot Diff. V.	pH	Concentration		Remarks
						Cl ppm.	SO$_4$ ppm.	
12	Top	Cinders	1489		4.2	324	185	
12	Middle	Silty Clay	903		4.6	396	48	Anode
				0.29				
12	Bottom	Ash	408		7.1	257	32	
13	Top	Clay	301		4.8	407	1648	
13	Middle	Cinders	504		4.4	130	1625	
				0.34				
13	Bottom	Ash	247		4.2	590	1374	
15	Top	Slag	808		5.5	434	82	
15	Middle	Ash	425		3.2	476	15	
				0.13				
15	Bottom	Clay	2707		5.5	88	33	Anode
-	-	Varved Clay	-	-		24	40	

high potential difference. Also given in Table 3 are the chloride and sulfate levels in the layers at the wing wall piles as well as the values from a remolded varved clay representing background values. Table 3 indicates that the levels of chloride and sulfate under the wing wall were substantially higher than the background found in the clay. One effect of these chemicals is to reduce the resistivity of the soil or cinders by making the pore water more conductive to electricity.

Other combinations of layers were tried in the laboratory to determine the range of potentials that may develop in a miscellaneous fill. Some of these values are given in Table 4. The largest potential difference is between crushed coal and coal ash. Coal, perhaps because it is almost pure carbon, develops the greatest potential with other materials. The data in Table 4 are presented to illustrate that various combinations of particulate materials tend to develop a difference in electrical potential when placed in contiguous layers.

MODELING THE CORROSION LOSS

To check the viability of the measured electrical properties causing the observed metal loss, a first approximation macro cell model was developed, as shown in Figure 7. Assuming

TABLE 4 ELECTRICAL PROPERTIES BETWEEN CONTIGUOUS LAYERS

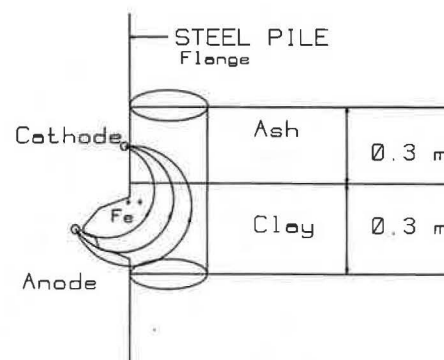| Anode	Cathode	Potential Difference	Samples
		(v)	
Silt	Conc. Sand	0.11	
Clay(lay.6)	Sand(lay.1)	0.14	from Pile 5,Pier 7
Silt(lay.3)	Sand(lay.1)	0.04	from Pile 5,Pier 7
Coal Ash	Coal	1.05	Both passing No.10 Sieve
Coal Ash	Cinders	0.06	
Coal	Cinders	0.82	
Varved Clay	Cinders	0.39	
Conc.Sand	Conc.Sand	0.01	

FIGURE 7 First approximation corrosion model of a macro cell in miscellaneous fill.

that the corrosion is caused by contiguous layers 0.3 m thick and that the center of the cathode and the center of the anode are in the center of these layers, the average length of current travel is between these centers, approximately 0.3 m apart. The area through which the current can travel is assumed to be circular and 0.15 m in diameter. A potential difference of 0.25 V between the electrodes and a soil resistivity of 500 ohm-cm allow enough current to pass during a 30-year period to remove nearly half the cross-sectional area. This model demonstrates that a macro cell with these properties is able to cause the observed metal losses.

INVESTIGATION OF POTENTIALLY AGGRESSIVE FILLS AND LOCATIONS

Locations whose depth profile contains thin layers, especially layers of ash and cinders interspersed with clay, should be

investigated carefully before designing a deep foundation with steel piles. At the present time the best way to determine whether the layers in a given area will be aggressive to steel piling is to plan a boring program for taking continuous samples and recover a specimen from each of the layers for laboratory testing. The specimens should be tested for resistivity of each layer and electrical potential between contiguous layers.

The corrosion observed here occurred in layers in which the soil resistivity was less than 1,000 ohm-cm and the measured potential difference was at least 0.10 V. These conditions identify aggressive corrosion locations for steel piling.

CONCLUSIONS

1. Significant corrosion loss can occur from steel piles driven through layered fills, especially fills containing layers of cinders, ash, and clay.

2. The layering in nonhomogeneous fills can cause a macro cell that overrides the normal protection provided the upper portion of the pile by the anodic portion below the groundwater table.

3. The local galvanic cell requires a potential difference of at least 0.10 V and a soil resistivity less than 1,000 ohm-cm to produce the losses observed in this study.

