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Corrosion of Steel Pilings in Soils

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Corrosion of Steel Pilings in Soils[1]

Melvin Romanoff

(April 18, 1962)

Steel pilings have been used for many years as structural members of dams, floodwalls, bulkheads, and as load-bearing foundations. While its use is presumably satisfactory, no evaluation of the material after long service has been made. In cooperation with the American Iron and Steel Institute and the U.S. Corps of Engineers, the National Bureau of Standards has undertaken a project to investigate the extent of corrosion on steel piles after many years of service.

Results of inspections made on steel pilings which have been in service in various underground structures under a wide variety of soil conditions for periods of exposure up to 40 years are presented.

In general, no appreciable corrosion of steel piling was found in undisturbed soil below the water table regardless of the soil types or soil properties encountered. Above the water table and in fill soils corrosion was found to be variable but not serious.

It is indicated that corrosion data previously published by the National Bureau of Standards on specimens exposed under disturbed soil conditions do not apply to pilings which are driven in undisturbed soils.

1. Introduction

Steel pilings have been used underground for many years to transmit loads to lower levels or to resist lateral pressures due to earth and water. Pipe- and H-piles are used as load-bearing foundations for the first purpose; sheet piles are used as structural members of dams, floodwalls, bulkheads, and other installations for the latter purpose. While its use is presumably satisfactory because no structural failures have been attributed to the corrosion of underground piles, there is considerable concern that damaging corrosion might occur on steel piles driven in different soil environments. This concern is enhanced by the corrosion that occurs in disturbed soils on actual structures, and by the results of corrosion investigations of the type conducted by the National Bureau of Standards [1],[2] in which corrosion of iron, steel, and other metals in different soil environments has been observed to range from a negligible rate to a very high rate.

As a basis for more accurate estimates of the useful life of steel pilings in soils, the National Bureau of Standards, in cooperation with the American Iron and Steel Institute and the U.S. Corps of Engineers, has undertaken a project to investigate the extent of corrosion on steel piles after many years of service.

Excavations to depths of 15 ft were made adjacent to various floodwall and dam structures along the Mississippi River to expose sheet steel pilings which have been in service from 7 to 20 yr. Soil samples and sections of the piles were returned to the laboratory for further study. The extraction of steel sheet and H-piles from other locations permitted examination of the entire length of piles at greater depths and for exposure periods up to 40 yr.

In this paper are presented the results obtained to date from the inspections of steel pilings. The investigation will be continued by additional inspections of pilings in other parts of the country in order to cover a wider range of soil environments.

2. Literature Survey

Although many references pertaining to the behavior of steel piling have been made in the literature during the past years, no systematic evaluation of the material after long service in soils has been made. Many of the reports make general statements without giving much or any information regarding the history of the structure or actual measurements relating to the condition of the piles examined.

Statements regarding the underground corrosion of steel piles are made in two texts on substructure design. Andersen [2] indicates that corrosion is not a serious problem when steel piles are completely below ground-water level but it must be guarded against where sea water is present, where ground water has a high salinity, or where the piles are subject to alternate wetting and drying. Hool and Kinne [3] state that the amount of corrosion on steel pipe piles in the ground is negligible. Piles that have been in the ground for over 25 yr have shown upon removal that corrosion did not penetrate more than $\frac{1}{64}$ in. into the metal. They also report that corrosion is slight on sheet pile below ground-water level.

Mason and Ogle [4] inspected a large number of steel pile foundations in bridge structures in Nebraska. They found little, if any, corrosion at depths greater than 18 in. below the stream bed or ground water level. It was estimated that the decrease in section due to corrosion had not been more than 1 percent in 20 yr, except in an area where the soils are saline to a marked degree. In that locality

[1] A paper presented at the Soil Mechanics and Foundations Division, American Society of Civil Engineers Convention at Houston, Texas, February 22, 1962.
[2] Figures in brackets indicate the literature references at the end of this paper.

several steel foundations showed a loss of section of about 2 to 2.5 percent.

The Harbor Commissioners of Quebec City [5] concluded from examination of a 16-yr-old steel sheet pile in the St. Charles River that steel buried in sand or ground or submerged in water, is less exposed to damage by corrosion than when exposed to the air. The examination in soil was limited to one sample of the pile which was 2 ft below ground surface. The sample was covered with a heavy crust of rust and difficult-to-remove corrosion products. After cleaning by sand blasting a good state of preservation was evident.

The Los Angeles Department of Engineering [6] removed some 39-yr-old piers which consisted of concrete cast in 4-ft diam cylindrical shells made of steel plates. Forty-one feet of the cylinders were below ground, the lower 11 ft below the ground-water level and the upper 30 ft in dry sand and gravel, part of which was wet occasionally. Some pits having a maximum depth of 1/16 in. were observed on the shell below ground water. Slightly more pitting was found in the zone above ground-water level; the average depth of the pits was again about 1/16 in.

It was found on examination of steel sheet piling which was removed after exposure for 19 yr from a bridge over the Monongahela River at Pittsburgh [7] that the zone between the water line to 2 ft below showed a 15-percent reduction in weight. The zone extending from 2 ft below the water line to and below the mud line was practically unaffected by corrosion. It was pointed out that during most of the year the river contained some free sulfuric acid.

In a report concerned with a study of the expected life of steel H-piling and thin wall cylinder piling under highway structures in the Texas Gulf Coast area, Gallaway [8] concluded that, with the exclusion of muck and peaty soils, steel piling driven in ordinary soil to a point below the water table should suffer very little corrosion except in the zone extending not more than 2 or 3 ft below the soil-water interface. Gallaway does not provide actual data to support the conclusion, nor does he indicate the extent of corrosion encountered in soils of muck and peaty materials.

Greulich [9] described the condition of a 12-in. 72-lb H-pile after exposure for 12 yr to a depth of 72 ft through various layers of sand and clay in the Texas Harbor at Houston. Calculations based on examination of a section of the pile between 1 and 2 ft below the mud line indicate that it would take a minimum of 85 yr for corrosion to reduce the thickness of the pile to the extent that it would not permit a safe design load of 17,000 psi (65-ton service load) when acting as a fully supported column. Greulich also reported on the excellent condition of a 122-ft length of H-pile which was extracted 17 yr after installation at Bonnet Carre Spillway in Louisiana. A discussion of the condition of this pile from data made available by the Lower Mississippi Valley Division of the Corps of Engineers will be given in a following section of this paper.

Steel piles which extended from 3 ft below the mud line into the atmosphere above the tidal range were exposed at six naval harbors for periods ranging from 13 to 27 yr [10]. At each of the sites the piles corroded at a higher rate in a zone located above the mud line than at the mud line level and below. The greatest corrosion generally occurred in the area of the splash zone above the high-water mark. The averages of the original pile thicknesses and the extent of maximum corrosion on the piles at and below the mud line are shown in table 1. The corrosion rates at the 1- and 3-ft levels (below the mud lines) varied only slightly from those which occurred at the mud line, except at San Diego where a high corrosion rate was found 3 ft below the mud line. This was attributed to local conditions which produced a lower *p*H in this level or to oxygen-concentration cells.

Lipp [11] observed from a survey of sheet steel pile bulkheads at Miami Beach that the steel below the sand line was in practically the same condition as the day it was installed, 8 yr previously. A 14 percent loss in piling thickness was observed in the areas exposed above the sand line.

The Beach Erosion Board of the Corps of Engineers [12, 13] conducted extensive investigations on the deterioration of sheet pilings in such shore structures as jetties, groins, harbor, and beach bulkheads. In a report [12] pertaining to the behavior of 3/8-in. steel pile groins at Palm Beach, Fla., it was shown that the average rates of loss in steel thickness of the parts not exposed to sand abrasion are relatively moderate, being about 0.011 in./yr for atmospheric

TABLE 1. *Thickness (percent of original) of piling after exposure at naval harbors* [10]

Level	Harbor location											
	Boston		Puget Sound		San Diego		Norfolk		Pearl Harbor [a]		Coco Solo [a]	
	Avg [b]	Min [c]	Avg	Min	Avg	Min	Avg	Min	Avg	Min	Avg	Min
ft												
Mud line 0	78.1	63.7	96.4	88.6	94.3	90.4	91.0	82.4	93.2	86.6	88.5	72.2
−1	92.8	84.8	95.3	89.6	92.5	89.4	94.0	84.6	96.8	88.0	93.8	81.6
−3	81.6	78.2	95.1	88.0	64.6	56.2	93.6	88.4	96.0	82.0	94.4	80.6
Years in service	17		13		17		27		13		24	

[a] Piling coated with bituminous material.
[b] Avg—average based on weight loss.
[c] Min—minimum based on thickness measurements on the thinnest section of test sample. This represents the maximum corrosion in the specified zone.

exposure, 0.005 in./yr for wetting and drying exposure, and 0.001 in./yr for subsand exposure. It was estimated that the time required for the perforation of ⅜-in. steel would be, respectively, 34 yr, 75 yr, and 375 yr. In the abrasion zone, the steel lost an average thickness of 0.117 in./yr.

Rayner and Ross [13] issued a comprehensive report on the durability of sheet steel pilings in 94 structures which have been in service for various periods up to about 25 yr along the Atlantic Coast and the Gulf Coast of Florida. Comparison of rates of loss of thickness for steel piles used in the bulkheads indicates that lack of backfill for all or part of the time greatly increased the rate of loss. For beach bulkheads the rate of loss rapidly decreased as the sand cover increased. For groins and jetties the rates of loss were uniformly high except for those covered on both sides. It was concluded that sand or earth cover materially decreased the loss of thickness of steel piles used in shore structures, the rates of loss for all practical purposes being negligible for pilings covered on both sides. Four groups of piles were pulled from moderately polluted sea water locations during the period of investigation, three of the groups located at Miami, Fla., which have been in service for 10 yr, and one group which had been in service for 18 yr at Stamford, Conn. Approximately 10 ft of the piles were driven below the ground line. The average annual rates of loss of thickness of the piles varied between 0.0009 and 0.0022 in. at the four sites. The maximum rate, which generally occurred within the zone 2 to 3 ft below the ground line, was 0.003 in./yr.

Bjerrum [14] made measurements on steel piles which were pulled from three locations in Norway. Observations on a 17-ft length of pile which was driven 17 yr prior to inspection in a silty clay having a resistivity between 2,000 and 4,000 ohm-cm showed an attack less than 0.003 in. Another 17-ft pile was pulled after exposure for 18 yr in a clay soil of marine origin. In spite of the low resistivity of this soil, 50 ohm-cm, the corrosion varied from 0.01 to 0.02 in. The third pile, exposed to a low resistivity marine clay for 6.5 yr, showed maximum corrosion of 0.10 in. which corresponds to an average rate of more than 0.01 in./yr in a 6-ft zone located between 11 and 17 ft below the ground line. Corrosion above or below this zone on the remaining pile areas did not exceed 0.02 in., or a rate of 0.003 in./yr. No mention is made of the water line elevation at any of the locations where the Norwegian piles were pulled. The writer, in view of his experiences in the examination of steel piles, suggests the possibility that the accelerated attack, reported by Bjerrum on the third pile, may have occurred in a water table zone.

3. Inspection Procedure

3.1. Piles Extracted From Location

Steel H-piles were pulled from two locations and steel sheet piles were pulled from six locations. The writer participated in all inspections on the pilings with the exception of the H-pile extracted from the Bonnet Carre Spillway. The data pertaining to the latter inspection were obtained from the files of the Corps of Engineers, U.S. Army Division, Lower Mississippi Valley.

After the soil and corrosion products were cleaned from the pile surface by utilizing wire brushes and scrapers, the extent of corrosion was determined by visual observation, pit depth measurements made with micrometers, and thickness measurements made with calipers.

Pile sections pulled from the Ouachita River Dam and Lock No. 8, the Grenada Dam Spillway, the Sardis Dam Spillway, and the Lumber River Cofferdam structure were shipped to the National Bureau of Standards. These were cleaned by sandblasting to permit a more comprehensive examination of the pile surfaces in the laboratory.

The results of all the inspections of the extracted piles are given in section 4.1.

3.2. Piles Inspected in Excavated Test Holes

At locations where it was not possible to pull the piles without disturbance to the existing structure, test holes were excavated adjacent to the sheet steel pilings to expose a width of piling at each location. At the start of the investigation it was planned to expose the pilings to a maximum depth of 15 ft from the surface, but at most locations the water table did not permit excavating to this depth.

Two excavations were made at each of four Corps of Engineers structures and one excavation at each of three Corps of Engineers structures to examine sheet steel pilings which have been in service in a variety of soil environments.

