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# NBS Papers on Underground Corrosion of Steel Piling 1962-1971

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

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[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.
[2] Part of the Center for Radiation Research.
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# NBS Papers on Underground Corrosion of Steel Piling

## 1962-1971

### Corrosion of Steel Pilings in Soils,
### Corrosion Evaluation of Steel Test Piles Exposed to Permafrost Soils,
### Performance of Steel Pilings in Soils,
### Polarization Measurements as Related to Corrosion of Underground Steel Piling

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U.S. DEPARTMENT OF COMMERCE, Peter G. Peterson, *Secretary*
NATIONAL BUREAU OF STANDARDS, Lewis M. Branscomb, *Director*,
Issued March 1972

This monograph is dedicated to the memory of Melvin Romanoff, who—until his death in October of 1970—was the guiding light and motivating force for research at the National Bureau of Standards on underground corrosion. His work is considered by corrosion engineers throughout the world to be indispensable for an understanding of the corrosion behavior of metals in soils. The studies described in the monograph embody pioneering concepts on the nature of driven piling corrosion developed by Mr. Romanoff toward the end of his career. Therefore this publication, which is a compilation of the papers resulting from those concepts, serves as a fitting memorial for Melvin Romanoff.

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ABSTRACT

This monograph is a collection of published papers on underground corrosion of steel piling. The papers are as follows:

(1) Romanoff, Melvin, Corrosion of Steel Pilings in Soils, Nat. Bur. Stand. (U.S.), Monogr. 58, (Oct. 1962).

(2) Romanoff, Melvin, Corrosion Evaluation of Steel Test Piles Exposed to Permafrost Soils, Proceedings 25th Conference, National Association of Corrosion Engineers, page 6 (March 1969).

(3) Romanoff, Melvin, Performance of Steel Pilings in Soils, Proceedings 25th Conference, National Association of Corrosion Engineers, page 14 (March 1969).

(4) Schwerdtfeger, W. J., Polarization Measurements as Related To Corrosion of Underground Steel Piling, J. Res. Nat. Bur. Stand. (U.S.), 75C (Eng. and Instr.) No. 2, 107-121 (April-June 1971).

The papers describe corrosion of various types of steel piling exposed underground in the United States under climatic conditions ranging from semi-tropical to frigid. Corrosion is described on driven piling above and below the water table after many years of exposure in soils having resistivities between 78 and 50,000 ohm-cm and ranging in pH from 2.3 to 8.8.

One of the papers demonstrates the value of a polarization technique in measuring corrosion. Polarization data were obtained on weighed steel pipe specimens exposed underground for seven years in backfilled soil trenches in the vicinity of driven sheet piling. The technique was evaluated by comparing calculated cumulative weight losses of specimens with their actual weight losses. The technique was also shown to be applicable to underground pipe piling.

Kew words: Active region; aerated soil; corrosion; disturbed soil; excavated; extracted; H-piling; instantaneous corrosion rate; mill scale; permafrost region; pipe piling; pit depth; polarization; sheet piling; undisturbed soil; weight loss.

Selected NBS Papers on
Underground Corrosion of Steel Piling

## Preface

The papers included in this monograph have been previously published. The work was under the direction of the National Bureau of Standards with excellent cooperation from the American Iron and Steel Institute and Corps of Engineers, Lower Mississippi Valley Division, Office of the Chief of Engineers. For those concerned about the vulnerability of steel piling to corrosive soils and fills, this composite publication should be of interest.

The papers reveal the difference in the nature and extent of corrosion observed on driven underground piling and that found on steel exposed to soil in backfilled trenches. A distinction is made between so-called undisturbed and disturbed soil. Strictly speaking, in reference to corrosion, there is no undisturbed soil. The difference between the two soil conditions must be considered as being relative. By way of definition, herein, an undisturbed soil is described as an underground environment disturbed only by penetration from the driven piling coupled with the assumption that there was no prior disturbance by recent excavation.