ACKNOWLEDGMENT

REFERENCES

1. M. Romanoff. *Corrosion of Steel Pilings in Soils*. Monograph 58. National Bureau of Standards, U.S. Department of Commerce, 1962, 22 pp.
2. M. Romanoff. Performance of Steel Pilings in Soils. In *NBS Papers on Underground Corrosion of Steel Piling*. Monograph 127. National Bureau of Standards, U.S. Department of Commerce, 1972.
3. Y. Ohsaki. Corrosion of Steel Piles Driven in Soil Deposits. *Soils and Foundations*, Vol. 22, No. 3, 1982, pp. 58–76.
4. W. J. Schwerdtfeger. Polarization Measurements as Related to Corrosion of Underground Steel Piling. In *NBS Papers on Underground Corrosion of Steel Piling*. Monograph 127. National Bureau of Standards, U.S. Department of Commerce, 1972.
5. W. J. Schwerdtfeger and M. Romanoff. *Corrosion Rates on Underground Steel Test Piles at Turcot Yard, Montreal, Canada—*

Part 1. Monograph 128. National Bureau of Standards, U.S. Department of Commerce, 1972, 12 pp.
6. *Durability of H-Piles in Earth*. Engineering Aids, Description Sheet 2254-B. Bethlehem Steel, Bethlehem, Pa., 1977.
7. W. R. Kinsey. Underground Pipeline Corrosion. *Journal of Transportation Engineering*, ASCE, Vol. 99, No. TE1, 1973, pp. 167–182.
8. M. G. Fontana and N. D. Greene. *Corrosion Engineering*. McGraw-Hill, New York, 1967.
9. H. H. Uhlig. *Corrosion and Corrosion Control*. John Wiley and Sons, Inc., New York, 1963.
10. *Method for Estimating the Service Life of Steel Culverts*. California Test Method 643. Division of Construction, Office of Transportation Laboratory, California Department of Transportation, Sacramento, Calif., 1978, 6 pp.
11. M. Romanoff. *Underground Corrosion*. Circular 579. National Bureau of Standards, U.S. Department of Commerce, 1957.
12. E. Escalante. The Effect of Soil Resistivity and Soil Temperature on the Corrosion of Galvanically Coupled Metals in Soil. *Galvanic Corrosion*. ASTM STP 978 (H. P. Hack, ed.). American Society for Testing and Materials, Philadelphia, Pa., 1986, pp. 193–202.
13. E. Escalante. Concepts of Underground Corrosion. *Effects of Soil Characteristics on Corrosion*. ASTM STP 1013 (V. Chaker and J. D. Palmer, eds.). American Society for Testing and Materials, Philadelphia, Pa., 1989, pp. 81–94.
14. J. R. Scully and K. J. Bundy. Electrochemical Methods for Measurement of Steel Pipe Corrosion Rates in Soil. *Materials Performance*. April 1985, pp. 18–25.
15. M. L. White and H. Leidheiser, Jr. The Corrosion Coulometer—A New Corrosion Monitor for Steel Structures. *Corrosion*, Vol. 46, No. 8, 1990, pp. 653–661.
16. A. W. Peabody. *Control of Pipeline Corrosion*. National Association of Corrosion Engineers, Houston, Tex., 1967.
17. N. D. Tomashov and Y. N. Mikhailovsky. Corrosivity of Soils. *Corrosion*, Vol. 15, 1959.
18. W. J. Oldfield. Electrochemical Theory of Galvanic Corrosion. *Galvanic Corrosion*. ASTM STP 978 (H. P. Hack, ed.). American Society for Testing and Materials, Philadelphia, Pa., 1988, pp. 5–22.
19. W. A. Hamilton. Sulphate-Reducing Bacteria and Anaerobic Corrosion. *Annual Review of Microbiology*, Vol. 39, 1985, pp. 195–217.
20. P. Rich. Trophic vs. Detrital Energetics: Is Detritus Productive? *Bulletin of Marine Science*, Vol. 35, No. 3, 1984, pp. 312–317.
21. D. S. Parasnis. *Principles of Applied Geophysics* (4th edition). Chapman and Hall, New York, 1986, pp. 104–115.
22. M. R. J. Wyllie. A Quantitative Analysis of the Electrochemical Component of the S.P. Curve. *Journal of Petroleum Technology*, Vol. 3, 1951, pp. 17–26.
23. M. Sato and H. M. Mooney. Electrochemical Mechanisms of Sulfide Self-Potentials. *Geophysics*, Vol. 25, No. 1, 1960, pp. 226–249.
24. H. W. Patnode. Relation of Drilling Mud Resistivity to Mud Filtrate Resistivity. *Journal of Petroleum Technology*, Vol. 1, 1949, pp. 14–16.
25. W. M. Telford, L. P. Geldart, R. E. Sheriff, and D. A. Keys. *Applied Geophysics*. Cambridge University Press, Cambridge, United Kingdom, 1976.
26. *Standard Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method*. Section 4, Vol. 4.08. G 57-78. The American Society for Testing and Materials, Philadelphia, Pa., pp. 1046–1050.