The soil and corrosion products were removed from the exposed piling by wire brushing and scraping. The condition from the top of the piles to the depth of excavation was determined by visual observation and pit depths were measured.

A portion of the pile web, approximately 1 ft by 2 ft, was cut from the area that showed the maximum amount of corrosion at each location. The removed portions were shipped to the Vicksburg District Foundation and Materials Branch Laboratory of the Corps of Engineers, and then to the National Bureau of Standards for further examination.

The results of examinations made on the piles in the excavated test holes are given in section 4.2.

3.3. Soil Characteristics and Properties

Determinations of the soil types for the different horizons at the locations where piles were pulled were made from soil samples adhering to the walls of the pilings. To serve as an additional check on the soil types, engineers in charge of the structures provided soil boring data for the excavations at Bonnet Carre Spillway, Grenada Dam Spillway, Wilmington Marine Terminal, and Sparrows Point. Soil samples removed from the pile surfaces were shipped to the National Bureau of Standards laboratory for measurements of soil resistivity and pH; at some locations, where shown in section 4, soil resistivity

TABLE 2. *Properties of soils from undisturbed soil samples taken from excavated test holes* [a]

Site	Elevation of soil sample (mean sea level)	Soil classification	Internal drainage [b]	Resistivity [c]	Moisture loss at 105 °C [d]		pH	Composition of water extract, mg-eq/100 g soil [e]							
					As received	After air-drying		Total acidity	Na+K as Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4
	ft			*Ohm-cm*	*Percent*	*Percent*									
Memphis Floodwall, station 56+14	219.5	Clayey silt	F	1,410	23.2	1.1	7.6	4.17	0.19	0.78	0.07	0.00	0.52	0.08	0.59
Memphis Floodwall, station 60+00	217	Silty clay	F	1,690	20.2	1.4	7.8	4.13	.12	.57	.06	.00	.43	.03	.21
Vicksburg Floodwall, station 16+32	82.5	Sandy silt	G	1,750	25.3	2.2	8.2	2.75	.19	.35	.16	.01	.35	.04	.00
Vicksburg Floodwall, station 23+83	83	Silty sand fill	G	3,900	24.4	2.3	8.6	0.00	.32	.96	.06	.05	1.24	.03	.00
Sardis Dam, fill soil	306	Clayey sand	P	>4,000	11.5	1.1	5.7	6.97	.07	.00	.27	.00	0.08	.04	.00
Sardis Dam, natural soil	303	Silty clay	P	>4,000	19.1	2.5	6.0	13.59	.05	.00	.16	.00	.00	.03	.02
Grenada Dam, north side	247	Clayey sand and clay	F	2,300	15.4	1.4	4.0	10.88	.20	.43	.50	.00	.02	.04	1.10
Grenada Dam, south side	248	Silty sand	G	>4,000	6.2	0.3	6.4	2.59	.19	.00	.29	.00	.04	.06	0.00
Berwick Lock, west side	2	Silty clay	P	1,410	20.0	4.5	8.5	1.88	.42	.46	.45	.03	.79	.05	.14
Berwick Lock, east side	2.5	Clay	P	1,050	18.1	3.4	8.1	2.16	.16	.64	.25	.01	.83	.04	.03
Algiers Lock		Silty clay and clay	P	1,140	20.6	4.0	8.4	2.10	.16	.57	.21	.02	.63	.05	.00
Enid Dam	284	Silty sand	F	>4,000	5.1	------	5.1	------	------	------	------	------	------	------	------

[a] Determinations made by Corp of Engineers, Waterways Experiment Station Laboratory, Vicksburg, Mississippi.
[b] Internal drainage: G, good; F, fair; P, poor.
[c] Measurements made in laboratory corrected to 70 °F.
[d] The amount of water lost in air drying at room temperature is the difference between the two values.
[e] All extractions made on air-dried samples.

determinations were made at the site with Shepard Canes or by the 4-pin method.

Determinations of the soil type at the sites where test holes were excavated adjacent to the pilings were made by visual inspection from the surface to the floor of the pit. Soil resistivities were measured at different levels by inserting Shepard Canes in the walls and floor of the excavation. Additional soil resistivity measurements were made at each site by the 4-pin method at 10-ft, 20-ft, and 30-ft pin spacings to give the average resistivities of the volume of soil from the surface to the depths corresponding to the respective spacings. The latter were made at the time of the pile inspection and at approximately 15 day intervals thereafter for a period of 7 months. The 4-pin resistivity measurements tabulated in section 4 represent an average of the many determinations.

During excavation of the test holes, samples of undisturbed soil, each sample having a volume of not less than ¼ ft,[3] were taken at different depths; chemical and physical properties of the samples were determined at the Waterways Experiment Station Laboratory. Additional samples of the same soils collected in tightly sealed pint jars were shipped to the National Bureau of Standards for laboratory measurements of *p*H and resistivity, the latter corrected to 70 °F. Data pertaining to the soil type, resistivity, and *p*H are given with the inspection results for each location in a following section. Other physical and chemical properties of the soils at the elevation from which portions of the pilings were removed are listed in table 2.

3.4. Thickness Measurements

The average thickness measurements reported for the extracted piles represent an average of many measurements made by means of calipers in the pile zone indicated, and takes into account corrosion on the two sides of the pile surface.

Average thickness measurements on the piles inspected in the test holes were confined to the 1 ft by 2 ft pile samples which were removed and shipped to the laboratory. After cleaning by sandblasting, the three most corroded 1-in.² areas were selected on each sample showing significant corrosion. Each area was divided into 25 sections on both sides of the pile sample and the pit depths in each section were determined. The sum of the average of the 25 pit depths on the two surfaces of each area was used to calculate the average reduction in pile thickness at the base of the pits.[3] These values actually represent the average reduction in pile thickness of the most corroded areas, 1 in.² in size, on the piles.

4. Results of Inspections

Historical facts pertaining to the steel pilings of various structures, the characteristics of the soils, and the condition of the piles are presented herewith for the piles inspected after extraction from the soil, and for those inspected in the test holes, respectively.

[3] Hereafter the reduction in thickness refers to this limitation.

4.1. Extracted Piles

a. Bonnet Carre Spillway, New Orleans, Louisiana

History:
A 12-in., 65-lb, test H-pile was driven to a depth of about 122 ft below natural ground surface in a swamp near the river side toe of the west approach ramp to the Airline Highway Bridge across Bonnet Carre Spillway.
Date pile driven: 1933
Date pile pulled: 1950
Age of piling: 17 years
Piling exposed: Elevation +2.0 to −120 ft msl.[4] Ground line at +2.5 ft; water line at 0 ft.
Soil characteristics:
+2.5 to −7 ft: Soft dark gray organic silty clay.
−7 to −40: Very soft dark gray highly organic clay and silt layers with few thin layers of peat and few thin layers of fine gray sand.
−40 to −62: Very soft dark gray clay and silt layers, slightly organic.
−62 to −67: Dense yellowish brown silty sand with hard clay layers at bottom.
−67 to −120: Light bluish gray plastic clay, hard at top, very stiff at bottom.

Soil resistivity and *p*H

Elevation		Resistivity	*p*H
ft		*Ohm-cm*	
+2.5 to −7.5	Min	920 (4-pin)	----
	Max	1,050 (4-pin)	----
	Avg	960 (4-pin)	----
+2.5 to −17.5	Min	540 (4-pin)	----
	Max	840 (4-pin)	----
	Avg	770 (4-pin)	----
+2.5 to −27.5	Min	460 (4-pin)	----
	Max	800 (4-pin)	----
	Avg	680 (4-pin)	----
+2.5		700 (Shepard Canes)	----
−1.5		750 (Shepard Canes)	6. 7
−22		400 (Laboratory)	7. 8
−45		400 (Laboratory)	8. 1

Condition of pile:
The space between the flanges of the pile was completely filled with soil and a layer of soil adhered to the outer edges of the flanges. Examination after cleaning showed no measurable corrosion. Mill scale was intact over almost the entire surface except for the 3-ft section in the area of the water table between elevation +1.5 and −1.5 ft. In this zone a crust of light colored hard substance coated the metal. Slight metal attack was found under the crust.

[4] msl refers to mean sea level. All elevation values in the paper refer to msl, nless otherwise noted.

b. H-Piles at Sparrows Point, Maryland

History:
In 1942, several 14-in. H-piles having an average flange thickness of 0.55 in. were driven at the Sparrows Point Plant of the Bethlehem Steel Company for test purposes. The American Iron and Steel Institute arranged with the Bethlehem Steel Company to extract two of the piles and to permit the writer to inspect and report on the condition of the piles as part of this investigation. The piles were 139 ft in length, 136 ft of which was driven below the ground line. The two piles were separated by a distance of 100 ft.
Date piles driven: 1942
Date piles pulled: November 1960
Age of piling: 18 years
Piling exposed: Elevation +13 to −126 ft. Ground line at +10 ft.
Soil characteristics:
This area was originally a peninsula surrounded by shallow water and marsh which was filled to about elevation +10 ft with slag and cinders.
+10 to 0 ft: Slag and cinder fill with some fine sand. Water line at +7.0 ft for pile No. I–S, and at +6.4 ft for pile No. II–S.
0 to −10: Natural soil starts at 0 ft. Light gray silty clay containing appreciable sand, underlain by a stiff brown silty clay and marbled gray clay.
−10 to −25: Light brown sandy silt to a soft dark gray silty clay at −15 ft.
−25 to −90: Transition from brownish to dark gray silty clay mixed with peat and organic matter at some levels.
−90 to −95: Dark brown silt underlain by fine brown sand.
−95 to −110: Transition from sand of different textures to dark brown silt.
−110 to −120: Coarse brown sand and gravel and some fine gray sand.
−120 to −126: Brownish and gray stiff clay.

Soil resistivity and *p*H

Pile No.	Elevation	Resistivity	*p*H
	ft	*Ohm-cm*	
I–S	−4	2, 500	3. 7
	−24	5, 100	4. 8
	*−24	1, 410	5. 6
	*−51	1, 820	7. 3
	−54	3, 000	5. 4
	*−54	1, 500	6. 1
	*−83	1, 700	6. 3
	−83	1, 370	6. 3
	*−92	2, 100	6. 4
	−102	7, 200	--------
	−120	12, 400	6. 4
II–S	−1	1, 130	6. 6
	−4	4, 000	4. 7
	−24	2, 500	4. 9
	−51	1, 450	6. 8
	−92	2, 500	6. 1

*Laboratory measurements made on soil samples taken from extracted pile. All other measurements made on soil sample borings obtained 1 ft from pile.

Condition of piles:

The pattern and amount of corrosion on the two piles were about the same. Corrosion was confined to two areas. One area extended from the top of the piles, which was above ground level, and extended through the zone exposed to the cinder and slag fill in the water table zone. The other corroded area occurred between elevations −115 to −118 ft where the piles passed through a sand and gravel bed.

Pile II–S was cleaned by sandblasting prior to examination, and pile I–S was cleaned with scrapers and wire brushes. Except as noted otherwise, the corrosion measurements reported are the maximum observed on the two piles.

+13 to +8 ft: Slight uniform corrosion and isolated pitting. Maximum depth of pitting, 35 mils. At least 50 percent of the mill scale was intact. Maximum reduction in flange thickness, 3 percent.

+8 to +6: This is the zone showing the maximum corrosion on both piles. The water line was at +7 ft for pile I–S, and at +6.4 ft for pile II–S. The mill scale was practically entirely removed; uniform corrosion and many pits were present. Most of the pitting occurred within the 1-ft area above and below the water line. The two maximum pit depths measured on pile I–S were 112 and 90 mils, a few pits were found between 60 and 75 mils, and other pits less then 60 mils in depth. On pile II–S, there were 10 pits between 55 and 72 mils in depth and other pits less than 50 mils in depth. The flange surfaces were more severely attacked than the web surfaces.

Measurements made on the flange within 1-ft of the water line showed that the original cross section of pile I–S was reduced by an average of 29 percent. For pile II–S, the average reduction was 14 percent. The reduction in pile thickness due to corrosion tapered off rapidly as the distance away from the water line was increased. The average reduction in flange cross section on the zone between 1 ft and 2 ft below and above the water line was 2 to 3 percent. No perceptible reduction in flange thickness was noted 4 ft above or below the water line.

+6 to −4: Mill scale intact over 90 percent of the pile surfaces. Negligible metal attack and localized pits which were less than 20 mils in depth, except for a few pits between 20 and 31 mils.