A brief statement in reference to each of the four papers follows. The first paper, "Corrosion of Steel Pilings in Soils" (Monograph 58) describes the physical appearance of piling after exposure from 7 to 40 years. Piles were extracted at eight locations and soil excavated from sheet piling at eleven sites for inspection and pit depth measurements. The piles were located in Southern States east of the Mississippi River. Soil resistivities varied from 300 to 50,000 ohm-cm and pH from 2.3 to 8.6.

The second paper, "Corrosion Evaluation of Steel Test Piles Exposed to Permafrost Soils", pertains to observations and pit depth measurements on piling in Fairbanks, Alaska. Piling had been exposed to soil affected by both permafrost and thawing conditions. Inspections were made on nine steel H and pipe piles after extraction which followed 6 to 11 years of exposure in soils ranging in resistivity from 1350 to 11,500 ohm-cm and in pH from 5.4 to 7.6.

The third paper, "Performance of Steel Pilings in Soils", involves physical inspection of steel piling in 25 locations covering much of the United States. Eight of the piles (all sheet piles, except one) were extracted for evaluation of corrosion and measurement of pit depths. The piling had been exposed from 21 to 50 years in soils having resistivities ranging from 78 to 41,000 ohm-cm and pH from 4.7 to 8. Thirteen of the piles were of the sheet type, inspected by excavation of adjacent soil, the age of piling being from 14 to 30 years. The four remaining piles, also sheet type, had been coated with coal tar enamel and exposed

8 to 24 years. Wherever excavations were made for the purpose of piling inspection, sections of piling were cut from the most severely corroded areas and shipped to the laboratory for removal of corrosion products and for pit depth measurements.

The final paper of this monograph, "Polarization Measurements as Related to Corrosion of Underground Steel Piling", relates how corrosion observed on piling at 4 sites, described in the first paper (Monograph 58), compared with that on weighed steel pipe specimens exposed nearby in backfilled trenches. In addition to weight losses and pit depths, involving exposure periods of 1,2,4 and 7 years, polarization measurements were made at periodic intervals on one of four specimens designated for each exposure period at each of the 4 sites. Based on verification by actual weight losses, following removal of corrosion products, it was demonstrated how periodic measurements of instantaneous corrosion currents could be used to calculate cumulative metal losses in reasonable agreement with actual weight losses. Finally, the corrosion rate measurement technique, based on specific changes in the slopes of polarization curves, was applied to measuring the instantaneous corrosion taking place on 12 in. diam. (30.5 cm) pipe piles, one 19 ft. (5.8 m) and the other 72 ft. (22 m) in length, exposed to a corrosive underground environment for 12 years.

The National Bureau of Standards continues to study the corrosion of underground steel piling. In 1966, three piling sites were installed at Montreal, Quebec, Canada during construction of the Trans-canadian highway. It is an international cooperative project. At each site, several steel H-piles, 12 in x 12 in x 30 ft (30.5 cm x 30.5 cm x 9.2 m), were driven to bedrock and the upper ends of the piles exposed to excavated soil and fill. At one site, all piles are exposed bare. At the second site, the upper part (about 5 ft or 1.5 m) of the piling, exposed to the fill soil, was protected with a coal-tar epoxy coating. At the third site, molded concrete caps were substituted for the epoxy coating. At each site, one pile identical with the others is placed horizontally in a backfilled trench.

At Montreal, polarization measurements have been made on a yearly basis since installation of the piling. A paper is currently under preparation describing the physical appearance of piling removed from each site after three years of exposure and also comparing physical measurements with corrosion rates as calculated from polarization data. Measurement of instantaneous corrosion rates will continue to be carried out yearly and removals of piling be done at prescribed intervals. Following removals, the results will be published.

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W. J. Schwerdtfeger

UNITED STATES DEPARTMENT OF COMMERCE • Luther H. Hodges, *Secretary*

NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

# Corrosion of Steel Pilings in Soils

Melvin Romanoff

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National Bureau of Standards Monograph 58

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## Contents

# 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 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 ⅙ 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 ⅙ 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 ⅜-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 $p$H; 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.

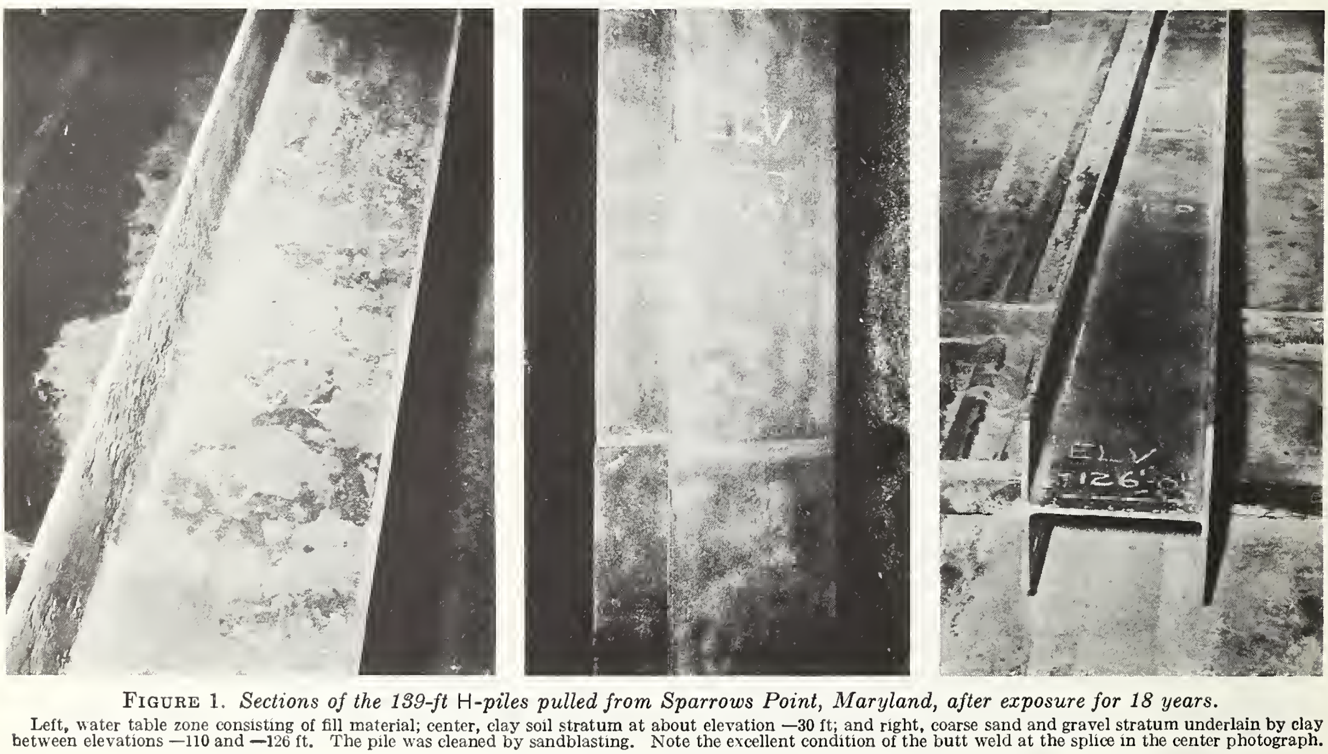

FIGURE 1. *Sections of the 139-ft* H*-piles pulled from Sparrows Point, Maryland, after exposure for 18 years.*

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.

#### 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

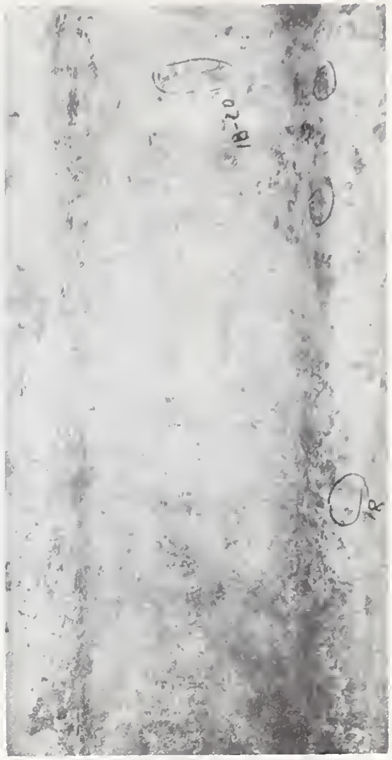

FIGURE 2. *Sandblasted 3-ft section from the 40-year-old piling extracted from an abutment wall in the Corps of Engineers Dam and Lock No. 8 on the Ouachita River near El Dorado, Arkansas.*

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.