−4 to −11: Slight metal attack in a 4-in.^{2} area with a maximum pit depth of 18 mils on pile II–S only. Mill scale intact over 95 percent of surface.

−11 to −115: No measurable pit depths. Mill scale intact over 95 percent of surface.

−115 to −118: At this depth the piles passed through a sand and gravel stratum. The steel surfaces were uniformly corroded and contained many localized pits which generally ranged in depth up to 50 mils; 12 pits measured between 50 and 65 mils and 2 pits had depths of 80 and 95 mils. The average reduction in flange thickness measured 9 and 4 percent, respectively, for pile I–S and for pile II–S.

−118 to −126: Practically unaffected by corrosion. Mill scale more than 95 percent intact.

Figure 1 shows the condition of pile II–S at three different levels.

c. Corps of Engineers, Dam and Lock No. 8, Ouachita River, Arkansas

History:

An end pile was pulled from the upstream abutment wall of the Corps of Engineers, Dam and Lock No. 8 on the Ouachita River near El Dorado, Ark.

FIGURE 1. *Sections of the 139-ft H-piles pulled from Sparrows Point, Maryland, after exposure for 18 years.*
Left, water table zone consisting of fill material; center, clay soil stratum at about elevation −30 ft; and right, coarse sand and gravel stratum underlain by clay between elevations −110 and −126 ft. The pile was cleaned by sandblasting. Note the excellent condition of the butt weld at the splice in the center photograph.

The pile was a shallow-arch sheet pile having a 15-in. driving width, and a web thickness which varied from 0.45 in. at the center to 0.67 in. near the edges. The length of the pile was 15 ft, the top 2 ft of which was embedded in a concrete cap.

Date pile driven: 1921
Date pile pulled: June 1961
Age of piling: 40 years
Piling exposed: Elevation 67.5 to 52.5 ft. Ground line at elevation 78.5 ft; water line at 76.5 ft. The top of the pile was encased in concrete to elevation 65.5 ft.

Soil characteristics:

78.5 to 76.5 ft: Silty clay fill with some organic material.

76.5 to 64.5: Blue clay containing about 40 percent sand.

64.5 to 60.5: Stiff blue clay containing about 10 percent sand.

60.5 to 52.5: Very stiff blue clay containing about 2 to 3 percent sand.

Soil resistivity and *p*H

Elevation	Resistivity	*p*H
ft	*Ohm–cm*	
78.5 (Surface)	2,900 (Shepard Canes)	----
65.5	3,200 (Laboratory)	4.3
60.0	1,540 (Laboratory)	6.2
55.0	1,540 (Laboratory)	4.6

Condition of pile

The entire length of the pile was driven below the water table. Corrosion was confined to a 2-ft section on the river side of the pile between elevation 59.8 to 61.8 ft. Pitting occurred in 11 places, each about 1 in.^{2} in area, along the fingers of the pile. The maximum pit depth was 26 mils and others ranged up to 22 mils. Several pits having a maximum depth of 20 mils were found in a 3-in^2. area in the center of the web. Ninety percent of the mill scale was intact in this moderately corroded zone. At least 95 percent of the original mill scale was found to be intact on the remaining areas of the pile, and no measurable pits or corrosion beyond the mill scale was observed. Based on the maximum pit depth, the total loss of pile thickness in the corroded zone could not exceed 5 percent of the original pile thickness.

The portion of the pile which contains the measurable pits is shown in figure 2.

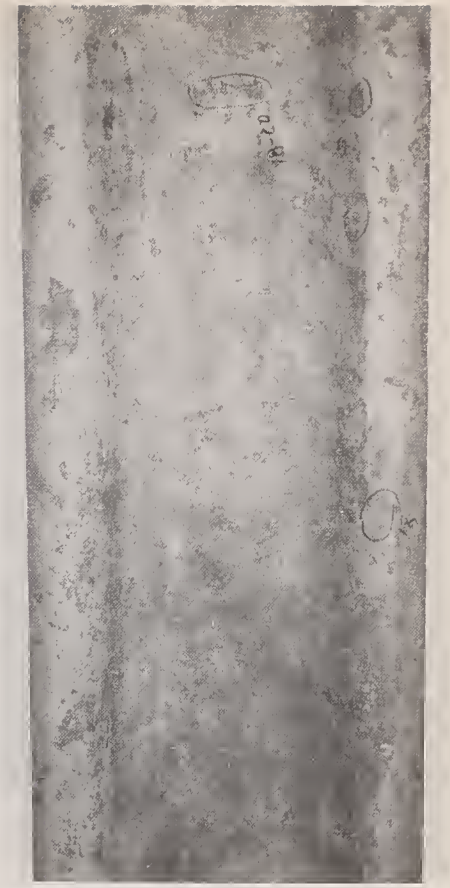

FIGURE 2. *Sandblasted 3-ft section from the 40-year-old piling extracted from an abutment wall in the Corps of Engineers Dam and Lock No. 8 on the Ouachita River near El Dorado, Arkansas.*

The section was exposed about 18 ft below the ground line and it is the only portion of the pile which contained pits of measureable depth. The maximum pit was 26 mils in depth.

d. Grenada Dam Spillway, Grenada, Mississippi

History:

A type A sheet pile was pulled for examination from the end of the north upstream wingwall of the Grenada Dam Spillway at Grenada, Miss. The pile was 14 ft in length, had a driving width of 19½ in. and a thickness of ⅜ in.

Date pile driven: October 1948
Date pile pulled: July 1960
Age of piling: 12 years
Piling exposed: Elevation 251.5 ft to 237.5 ft; ground elevation at 256 ft, water table much below the bottom of pile.

Soil characteristics:

256.0 to 250.5 ft: Fill soil, reddish brown sandy loam.

Soil resistivity and *p*H

Elevation	Resistivity		*p*H
ft		*Ohm-cm*	
256 to 246	Min	11,700 (4-pin)	----
	Max	15,400 (4-pin)	----
	Avg	13,900 (4-pin)	----
256 to 236	Min	4,600 (4-pin)	----
	Max	9,600 (4-pin)	----
	Avg	6,900 (4-pin)	----
256 to 226	Min	4,300 (4-pin)	----
	Max	7,300 (4-pin)	----
	Avg	6,200 (4-pin)	----
256		2,800 (Shepard Canes)	----
250		>4,000 (Laboratory)	4.9
245.5		>4,000 (Laboratory)	4.9
241		3,800 (Laboratory)	3.6

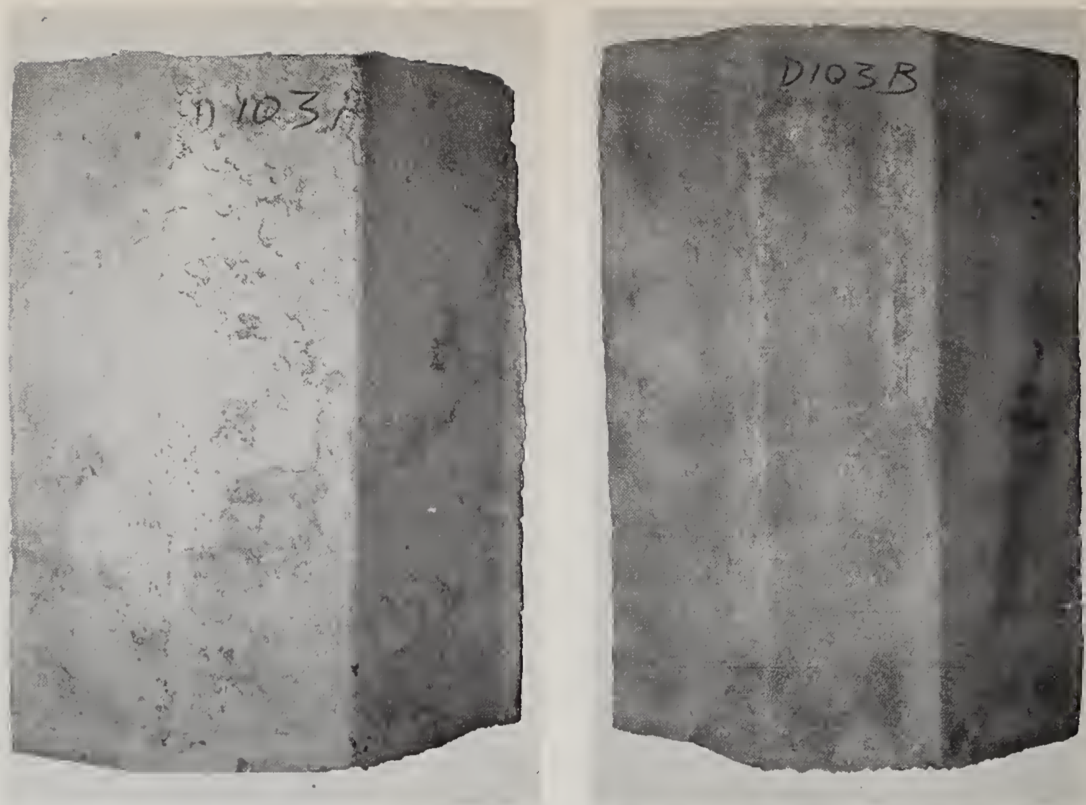

FIGURE 3. *Sections (1.5 ft by 1 ft) cut from a piling which was pulled from the north upstream wingwall of the Grenada Dam Spillway at Grenada, Mississippi, after exposure for 12 years.*

Sections were cleaned by sandblasting.
D103A, section of pile exposed to fill soil.
D103B, section of pile exposed to natural soil.

250.5 to 246.6: Fill soil, tan silty sand.

246.5 to 244.5: Natural soil layer, grayish blue fractured shale.

244.5 to 237.5: Transition from light brown to gray clay. Gravel and dark gray shale intermingled throughout horizon. Many fine roots present.

Condition of pile:

251.5 to 246.0 ft: Many scattered pits up to 50 mils in depth. Seven pits measured between 68 and 80 mils, and two pits 88 and 122 mils in depth. Pits were of similar depth on both sides of the pile, but much less numerous on the side facing the spillway. About 50 percent of the mill scale was intact on the spillway side and 10 percent on the other side. The reduction in cross section of the three most corroded areas measured between 6 to 8 percent of the original wall thickness.

246.0 to 244.0: No measureable pits beyond the thickness of the mill scale (8 mils) were found in this zone. About 50 percent of the mill scale was intact in this area.

244.0 to 237.5: About 75 percent of the mill scale was present over the surfaces in this zone. No measurable pits were found except two at elevation 241.0 ft which were 13 mils in depth. The average wall thickness of a 17 × 22 in. section removed from this zone was 0.37 in. after cleaning by sandblasting.

Sections of the pile which were exposed to the fill and natural soils are shown in figure 3.

e. Sardis Dam Outlet, Sardis, Mississippi

History:

A 3.5 ft length of steel sheet piling was cut from a length of pile pulled from the Sardis Dam Outlet channel on the Little Tallahatchie River near Sardis, Miss. The arch-type pile had a driving width of 19⅝ in. and a wall thickness of ⅜ in.

Date pile driven: Early 1939
Date pile pulled: October 1959
Age of piling: 20.5 years
Piling exposed: Elevation 190.5 to 187 ft
Surface elevation: 194.5 ft
Water table elevation: Above 194.5 ft.
Soil characteristics:

194.5 to 190.5 ft: Riprap fill.
190.5 to 189.5: Gravel bed.
189.5 to 187: Black lignitic clay with layers of sand.

Soil resistivity and *p*H

Elevation	Resistivity	*p*H
ft	*Ohm-cm*	
190	610 (Laboratory)	3. 0
187	1,690 (Laboratory)	2. 9

Condition of piles:

Metal attack occurred in the form of uniform corrosion and general pitting over most of the surface. The section exposed to the gravel bed above elevation 189.5 ft showed a 19 percent reduction in cross section, and maximum depth of pitting up to 60 mils. The average thickness of the pile section exposed to lignitic clay below elevation 189.5 ft was reduced by 11 percent; the pit depths ranged up to 30 mils.

f. Chef Menteur Pass, New Orleans, Louisiana

History:

In connection with construction work on the Simpson-Long Bridge across Chef Menteur Pass on U.S. Highway 90, about 11 miles west of New Orleans, it was necessary to pull about 60 tons of sheet steel pilings. The pilings formed a retaining wall for the abutment of the bridge. The sheet piles were 33 ft in length, arch type with a driving width of 19⅝ in., and a thickness of ⅜ in. at the center of the web.