*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 |

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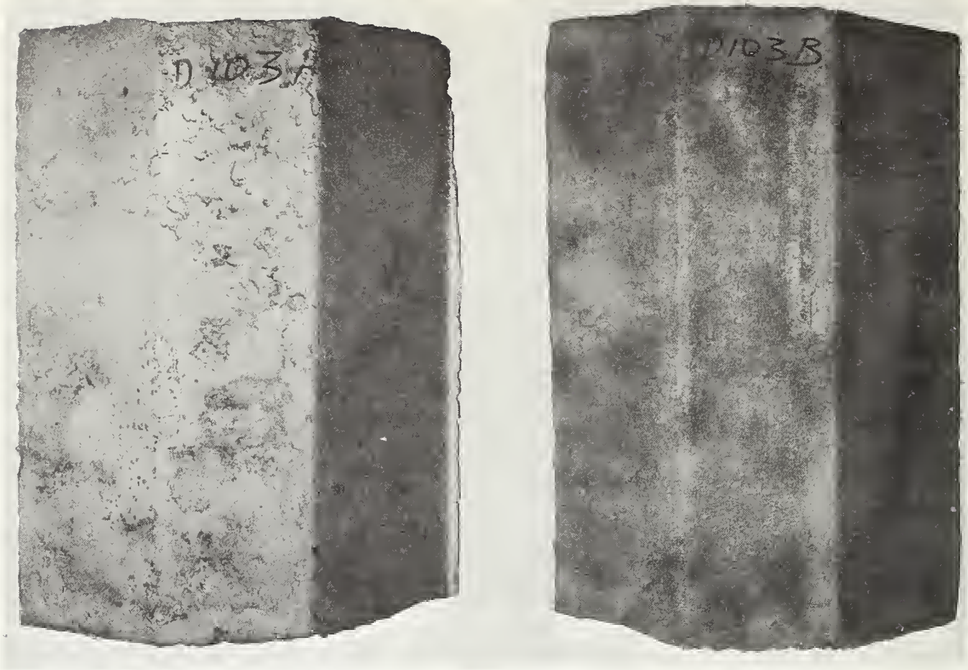

FIGURE 3. *Sections (1.5 ft by 1 ft) cut from a piling which was pulled from the north upstream wingwall of the Grenada Dam Spillway at Grenada, Mississippi, after exposure for 12 years.*

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 *p*H

| Elevation | Resistivity | *p*H |
|---|---|---|
| *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 $pH$

| Elevation | Resistivity | | pH |
|---|---|---|---|
| *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 $pH$

| Elevation | Resistivity | | pH |
|---|---|---|---|
| *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 $pH$

| Elevation | Resistivity | $pH$ |
|---|---|---|
| *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 ⅜ 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 $pH$

| Elevation | | Resistivity | $pH$ |
|---|---|---|---|
| *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 $pH$

| Elevation | | Resistivity | $pH$ |
|---|---|---|---|
| *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 ⅜ in. at the web and ½ 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 *p*H | | |
|---|---|---|
| Elevation | Resistivity | *p*H |
| *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 *p*H 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.