Date piles driven: 1929
Date piles pulled: 1961
Age of piling: 32 years
Piling exposed: +6 to −27 ft: Water side, +6 to +3±1 ft in atmosphere; +3±1 ft to 0 ft (mud line) in brackish salt water. Soil side, +6 to +4 ft in atmosphere; ground line at +4 ft.

Soil characteristics:

+4 to −4 ft: Light gray loose silty sand.
−4 to −27: Very tight gray clay.

Soil resistivity and pH

Elevation	Resistivity	pH
ft	*Ohm-cm*	
−3	440 (Laboratory)	7.8
−10	300 (Laboratory)	6.9
−24	330 (Laboratory)	7.4

Condition of piles:

Detailed examination of four lengths of pilings showed that the degree and pattern of corrosion were similar. The condition of the pile exhibiting the maximum amount of corrosion is reported herewith. Both sides of the top 4 ft sections of the piles were coated with a protective aluminum-type paint and an undercoat of red lead.

Water side:

+6 to +4 ft: Paint was intact, unaffected by corrosion.

+4 to +2: Rust and slight metal attack, two pits measured 23 and 38 mils in depth, other pits about 10 mils.

+2 to 0: Thick crust of corrosion products on the finger interlock edge between 25 and 40 mils thick, localized pitting and metal attack beneath the crust, some pits between 40 and 50 mils in depth. Thin layer of corrosion products on flanges, web and thumb interlock with pitting less than 10 mils in depth, except for a few pits between 25 and 60 mils on one side of the flange at 1 ft. Mill scale almost completely removed from this zone.

0 to −1: Metal attack and slight pitting (less than 10 mils) on interlock only.

−1 to −14: Mill scale intact over 95 percent of surface. Flanges and webs unaffected by corrosion. Slight metal attack and three scattered pits (maximum depth, 70 mils) on finger interlock at −11 to −12 ft.

−14 to −17: Metal attack and 6 pits ranging in depth between 60 to 145 mils along finger interlock. Two pits (65 and 70 mils) on thumb interlock. No measureable pits on web or flange. Mill scale intact over 80 percent of surface.

−17 to −19: Slight metal attack, mill scale intact over 80 percent of surface.

−19 to −20: Mill scale intact over 75 percent of surface. Four pits between 33 and 88 mils in depth on the thumb interlock and flange; two pits, 95 and 58 mils in depth, on other flange.

−20 to −27: Mill scale intact over 90 percent of surface. Only two measurable pits, 80 and 104 mils in depth, at −26 ft on finger interlock.

Soil side:

+6 to +4 ft: Uniform thin layer of rust, no measureable pits.

+4 to 0: Uniform layer of rust and scale over surface to a thickness of 40 mils. No measureable pits.

0 to −27: Metal attack in many areas. About 75 percent of surface covered with mill scale. No measurable pits greater than 10 mils except at elevation −24 ft where a few pits were found on the finger interlock of one pile. Maximum pit depth, 25 mils.

g. Wilmington Marine Terminal, Christiana River, Delaware

History:

Four hundred and thirty two uncoated steel interlocking-arch-type piles, with a driving width of 19⅝ in. and an average web thickness of ⅜ in. were pulled by the Wilmington Harbor Commission from a pile jetty which was used as a shoring along the banks of the Christiana River. The piles were pulled in preparation for extension of the dock. The piles were 60 and 100 ft in length. Each ninth pile was driven 100 ft to serve as an anchor. The 100 ft piles consisted of a 60 ft section welded to a 40 ft section.

Date piles driven: 1937
Date piles pulled: 1960
Age of piling: 23 years
Piling exposed: Elevation +10 to −90 ft for 100 ft lengths; +10 to −50 ft for 60 ft lengths. River side, top 10 ft of pile exposed to water or atmosphere. Land side, top 4 ft of pile exposed to water or atmosphere.

Soil characteristics:

+6 to 0 ft: Cinder fill.

+2 to +1: Water table at low tide. River water is nonbrackish fresh water. Mean low water at 0 ft.

0 to −48: Soft black organic silt.

−48 to −86: Black organic silt with some fine sand and clay intermingled.

−86 to −88: Fine brown silty sand, trace of mica.

−88 to −91: Gray to brown coarse sand and river gravel.

−91 to −114: Sand and silty sand underlain by clay.

Condition of piles:

Seven full lengths and the interlock edges of 70 piles were inspected. All the piles were in excellent condition from the mud line (elevation 0 ft where the natural soil starts) down to the bottom of the piles. The piles are to be reused in the new dock structure at the same site.

+10 to 0 ft: Moderate corrosion on surfaces exposed to water and the atmosphere on the river side, and to cinder fill, water and atmosphere on the land side. Surfaces were uniformily corroded, the original thickness of the piles being reduced by an average not exceeding 10 percent. Widely scattered pits present; most of the pits had depths less than 75 mils, but a few had depths between 75 to 150 mils.

0 to bottom of piles: Accumulation of slick clay over most of the surface. No measurable pits. Mill scale intact over more than 90 percent of the surfaces.

h. Lumber River Near Boardman, North Carolina

History:

The North Carolina State Highway Department extracted 120 piles which formed a rectangular-shaped cofferdam for a bridge support over the Lumber River near Boardman, N.C. The structure was removed in connection with road improvements which required replacement of the old bridge.

The steel piles were 20-ft lengths of interlocking I-beams having a driving width of 8 in. and a wall thickness of 0.25 in. The corners of the cofferdam consisted of steel angles to which interlock sections of pilings were attached by steel rivets, spaced 9 in. apart.

Date piles driven: 1921
Date piles pulled: December 1958
Age of piling: 37 years

Piling exposed: 2.5 ft above ground to 17.5 ft below the ground line (+2.5 to −17.5 ft). The portion of the piles above the ground line was subjected to partial or total immersion from water of the Lumber River about 50 percent of the year, and to the atmosphere when the river was dry during the remaining half year. The sides of the pilings which were exposed to the excavated side of the cofferdam were in contact with concrete, except fort he bottom 3 ft which was entirely surrounded by soil.

Soil characteristics:

0 (ground line) to −8 ft: Gray fine sandy loam.

−8 to −14: Bluish-gray plastic silty clay.

−14 to −17.5: Gray-black fine sandy loam containing appreciable gravel.

Soil resistivity and *p*H

Elevation	Resistivity	*p*H
ft	*Ohm-cm*	
−3	1, 240	3. 4
−10	1, 100	2. 3
−16	4, 900	5. 9

Condition of piles:

Visual inspection of the pilings revealed that they had all corroded to about the same extent. A section of the cofferdam consisting of two full lengths of piles and a corner angle was shipped to the laboratory for further examination.

Practically no mill scale remained on the pile surfaces in the zone extending from 3 ft below the ground line to the top of the piles. In the lower zones, approximately 20 percent of the mill scale was intact.

Thin concrete deposits were found on the surfaces where the steel had been in contact with concrete on the excavated side of the cofferdam. There was a thick scale of rusted corrosion products and soil over the entire surface exposed directly to the soil environments. The scale was flakey and easily removed by scraping.

The following conditions were observed after the piles were cleaned by sandblasting:

+2.5 to 0 ft: Section exposed to total or partial water immersion, or atmosphere. Uniform corrosion of surface. Measurements of the cross section in the top 6 in. of the piles (elevation +2.5 to +2.0) showed a minimum thickness of 0.06 in. in places. This represents a loss of 76 percent in the original pile thickness. The maximum thickness measured on uncorroded surfaces near the bottom of the piles was 0.26 in. Piles in the zone between +2.0 ft to the ground line showed a maximum reduction in thickness of 60 percent.

0 to −0.5: This area showed an amount of corrosion similar to that on the adjacent areas above. The original pile thickness in this zone was reduced by a maximum of 40 percent, and isolated pits ranged in depth up to 60 mils.

−0.5 to −1.0: The pattern of corrosion in this zone was similar to that noted above. Maximum reduction in pile thickness was 36 percent.

−1.0 to −3.0: Uniform corrosion, general roughening of surface, numerous shallow pits and many isolated pits up to 60 mils. Maximum reduction in cross section was 28 percent.

−3 to −17.5: In this zone the condition of the surface was similar to that described above, but was less severely corroded. Many isolated pits measured up to 30 mils in depth, and relatively few up to 60 mils. A maximum reduction in pile cross section of 12 percent was noted in this zone.

The corner angle along the entire piling section showed the same extent of corrosion as the I–beams. All rivets were uniformly corroded. The original contour of the rivets was intact.

A 3-ft corner section of the piling exposed immediately below the soil line is shown in figure 4.

4.2. Pilings Exposed in Excavations

a. Memphis Floodwall, Memphis, Tennessee

History:

Excavations were made to expose pilings at two locations on the river side of the Memphis Floodwall. The walls consist of type Z 27 sheet pilings having an 18-in. driving width, and a thickness of ⅜-in. at the web and flanges. The pilings at station 56+14 were given two coats of cold applied coal-tar-base enamel before driving, and the pilings at station 60+00 were uncoated.

Date piles driven: November 1953
Date of inspection: March 1960
Age of piling: 6.3 years

STATION 56+14

Piling exposed: An 8-ft width of the floodwall was exposed between elevation 223.0 to 216.5 ft.
Surface elevation: 228 ft
Water table elevation: 217.5 ft
Soil characteristics:

228 to 223 ft: Friable brown lean clay.

223 to 221.5: Plastic and friable gray silty clay.

221.5 to 217.5: Plastic light brown clayey silt. Excessive water below 219.5 ft.

217.5 to 216.5: Tight gray clay mixed with decomposed wood.

Soil resistivity and *p*H

Elevation		Resistivity	*p*H
ft		*Ohm-cm*	
228 to 218	Min	1,220 (4-pin)	----
	Max	8,600 (4-pin)	----
	Avg	4,400 (4-pin)	----
228 to 208	Min	960 (4-pin)	----
	Max	6,900 (4-pin)	----
	Avg	2,600 (4-pin)	----
228 to 198	Min	1,030 (4-pin)	----
	Max	3,400 (4-pin)	----
	Avg	1,850 (4-pin)	----
223		1,900 (Shepard Canes)	----
222		3,100 (Shepard Canes)	----
221		2,240 (Laboratory)	7. 8
221		2,300 (Shepard Canes)	----
219.5		1,700 (Shepard Canes)	----
219		1,410 (Laboratory)	7. 6
218		2,200 (Shepard Canes)	----
216.5		1,000 (Shepard Canes)	----

Condition of piles:

The coal tar coating was intact over the entire surface except at elevation 220.5 to 219.5 ft where the coating was damaged in an area 1-ft in vertical direction by 1-in. in width. The maximum depth of pitting of the steel exposed by the damaged coating was 35 mils (fig. 5). The steel beneath the rest of the coating was unaffected by corrosion and the mill scale was intact.

STATION 60+00

Piling exposed: An 8-ft width of the floodwall was exposed between elevation 222.5 and 213.5 ft.
Surface elevation: 226.5 ft
Water table elevation: Below 213.5 ft
Soil characteristics:

226.5 to 224 ft: Brown lean clay.

224 to 222.5: Gray silty clay.

222.5 to 218.5: Friable brown silty clay. Some cinders mixed with the clay between 223 and 220 ft.

218.5 to 213.5: Friable and plastic reddish brown silty clay. Very impervious to water.

Soil resistivity and *p*H

Elevation		Resistivity	*p*H
ft		*Ohm-cm*	
226.5 to 216.5	Min	2,180 (4-pin)	----
	Max	5,700 (4-pin)	----
	Avg	4,100 (4-pin)	----
226.5 to 206.5	Min	1,920 (4-pin)	----
	Max	7,900 (4-pin)	----
	Avg	4,200 (4-pin)	----
226.5 to 196.5	Min	1,030 (4-pin)	----
	Max	2,300 (4-pin)	----
	Avg	1,650 (4-pin)	----
222		3,200 (Shepard Canes)	----
221		2,500 (Shepard Canes)	----
221		2,200 (Laboratory)	6. 8
219.5		2,600 (Shepard Canes)	----
218.5		2,100 (Shepard Canes)	----
217		1,690 (Laboratory)	7. 8
214		1,630 (Laboratory)	7. 5
213.5		1,500 (Shepard Canes)	----

Condition of piles:

The entire surface of the pilings was in excellent condition. More than 90 percent of the mill scale was intact. There was very slight uniform metal attack in small localized areas. No measurable pits were found on the entire surface. From elevation 218 to the bottom of the excavated pit, the clay adhered very tightly to the piling. On removal, the soil peeled off in layers leaving free water on the steel surface.

A 2 ft by 1 ft section removed from the pile is shown in figure 5.

FIGURE 4. *A 3-ft section of steel sheet piling exposed below the soil line in a cofferdam structure in the Lumber River near Boardman, North Carolina.*

Exposure, 37 years.

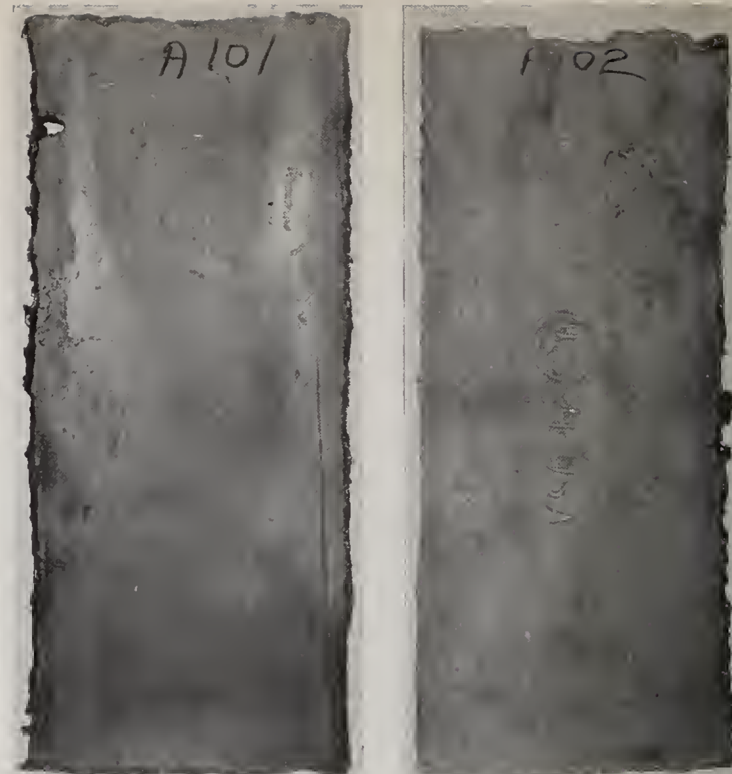

FIGURE 5. *Steel sheet piling sections (2 ft by 1 ft) cut from two locations on the Memphis Floodwall after exposure for 6.3 years.*

The sections were cleaned by sandblasting.
A101, section of coated piling showing pits up to 35 mils in depth, occurring in area of damaged coating.
A102, section of uncoated piling exposed to a silty clay containing cinders showing no measureable corrosion.

b. Vicksburg Floodwall, Vicksburg, Mississippi

History:
Excavations were made to expose steel sheet pilings at two locations on the riverside of the Vicksburg Floodwall. The walls were constructed of type Z 38 sheet piling which has a driving width of 18 in., a thickness of ⅜ in. at the web, and a thickness of ½ in. at the flanges.
Date piles driven: January 1953
Date of inspection: March 1960
Age of piling: 7.2 years

STATION 16+32

Piling exposed: A 38-in. width of the floodwall was exposed between elevation 89 and 80.5 ft.
Surface elevation: 93 ft
Water table elevation: 80.5 ft
Soil characteristics:
93 to 86 ft: Bluish black fat clay, sticky, plastic, and very retentive of water. Small patches of red and yellow sand dispersed throughout the profile.
86.0 to 85.5: Black silty plastic clay, containing more than 50 percent cinders.
85.5 to 84.5: Light brown sandy loam with cinders and gravel dispersed throughout.
84.5 to 84.0: Layer of black cinders.
84.0 to 80.5: Gray sandy silt containing cinders. Wet cinders on floor of excavation at 80.5 ft.

Soil resistivity and *p*H

Elevation	Resistivity		*p*H
ft		*Ohm-cm*	
93 to 83	Min	3,400 (4-pin)	----
	Max	7,000 (4-pin)	----
	Avg	6,000 (4-pin)	----
93 to 73	Min	2,200 (4-pin)	----
	Max	4,300 (4-pin)	----
	Avg	3,300 (4-pin)	----
93 to 63	Min	920 (4-pin)	----
	Max	2,400 (4-pin)	----
	Avg	1,550 (4-pin)	----
88		1,190 (Laboratory)	7. 4
88 to 87	Min	850 (Shepard Canes)	----
	Max	1,300 (Shepard Canes)	----
85	Min	1,700 (Shepard Canes)	----
	Max	2,500 (Shepard Canes)	----
83		2,500 (Laboratory)	7. 6
82.5		1,750 (Laboratory)	8. 2
82 to 80	Min	1,550 (Shepard Canes)	----
	Max	4,000 (Shepard Canes)	----
80.5	Min	850 (Shepard Canes)	----
	Max	1,400 (Shepard Canes)	----

FIGURE 6. *Sandblasted sections of Z-type sheet piling cut from two different locations in the Vicksburg Floodwall after exposure for 7 years.*

Although cinders were present in the soil at both locations, no significant corrosion occurred.
B101, Section removed from floodwall at station 16+32.
B102, Section removed from floodwall at station 23+83.

Condition of piles:

Approximately 30 to 40 percent of the steel surfaces was covered with mill scale. Soil adhered in many areas of about 1-in.^{2} like barnacles, beneath which appeared uniform metal attack or shallow pitting. Pitting up to 40 mils in depth was widely scattered and confined to areas of less than 1 in.^{2} At elevation 83.5 to 81.5 ft, there were a few pits with depths between 40 and 45 mils. Measurements made on the three most corroded 1 in.^{2} areas showed an average reduction in the cross section of the web of 4 to 6 percent. A section removed from the most corroded area of the pile is shown in figure 6.

STATION 23+83

Piling exposed: A 41-in. width of the floodwall was exposed between elevation 89 and 80.5 ft.
Surface elevation: 93 ft
Water table elevation: 80.5 ft

Soil characteristics:

93 to 84 ft: Bluish-gray clay with nodules of brown clay dispersed throughout.

84 to 83.5: Plastic and sticky light brown to reddish brown clay containing some cinders.

83.5 to 80.5: Dark gray silty sand mixed with appreciable quantities of cinders, gravel, stones, and bricks. This horizon appears to be a fill material. Free water at bottom of trench.

Soil resistivity and *p*H

Elevation		Resistivity	*p*H
ft		*Ohm-cm*	
93 to 83	Min	2,800 (4-pin)	----
	Max	9,200 (4-pin)	----
	Avg	5,000 (4-pin)	----
93 to 73	Min	1,300 (4-pin)	----
	Max	3,700 (4-pin)	----
	Avg	2,800 (4-pin)	----
93 to 63	Min	740 (4-pin)	----
	Max	2,000 (4-pin)	----
	Avg	1,400 (4-pin)	----
89 to 84	Min	625 (Shepard Canes)	----
	Max	825 (Shepard Canes)	----
	Avg	725 (Shepard Canes)	----
88.5		910 (Laboratory)	7. 1
83.5		1,700 (Shepard Canes)	----
83		3,900 (Laboratory)	8. 6
81		1,050 (Laboratory)	7. 7
83.5 to 80.5	Min	1,100 (Shepard Canes)	----
	Max	1,400 (Shepard Canes)	----
	Avg	1,300 (Shepard Canes)	----

Condition of piles:

Mill scale was intact on about 70 percent of the piling surfaces. There was no difference in the appearance of the surface at the different horizons. Where the mill scale had been removed, there was a film of red rust which was brushed off with ease. Under the rust, the steel surfaces were smooth. No measureable pits were found on the exposed pilings. Measurements fail to show a perceptible reduction in wall thickness (fig. 6).

c. Sardis Dam Spillway, Sardis, Mississippi

History:

An excavation was made to expose a 7-ft width of pilings from the upstream wingwall on the east side of the Sardis Dam Spillway. The structure consisted of arch-type sheet piles with a 15-in. driving width and a wall thickness of ⅜ in.
Date piles driven: Early 1940
Date of inspection: March 1960
Age of piling: 20 years
Piling exposed: A 7-ft width of the wingwall was exposed from elevation 307 to 302 ft.
Surface elevation: 312 ft
Water table elevation: 305 ft

Soil characteristics:

312 to 305 ft: Fill soil consisting of uniform reddish sandy loam.

305 to 302: Natural soil, reddish brown tight impervious plastic clay.

Soil resistivity and *p*H

Elevation	Resistivity	*p*H
ft	*Ohm-cm*	
312 to 302	Min. 43,600 (4-pin)	----
	Max. 50,200 (4-pin)	----
	Avg. 46,500 (4-pin)	----
312 to 192	Min. 29,100 (4-pin)	----
	Max. 36,000 (4-pin)	----
	Avg. 32,800 (4-pin)	----
312 to 182	Min. 23,800 (4-pin)	----
	Max. 29,300 (4-pin)	----
	Avg. 26,000 (4-pin)	----
312	>10,000 (Shepard Canes)	----
310	>10,000 (Shepard Canes)	----
306	15,400 (Laboratory)	5.7
303	>4,000 (Laboratory)	6.0
302	7,510 (Laboratory)	5.4
302	3,000 (Shepard Canes)	----

Condition of piles:

Mill scale was intact over approximately 90 percent of the pile surfaces. In localized areas, which were predominant in the top 8-in. section of the piles, there was slight metal attack and shallow pitting, not exceeding 10 mils in depth. In an area covering a width of about 2 ft between elevation 304 and 302.5 ft, there were isolated pits which measured between 10 and 20 mils in depth, and three pits between 20 and 28 mils. The average reduction in pile thickness measured in the three most corroded areas in this zone was between 3 and 4 percent.

d. Grenada Dam Spillway, Grenada, Mississippi

History:

Two excavations were made to expose steel sheet pilings for examination on the north side and the south side of the upstream wingwalls of the Grenada Dam Spillway on the Yalobusha River. The pilings consisted of the arch-sheet type with a driving width of 15 in. and a wall thickness of 3/8 in.

Date piles driven: October 1948

Date of inspection: March 1960

Age of piling: 11.4 years

UPSTREAM WINGWALL—NORTH SIDE

Piling exposed: A 6.7 ft width of the wingwall was exposed between elevation 251.5 and 246 ft.

Surface elevation: 256 ft

Water table elevation: Much below 246 ft

Soil characteristics:

256 to 246 ft: Fill material consisting of friable reddish brown clayey sand or silt loam with clods of grayish sandy clay and patches of very fine yellowish brown sand throughout the pit. Gravel, stones, pieces of dark gray shale, and fine roots present.

Soil resistivity and *p*H

Elevation		Resistivity	*p*H
ft		*Ohm-cm*	
256–246	Min	12,500 (4-pin)	----
	Max	16,500 (4-pin)	----
	Avg	13,900 (4-pin)	----
256–236	Min	4,700 (4-pin)	----
	Max	9,600 (4-pin)	----
	Avg	6,900 (4-pin)	----
256–226	Min	4,300 (4-pin)	----
	Max	7,200 (4-pin)	----
	Avg	6,200 (4-pin)	----
255		9,000 (Shepard Canes)	----
249		2,400 (Laboratory)	4.4
247		2,300 (Laboratory)	4.0
246	Min	1,700 (Shepard Canes)	----
	Max	3,500 (Shepard Canes)	----
	Avg	2,400 (Shepard Canes)	----

Condition of piles:

Mill scale was intact on about 20 percent of the pile surfaces. Approximately 60 percent of the surface was uniformly corroded to shallow depths and contained many scattered pits which generally ranged in depth between 40 and 90 mils. A few pits between 90 and 108 mils in depth were present. The deepest pits were mainly concentrated between elevation 248 and 247 ft. The deeper pits were highly localized and were found under nodules of soil particles which appeared to be cemented to the steel and were difficult to scrape away. Measurements of the three most corroded areas showed average reductions in the thickness of the piles of 16, 13, and 10 percent.

UPSTREAM WINGWALL—SOUTH SIDE

Piling exposed: A 7-ft width of the pilings in the wingwall was exposed between elevation 251.5 and 246 ft.

Surface elevation: 256 ft

Water table elevation: Much below 246 ft

Soil characteristics:

256 to 248 ft: Reddish brown fine sandy loam with clods of light gray clay dispersed throughout the profile. This is a fill soil containing many fine roots.

248 to 246: Mixture of fine rust colored very fine light yellow silty sand intermingled with pieces of light gray shale.

Soil resistivity and *p*H

Elevation		Resistivity	*p*H
ft		*Ohm-cm*	
256 to 246	Min	5,900 (4-pin)	----
	Max	8,000 (4-pin)	----
	Avg	7,000 (4-pin)	----

Soil resistivity and pH—Continued

Elevation		Resistivity	pH
ft		*Ohm-cm*	
256 to 236	Min	3,400 (4-pin)	----
	Max	6,900 (4-pin)	----
	Avg	4,300 (4-pin)	----
256 to 226	Min	2,700 (4-pin)	----
	Max	3,800 (4-pin)	----
	Avg	3,500 (4-pin)	----
250		2,400 (Laboratory)	4. 4
248.5		4,000 (Laboratory)	6. 4
247		4,300 (Laboratory)	6. 9
246	Min	5,000 (Shepard Canes)	----
	Max	11,000 (Shepard Canes)	----
	Avg	7,900 (Shepard Canes)	----

Condition of piles:

251.5 to 248 ft: Mill scale was present over 70 percent of the surface. Many highly localized pits corroded about 15 percent of the surface, the remaining 85 percent of the surface was unaffected by corrosion. Six pits were found between 100 and 172 mils in depth, eight pits between 50 and 95 mils, and other pits measured less than 50 mils. The corrosion products and soil particles adhering to the steel in this zone were easily scraped off.

248 to 246: About 30 percent of the piling surfaces were affected by scattered pits, the other areas being unaffected by corrosion. Mill scale was intact over more than 50 percent of the surface. The seven deepest pits ranged between 105 and 160 mils in depth. Also present were 11 pits between 50 and 95 mils and other pits less than 50 mils in depth. The average reduction in wall thickness measured in the three most corroded areas was between 12 and 19 percent. In this zone, the soil particles were easily scraped from the steel surfaces, but a black crust of ferric oxide which was embedded in the pits was difficult to break away.

e. Berwick Lock, Berwick, Louisiana

History:

Two excavations were made to expose steel pilings in the cutoff walls on the west side and east side of the north end of the Berwick Lock which is located between the Lower Atchafalaya River and Berwick Bay near Berwick, La. The arch-type sheet steel pilings had a driving width of 19⅝ in. and a ⅜ in. wall thickness.

Date piles driven: March 1949

Date of inspection: April 1960

Age of piling: 11.1 years

NORTH END OF LOCK—WEST SIDE

Piling exposed: A 5-ft width of pilings was exposed between elevation +3.5 to −1.5 ft. One side of the pilings which was uncoated, was totally exposed to the soil environment. The other side of the pilings had a coal tar coating and was exposed to water.

Surface elevation: +5 ft

Water table elevation: −0.5 ft

Soil characteristics:

+5 to +2 ft: Fill material consisting of a mixture of gray and brown silty clay containing some gravel and small shells.

+2 to −1.5: Natural soil consisting of tight bluish gray impervious plastic clay with patches of tight brown clay dispersed throughout the profile.

Soil resistivity and pH

Elevation		Resistivity	pH
ft		*Ohm-cm*	
+5 to −5	Min	860 (4-pin)	----
	Max	960 (4-pin)	----
	Avg	900 (4-pin)	----
+5 to −15	Min	990 (4-pin)	----
	Max	1, 260 (4-pin)	----
	Avg	1, 190 (4-pin)	----
+5 to −25	Min	1, 380 (4-pin)	----
	Max	1, 550 (4-pin)	----
	Avg	1, 440 (4-pin)	----
+4	Min	680 (Shepard Canes)	----
	Max	950 (Shepard Canes)	----
	Avg	820 (Shepard Canes)	----
+2		1, 000 (Shepard Canes)	----
+2		1, 400 (Laboratory)	8. 5
+1		1, 290 (Laboratory)	8. 1
+1		850 (Shepard Canes)	----
0		800 (Shepard Canes)	----
−1.5		850 (Shepard Canes)	----

Condition of piles:

+3.5 to +1.5 ft: Mill scale was intact over 40 percent of the surface. The remaining surface was uniformly attacked and had many shallow pits less than 25 mils in depth, and some deeper pits. A few pits ranged between 55 and 61 mils in depth, and many others ranged between 25 and 55 mils. The average reduction in wall thickness observed on the three most corroded areas was between 6 and 8 percent.

+1.5 to −1.5 ft: Mill scale was intact over about 60 percent of the surface. Slight uniform corrosion was present on the remaining surface and there were many pits which did not exceed 25 mils in depth.

There was slight general metal attack and pitting over the entire coated side of the pilings which was exposed on the water side. The river water had a resistivity of 2,500 ohm-cm, and a salt content of 40 ppm.

NORTH END OF LOCK—EAST SIDE

Piling exposed: A 5 ft width of the wall was exposed between elevation +3.5 and 0 ft.

Surface elevation: +5 ft

Water table elevation: +1 ft

Soil characteristics:

+5 to +3 ft: Fill consisting of a mixture of slightly friable reddish brown and gray tight clay containing gravel and many stones.

+3 to 0: Natural soil consisting of brown fat plastic clay.

Soil resistivity and *p*H

Elevation		Resistivity	*p*H
ft		*Ohm-cm*	
+5 to −5	Min	960 (4-pin)	----
	Max	1, 280 (4-pin)	----
	Avg	1, 130	----
+5 to −15	Min	1, 150	----
	Max	1, 530	----
	Avg	1, 370	----
+5 to −25	Min	1, 210	----
	Max	1, 610	----
	Avg	1, 480	----
+4	Min	950 (Shepard Canes)	----
	Max	1, 300 (Shepard Canes)	----
+2.5		1, 050 (Laboratory)	8. 1
+1.5		1, 220 (Laboratory)	7. 9
+1	Min	870 (Shepard Canes)	----
	Max	1, 000 (Shepard Canes)	----
0	Min	750 (Shepard Canes)	----
	Max	1, 200 (Shepard Canes)	----

Condition of piles:

+3 to +1 ft: Mill scale was present on 40 percent of pile surfaces. There was uniform corrosion and pitting where the mill scale was missing. The three deepest pits were between 75 and 90 mils in depth. About 30 pits measured between 20 and 75 mils in depth, and many other pits were shallower than 20 mils. The average reduction in pile thickness observed in the three most corroded areas was between 8 and 11 percent.

+1 to 0: About 75 percent of the mill scale was intact in this zone. The pile surfaces were smooth, had little metal attack, and all pits were less than 20 mils in depth.

The condition of the coated piles exposed to the water side was similar to that described for the piling on the west side of the lock.

f. Algiers Lock, New Orleans, Louisiana

History:

An excavation was made to expose type Z 32 sheet pilings in the cutoff wall on the east side of the south end of Algiers Lock, which is located on the Algiers Canal at the Mississippi River, New Orleans, La. The piles have a driving width of 21 in. and wall thicknesses of 3/8 in. at the web and 1/2 in. at the flanges.

Date piles driven: May 1948

Date of inspection: April 1960

Age of piling: 11.9 years

Piling exposed: A 5-ft width of the cutoff wall was exposed between elevation +3.5 to +1 ft

Surface elevation: +5 ft

Water table elevation: +2 ft

Soil characteristics:

+5 to 3.5 ft: Brown silty clay fill material.

+3.5 to +1: Brown silty clay with pockets of tight plastic grayish blue clay dispersed throughout the profile with large quantities of organic matter, rotted wood, gravel, and small stones.

Soil resistivity and *p*H

Elevation		Resistivity	*p*H
ft		*Ohm-cm*	
+5 to −5	Min	800 (4-pin)	----
	Max	840 (4-pin)	----
	Avg	820 (4-pin)	----
+5 to −15	Min	575 (4-pin)	----
	Max	650 (4-pin)	----
	Avg	600 (4-pin)	----
+5 to −25	Min	345 (4-pin)	----
	Max	460 (4-pin)	----
	Avg	410 (4-pin)	----
+5	Min	700 (Shepard Canes)	----
	Max	1, 150 (Shepard Canes)	----
+3		1, 300 (Shepard Canes)	----
		1, 140 (Laboratory)	8. 4
+2		1, 290 (Laboratory)	7. 7
	Min	650 (Shepard Canes)	----
	Max	1, 200 (Shepard Canes)	----
+1		1, 300 (Shepard Canes)	----

Condition of piles:

Mill scale was present over approximately 85 percent of the surface. Nodules of clay adhered to the steel surface in scattered small areas, generally not exceeding 1 in.^{2} in size, beneath which were light metal attack or pitting. The deepest pit measured 40 mils in depth. Nine pits measured between 22 and 32 mils in depth, and other pits measured less than 20 mils. The average reduction in wall thickness measured on the three most corroded areas of the sample pile section cut from the wall was between 3 and 4 percent.

g. Enid Dam Spillway, Enid, Mississippi

History:

An 8-ft width of steel sheet pilings was exposed on the north side of the upstream wingwall in the Enid Dam Spillway. The piles consisted of interlocking arch-type beams having a driving width of 18 in.

Date piles driven: September 1949

Date of inspection: May 1961

Age of piling: 11.7 years

Piling exposed: An 8-ft width of the pilings was exposed between elevation 288 and 282.5 ft.

Surface elevation: 293 ft

Water table elevation: Much below 282.5 ft

Soil characteristics:

293 to 290.5 ft: Brown silty clay, somewhat plastic.

290.5 to 282.5: Reddish brown coarse sand containing much silt and gravel.

Soil resistivity and pH		
Elevation	Resistivity	pH
ft	*Ohm-cm*	
293	8,500 (Shepard Canes)	----
290.5	8,000 (Shepard Canes)	----
288	10,000 (Shepard Canes)	----
284	>4,000 (Laboratory)	5. 1
282	10,200 (Laboratory)	5. 3
282.5	9,500 (Shepard Canes)	----

Condition of piles:

Mill scale was intact over more than 90 percent of the surface. Slight metal attack was present in a few small areas, approximately 1 in. in diameter. There were no measurable pits.

5. Discussion

Previous investigations on soil corrosion conducted by the National Bureau of Standards have been restricted to the behavior of metals in disturbed soils; trenches or excavations were dug and backfilled after installation of the specimens. Because no prior systematic investigation pertaining to the behavior of metals in undisturbed soils had been conducted, it became general practice because no other data were available to apply the information provided by the NBS soil investigations as a guide to estimate the corrosion of metals in all types of underground installations, under both disturbed and undisturbed soil conditions.

The findings of the National Bureau of Standards with respect to the action of soils on metals have been presented on numerous occasions in various ways, and more recently assembled in the National Bureau of Standards Circular 579 [1]. The following repetition of the previously obtained major conclusions pertaining to the corrosion of iron and steel is not for the purpose of imparting new information, but to establish a basis for discussion of the data obtained from the piling inspections.

Briefly, the Bureau has found, first, that the corrosion of the commonly used ferrous metals is of the same type and order of magnitude when exposed to a given soil environment; and second, that the corrosion of ferrous metals in different soil environments varies widely. In general, in well-drained high-resistivity soils, the rate of corrosion may be high initially, but decreases after a few years to almost complete cessation of pitting. Conversely, in poorly drained soils having low resistivities, the rate of corrosion is nearly constant with time after the initial period.

One of the most interesting characteristics of underground corrosion is the irregular nature of the attack. A section of pipe is often penetrated at only one or more points and practically no corrosion is found elsewhere on the section. Usually, the loss of ferrous metal is too small to be of importance if it were uniformly distributed over a metal surface.

The major cause of corrosion can be attributed to the nonuniformity in the distribution of oxygen and moisture along the surface of a buried metallic structure. Variations in the supply of oxygen can set up oxygen-concentration cells in which the metal surfaces which are least accessible to oxygen are anodic to the surfaces to which oxygen is more readily accessible. The corrosion may be either general or localized depending upon the relative size of the anodic and cathodic areas. For a given difference in potential between the two areas, if the anode area is relatively large compared to the cathode area, the total current produced may be small or negligible and the little damage to the anode area will be distributed over an appreciable area in the form of uniform corrosion. On the other hand, if the anodic area is relatively small compared to the cathodic area, the corrosion is localized and severe damage may result due to penetration of the metal by pitting.

The pitting type of corrosion is of major importance in pipe lines or other structures designed to carry liquids or gas. On the other hand, for underground structures that are primarily load-bearing the depth of pitting is of less interest than the overall loss in weight or strength. Hence, in relating corrosion damage to the useful life of piling the most important measurement involves the amount of uniform corrosion that will result in a reduction of the cross section.

The data from 19 installations listed in section 4 provide information on the behavior of steel pilings to depths of 136 ft and for exposures of 7 to 40 yr in a wide variety of soil conditions. The data are summarized in table 3 to facilitate interpretation and to bring out any relationship that may exist between the corrosion observed on the pilings and the characteristics and properties of the soils.

Fill material which varied in content from riprap, cinders, slag, and combinations of sand, silt, loam, and clay was present at nine locations above the water table. The undisturbed natural soils covered a range from well-drained sands to impervious tight clays. The resistivities of the soils ranged from 300 ohm-cm (indicating the presence of large quantities of soluble salts) to 50,200 ohm-cm, (indicating the absence of soluble salts). The pH of the soil ranged from 2.3 to 8.6.

Any attempt to estimate the corrosiveness of the soils to which the pilings were exposed by association of the soil properties and characteristics with data obtained from similar soil environments from either NBS field tests, or actual service history of structures in disturbed soils, could only lead to the expectation of severe corrosion at most of the sites. Skipp [15] suggested that engineers make a thorough site investigation in designing structures utilizing buried steel piles in order that due allowance may be made for corrosion and its prevention. The investigation procedures he recommended to determine the likelihood of corrosion and its possible severity are essentially those used to predict corro-

TABLE 3. *Summary of inspections on steel pilings*

Location [a]	Age of piling	Soil types	Piling exposed [b]			Soil resistivity [c]		pH		Partial chemical composition (mg-eq/100 g soil)				Condition of piling [d]			Surface with original mill scale intact			Maximum reduction of thickness in local areas [e]		
			Above water table	In water table zone	Below water table	Minimum	Maximum	Minimum	Maximum	CO_3	HCO_3	Cl	SO_4	Above water table	In water table zone	Below water table	Above water table	In water table zone	Below water table	Above water table	In water table zone	Below water table
Extracted Piles:	*Yr*					*Ohm-cm*	*Ohm-cm*										*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Bonnet Carre Spillway	17	Sand, organic silt and clay	X	X	X	400	1,050	6.7	8.1	0.53	1.40	11.94	0.04	U	M	U	95+	0	95+	Nil	Nil	Nil
Sparrows Point, Md.	18	Fill—cinders, slag and sand	X	X	X	1,130	4,000	3.7	6.6	—	—	—	—	P, 35	P, 112	S	50+	0	90+	3	29	Nil
		Natural—sand, silt and clay	—	—	X	1,370	12,400	4.9	7.3	—	—	—	—	—	—	U [f]	—	—	95+	—	—	Nil [f]
Ouachita River Lock No. 8	40	Silty clay and clay	—	—	X	1,540	3,200	4.3	6.2	—	—	—	—	—	—	S	—	—	95+	—	—	Nil
Grenada Dam; North side	12	Fill—sandy loam and silty sand	X	—	—	2,800	15,400	—	4.9	—	—	—	—	P, 122	—	—	30	—	—	8	—	—
		Natural—shale and and organic clay	X	—	—	3,800	15,400	3.6	4.9	—	—	—	—	M	—	—	75	—	—	Nil	—	—
Sardis Dam	20	Fill—riprap	—	—	X	—	610	—	3.0	—	—	—	—	—	—	P, 60	—	—	—	—	—	19
		Natural—sand and lignitic clay	—	—	X	—	1,690	—	2.9	—	—	—	—	—	—	P, 30	—	—	—	—	—	11
Chef Menteur Pass	32	Slty sand and clay	—	X	X	300	440	6.9	7.8	—	—	—	—	—	M	P, 145	—	75	85	—	Nil	Nil
Wilmington Marine Terminal	23	Fill—cinders	X	—	—	—	—	—	—	—	—	—	—	P, 150	—	—	—	—	—	10	—	—
		Natural—organic silt, sand, clay	—	X	X	—	—	—	—	—	—	—	—	—	P, 75	M	—	—	90+		10	Nil
Lumber River	37	Sandy loam and silty clay	—	X	X	1,100	4,900	2.3	5.9	—	—	—	—	—	P, 60	P, 60	—	0	20	—	40	12
Piles in excavations:																						
Memphis Floodwall, Sta. 56+14[g]	7	Clay and silty clay	X	X	—	1,000	8,600	7.6	7.8	.00	0.52	0.08	.59	U	P, 35	—	95+	95+	—	Nil	Nil	—
Memphis Floodwall, Sta. 60+00	7	Clay and silty clay	X	X	—	1,030	7,900	6.8	7.8	.00	.43	.03	.21	U	U	—	90+	90+	—	Nil	Nil	—
Vicksburg Floodwall, Sta. 16+32	7	Sandy loam, clay and cinders	X	X	—	850	7,000	7.4	8.2	.01	.35	.04	.00	P, 40	P, 45	—	30	40	—	6	4	—
Vicksburg Floodwall, Sta. 23+83	7	Silty sand, clay and cinders	X	X	—	625	9.200	7.1	8.6	.05	1.24	.03	.00	M	M	—	70	70	—	Nil	Nil	—
Sardis Dam	20	Fill—sandy loam	X	—	—	>10,000	50,200	—	5.7	.00	0.08	.00	.00	M	—	—	90	—	—	Nil	—	—
		Natural—clay	—	X	X	3,000	7,510	5.4	6.0	.00	.00	.03	.02	—	M	S	—	90	90	—	Nil	4
Grenada Dam, North side	11	Fill—clayey sand and silt loam	X	—	—	1,700	16,500	4.0	4.4	.00	.02	.04	1.10	P, 108	—	—	20	—	—	16	—	—
Grenada Dam, South side	11	Fill—sandy loam	X	—	—	2,400	8,000	4.4	6.4	—	—	—	—	P, 172	—	—	70	—	—	—	—	—
		Natural—silty sand	X	—	—	4,300	11,000	—	6.9	.00	.04	.06	0.00	P, 160	—	—	50	—	—	19	—	—
Berwick Lock, West side	11	Fill—silty clay	X	—	—	680	1,550	—	8.5	—	—	—	—	P, 61	—	—	40	—	—	8	—	—
		Natural—clay	X	X	X	800	1,290	—	8.1	.03	.79	.05	.14	S	S	S	60	60	60	Nil	Nil	Nil
Berwick Lock, East side	11	Fill—clay	X	—	—	950	1,610	—	—	—	—	—	—	P, 90	—	—	40	—	—	11	—	—
		Natural—clay	—	X	X	750	1,610	7.9	8.1	.01	.83	.04	.03	—	P, 75	S	—	40	75	—	8	Nil
Algiers Lock	12	Fill—silty clay (above piling)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
		Natural—silty clay and organic clay	—	X	—	345	1,300	7.7	8.4	.02	.63	.05	.00	—	P, 40	—	—	85	—	—	4	—
Enid Dam	12	Silty clay, sand and silt	X	—	—	8,000	10,200	5.1	5.3	—	—	—	—	M	—	—	90	—	—	Nil	—	—

[a] See sections 4.1 and 4.2 for additional information pertaining to location, type and length of piling examined.

[b] An "X" indicates the soil level with reference to the water table in which piling was examined. The water table zone includes 2 ft above and below the water line. A dash indicates that piling was not examined at that level.

[c] Includes all soil resistivity determinations measured by Shepard Canes, 4-pin method, or in the laboratory.

[d] Condition of piling is described in accordance with the following code:

U, no corrosion, surface is entirely unaffected as indicated by the presence of mill scale over practically the entire surface. The surface may be roughened in small areas but no pits have a depth greater than the thickness of the mill scale.

M, uniform metal attack indicated by removal of mill scale over large areas and roughening of the surface. Pit depths do not exceed the thickness of the mill scale.

S, shallow metal attack, sufficient corrosion to have removed a perceptible amount of metal in localized areas. Pits do not exceed 25 mils in depth.

P, pitting, grooving or scaling to a depth greater than 25 mils. The numbers indicate the maximum pit depth (in mils).

[e] It should be noted that the average reduction in thickness does not refer to the entire section of piling, but to a very small area, usually 1 in.^{2} of the most corroded area of the piling. Refer to section 3.4 for further explanation. "Nil" indicates that the reduction in thickness is negligible.

[f] Pilings passed through a sand and gravel stratum at a depth of about −116 ft. A 3-ft section of the pile at this level showed moderate corrosion as indicated in section 4.1.

[g] This was the only coated piling inspected.

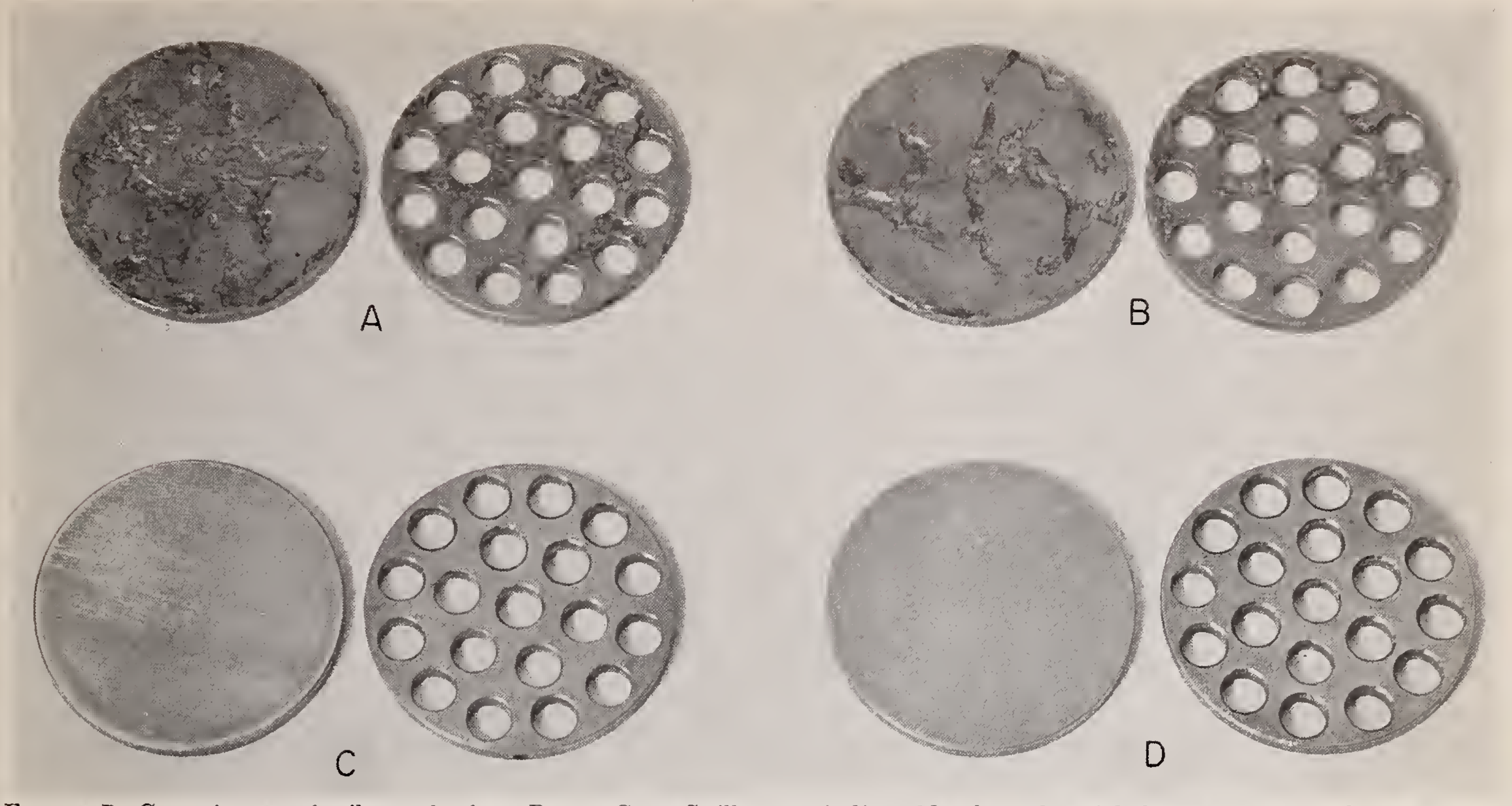

FIGURE 7. *Corrosiveness of soil samples from Bonnet Carre Spillway as indicated by electrode weight losses after 6 months in modified Denison corrosion cells.*

Electrode sets A and C set up under aerated and unaerated conditions, respectively, with soil samples obtained at 22 ft depth from surface of ground.
Electrode sets B and D set up under aerated and unaerated conditions, respectively, with soil samples obtained at 45 ft depth.

Electrode	Loss in weight
	oz/ft²
A	2.03
B	1.82
C	0.064
D	0.15

sion of structures, such as pipelines, in disturbed soils. Emphasis was placed on survey methods involving measurements of pH, soil electrical resistivity, redox potential, and bacterial activity.

It is evident from an evaluation of the data in table 3 that the survey methods recommended by Skipp, which presently are the methods widely used by engineers, are misleading in that they overestimate the corrosion of steel pilings driven in soils. For example, the 122-ft length of H-pile pulled from the Bonnet Carre Spillway after exposure for 17 yr was subjected to varying soil types at different horizons under poorly aerated conditions. At the time the pile was inspected, soil samples collected from the pile walls at depths of about 22 ft and 45 ft from the surface were shipped to the National Bureau of Standards. The soils consisted of clay having a resistivity of 400 ohm-cm and a pH between 7.8 and 8.1. Chemical analysis detected the presence of appreciable quantities of soluble salts in the form of carbonates, bicarbonates, sulfates and chlorides, the latter being predominant (table 3). The properties of this soil are nearly similar to those of a Docas clay soil found at Site 64, one of the most corrosive soils in the NBS corrosion field tests. At this site, carbon steel pipe specimens with a wall thickness of 0.154 in. were perforated by corrosion within 5 yr and had large weight losses.

The soil samples from the Bonnet Carre Site were subjected to the modified Denison corrosion cell test in the laboratory [1,16]; by means of this cell the behavior of iron or steel in different soils can be investigated under controlled conditions of moisture and aeration. In the aerated condition, the moisture content is controlled to make the soil sufficiently permeable for access of oxygen to the cathode. In the unaerated condition, all the soil is puddled at the time of setting up the cells, thus limiting access of oxygen to the electrodes. The small amount of oxygen available in the unaerated cell is rapidly depleted during the initial corrosion process and the replenishment of oxygen at the cathode becomes difficult because of the puddled soil.

An estimate of the corrosiveness of a soil is determined in the Denison cell by a measurement of the galvanic current between the electrodes or preferably by the combined weight losses of the two electrodes. Good correlations were obtained between the weight losses of corrosion cells set up for six months under aerated conditions using soils from NBS test sites and the weight losses occurring in the field at the test sites on wrought ferrous pipe specimens exposed for 10 yr [1,16].

The results obtained with the modified Denison cell on the Bonnet Carre soil samples for six months' exposure in the laboratory under aerated and unaerated conditions are shown in figure 7.

It was previously pointed out that the soil samples from the piling which was extracted from the Bonnet Carre Spillway had properties similar to those of the severely corrosive Docas clay soil in the NBS field tests. The laboratory corrosion cell set up under the aerated conditions produced weight losses of the same order of magnitude for the Bonnet Carre (fig. 7, A and B) and Docas clay soils [1,16] indicating that the Bonnet Carre soil is equally as corrosive as the Docas clay soil under aerated conditions. The weight losses of ferrous pipe specimens which were exposed in the disturbed soil at the Docas clay site are in relatively good agreement with the results obtained in the laboratory under aerated conditions.

On the other hand, the piling extracted from the Bonnet Carre Spillway after exposure for 17 yr was unaffected by corrosion at all depths below the water table zone, and showed but a negligible amount of corrosion in the water table zone. This is in complete accord with the results from the laboratory cell test which showed a relatively negligible amount of corrosion for the cell electrodes set up under unaerated conditions as compared with that of the cell electrodes set up under aerated conditions.

The data presented in section 4 and summarized in table 3 show that, in general, the amount of corrosion of the pilings exposed below the water table zone at any of the sites was not sufficient to have an appreciable effect on the strength of the pilings for the periods of exposure. The water table zone is defined as the zone lying between ± 2 ft of the water table.

At Sparrows Point, a 3-ft section of each of the two H-piles contained some moderate corrosion below the water table at elevation of about -116 ft. These sections of the piles passed through a coarse sand and gravel bed through which ground water flowed more freely than in the other strata. The corrosion can possibly be attributed to the action of dissolved carbon dioxide. The sections of the piles above the sand and gravel stratum to the water line zone and below the sand and gravel stratum to the bottom of the piles were almost entirely coated with mill scale. The condition of three sections of one of the H-piles pulled from Sparrows Point is shown in figure 1.

Corrosion was found on steel piles exposed below the water table at the Sardis Dam, Chef Menteur Pass Bridge, and the Lumber River structures. The pits were highly localized as indicated by the large amount of mill scale intact on the pile surfaces. Only small or negligible reductions in wall thicknesses were observed.

The portions of pilings which appeared to be the most vulnerable to corrosion were the sections exposed in fill soil located above the water table level or in the water table zone. In the water table zone, corrosion was found on the pilings extracted from the Sparrows Point and Lumber River locations; reductions of 29 and 40 percent were observed in the cross sections of the piles after 18 and 37 yr, respectively. Corrosion tapered off rapidly and was not appreciable below the water table zone.

Significant corrosion occurred above the water table only in fill soils at Grenada Dam, Berwick Lock, and at the Wilmington Marine Terminal (table 3). The corrosion at these locations was highly localized as shown by the reductions in wall thickness of the piles.

Inspections of the pilings in the test holes at Grenada Dam were made early in the investigation. The pitting type of corrosion found on the piles exposed to the fill soil were of concern to personnel of the Corps of Engineers. As a result, a pile section was pulled from the north wingwall structure to observe the condition of the pile at greater depths. No corrosion of any significance was found in the natural soil below the fill layer.

The data indicate that the depths of maximum pitting give no indication of the extent of corrosion on pilings. A review of each case history in section 4 shows that the number of deep pits are relatively few for the large areas of pile surface involved, and that most of the measured pit depths are considerably less than the maximum reported in table 3. Furthermore, corrosion by pitting covers a relatively small area of the pilings, especially below the water table zone. Significant pitting was not observed on many of the piles below the water line. An example of this is illustrated in figure 2 for the piling pulled from the Ouachita River Lock after 40 yr of exposure.

It should also be noted that there is generally a marked difference between the maximum depth of pitting and the reduction in cross section area. For example, maximum pit depths of the order of 145 mils found on the pilings from the Chef Menteur Pass Bridge might cause considerable concern for a fluid-carrying structure regardless of the condition of other portions of the structure. On the other hand, because of the localized and isolated nature of attack, pit depths of this magnitude do not have an appreciable effect on the strength or useful life of piling structures because the reduction in pile cross section after exposure for 32 yr is not significant.

At the time of driving the H-piles at Sparrows Point and the 100-ft lengths of the sheet piles at the Wilmington Marine Terminal, sections forming the full pile length were joined by butt welds. The welds showed no evidence of corrosion at the time of inspection after the piles were pulled. A welded joint on the Sparrows Point pile is shown in figure 1.

Stray currents have been detected and measured throughout the entire area where the two piles were extracted at Sparrows Point. Several months after the piles were pulled, an engineer of the Bethlehem Steel Company and the writer conducted measurements on a 9-ft section of 36-in. cast iron water pipe which was located about 600 ft from the piles. A maximum current of 40.5 amp with an average of 13.5 amp was measured over a 20-hr period. On another pipe of similar dimensions located approximately 100 ft from the site of pile I–S, stray-current measurements averaged 3 amp with a maximum of 4 amp over the 20-hr period. The absence of highly localized corrosion on the pilings indicated that they were not acting as conductors for the stray currents in the area.

It is also of interest to mention the excellent condition of a group of identification numbers which was stamped in the steel with ¼-in. dies on the 40-yr pile from the Ouachita River Lock. Although the mill scale was broken by the dies, the numbers and the surrounding area were unaffected by corrosion, as were the roll marks on the pile indicating the manufacturers identification and patent number. At all locations, roll marks on the piles where detected were legible and were in the same condition as the surrounding surfaces (figs. 4, 5, and 6).

In general the data obtained from the piling inspections do not show any correlation between soil properties and the condition of the pile surfaces in the different soil environments, with the possible exception of *p*H. Maximum corrosion was observed on the pilings exposed to extremely acid soils in the water table zone at Lumber River (*p*H 2.3) and Sparrows Point (*p*H 3.7), and below the water table zone at Sardis Dam (*p*H 2.9). The soils in the piling investigation cover as wide a range of properties as the soils included in the early NBS field tests. The results of the earlier tests showed that there is at least a rough correlation between the corrosion of iron or steel and certain soil properties, such as resistivity, *p*H and chemical composition.

The major difference between the soils at the NBS test sites and the soils into which the pilings were driven appears to be the oxygen content. The data from the early soil-corrosion tests and most corrosion data reported previously on service structures were obtained on specimens or structures located in backfilled soil. The backfilling causes a drastic disturbance in the oxygen content of the soil and promotes corrosion of iron and steel by differential aeration. On the other hand, the oxygen concentration of undisturbed soils is not sufficient to cause appreciable corrosion of pilings that are driven into the ground.

It would seem that the soil types which range from pervious sands to tight impermeable clays at different horizons at the same locations, would differ sufficiently in oxygen content to promote corrosion by differential aeration. Accelerated corrosion on pilings could also be expected to occur due to galvanic effects resulting from the presence of mill scale and exposed bare metal in adjacent areas. However, the data from the piling inspections indicate that there is not enough oxygen available a short distance below the ground line, and especially below water table zones, to promote corrosion by differential aeration or other causes. Obviously, regardless of the soil properties, sufficient circulation of oxygen is essential for corrosion to occur.

Evidently some corrosion of steel piles takes place initially after the piles are driven as indicated by the removal of mill scale in small areas and localized pitting at some of the locations. The corrosion is evidently arrested after the limited amount of oxygen has been depleted by the initial corrosion process and corrosion ceases thereafter because of the inability of the soil to replenish the oxygen.

The importance of oxygen as a factor in the corrosion process was previously indicated, by the behavior of steel in the modified Denison corrosion cell set up under aerated and unaerated conditions in the laboratory on soil samples from the Bonnet Carre Spillway (fig. 7).

The data obtained from the inspections of steel pilings indicate that there is not sufficient oxygen available in undisturbed soils to cause appreciable corrosion on driven pilings regardless of the soil properties. Even wet cinders which were present in the water table zone adjacent to the floodwalls excavated at Vicksburg and Memphis had no corrosive effect on the steel pile surfaces.

Appreciable quantities of soluble salts in the form of sulfates and other ions were present in the soil to which the pilings from the Memphis Floodwall and Berwick Lock were exposed. The internal drainage at the sites, soil *p*H, and the presence of organic matter constituted conditions under which sulfate-reducing bacteria would be expected to thrive. However, no evidence of accelerated corrosion by the anaerobic bacteria were detected on the piles at these sites. In fact, at none of the locations where pilings were examined were sulfides detected in the corrosion products.

Examination of the data in table 3 and section 4 shows that in general soil type, drainage, soil resistivity, *p*H, or chemical composition of soils are of no importance in determining the corrosion of steel pilings driven in undisturbed soils. This is contrary to everything published pertaining to the behavior of iron and steel under disturbed or backfilled soil conditions. Hence, soil corrosion data published in NBS Circular 579 [1] are not applicable and should not be used for estimating the behavior of steel pilings driven in undisturbed soils. Likewise, survey methods, as recommended by Skipp [15] and others, are of no practical value in predicting the extent of corrosion of steel pilings underground.

6. Summary

Steel pilings which have been in service in various underground structures for periods ranging between 7 and 40 yr were inspected by pulling piles at 8 locations and making excavations to expose pile sections at 11 locations. The conditions at the sites varied widely, as indicated by the soil types which ranged from well-drained sands to impervious clays, soil resistivities which ranged from 300 ohm-cm to 50,200 ohm-cm, and soil *p*H which ranged from 2.3 to 8.6.

The data indicate that the type and amount of corrosion observed on the steel pilings driven into undisturbed natural soil, regardless of the soil characteristics and properties, is not sufficient to significantly affect the strength or useful life of pilings as load-bearing structures.

Moderate corrosion occurred on several piles exposed to fill soils which were above the water table level or in the water table zone. At these levels the pile sections are accessible if the need for protection should be deemed necessary.

It was observed that soil environments which are severely corrosive to iron and steel buried under disturbed conditions in excavated trenches were not corrosive to steel pilings driven in the undisturbed soil. The difference in corrosion is attributed to the differences in oxygen concentration. The data indicate that undisturbed soils are so deficient in oxygen at levels a few feet below the ground line or below the water table zone, that steel pilings are not appreciably affected by corrosion, regardless of the soil types or the soil properties. Properties of soils such as type, drainage, resistivity, *p*H or chemical composition are of no practical value in determining the corrosiveness of soils toward steel pilings driven underground. This is contrary to everything previously published pertaining to the behavior of steel under disturbed soil conditions. Hence, it can be concluded that National Bureau of Standards data previously published on specimens exposed in disturbed soils do not apply to steel pilings which are driven in undisturbed soils.

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