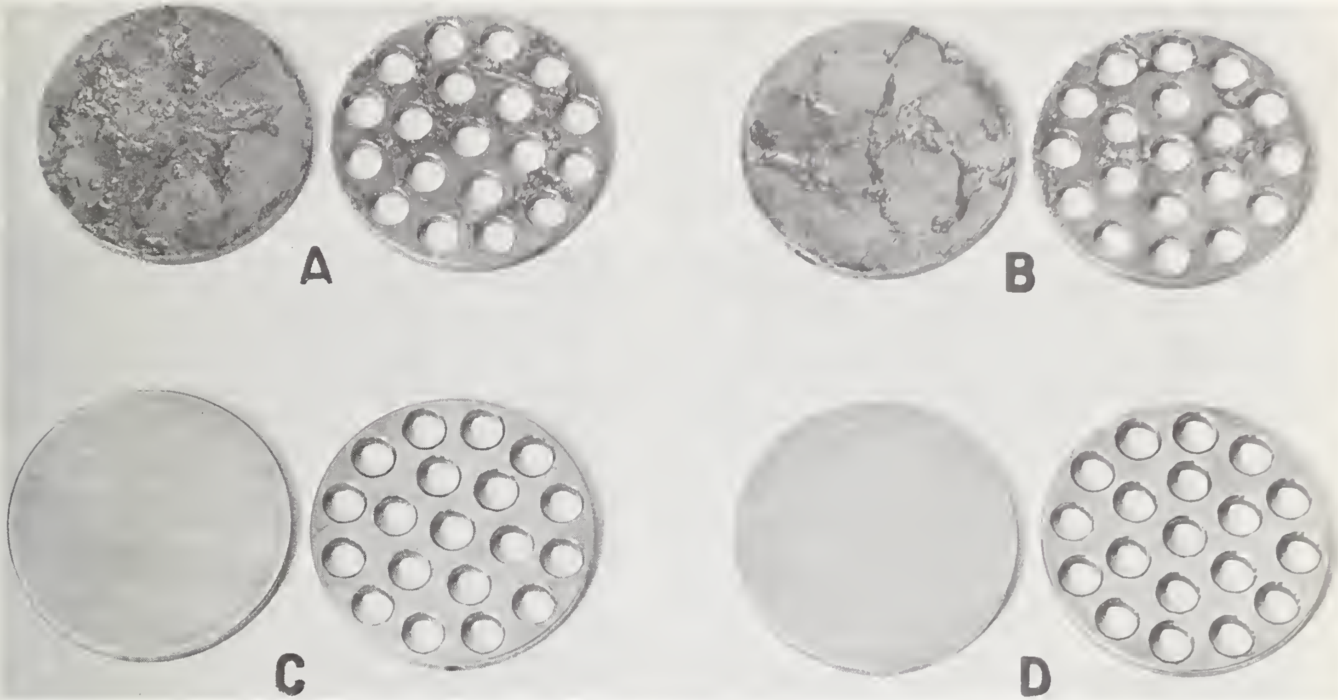


FIGURE 7. *Corrosiveness of soil samples from Bonnet Carre Spillway as indicated by electrode weight losses after 6 months in modified Denison corrosion cells.*

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 $p$H, 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 $p$H 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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# CORROSION EVALUATION OF STEEL TEST PILES EXPOSED TO PERMAFROST SOILS

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# CORROSION EVALUATION OF STEEL TEST PILES EXPOSED TO PERMAFROST SOILS

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## Introduction

The performance of steel pilings in soils is being investigated by the National Bureau of Standards (NBS) with the cooperation of the American Iron and Steel Institute and the U. S. Army Office of Chief of Engineers (OCE).

The purpose of the investigation was to obtain more accurate estimates of the useful life of steel pilings by determining the extent of corrosion on pilings after many years of service in different underground environments. The results of the first stage of the investigation have been published.[1]

The U. S. Army Cold Regions Research and Engineering Laboratory (CRREL) installed test piles at their Alaska Field Station (AFS) between 1952 and 1957. The purpose of the investigation was to determine the time for failure of the soil-to-pipe bond resulting from load-settlement tests conducted by CRREL; and, also, to investigate the corrosion of steel pilings in permanently frozen soils. This paper is concerned with only the corrosion aspect.

As part of the joint investigation being conducted by NBS and OCE on the corrosion of steel piles in underground environments, CRREL arranged for representatives of NBS and the U. S. Army Engineers Division, Lower Mississippi Valley, Corps of Engineers, to extract 9 steel test piles from the AFS sites. The pile specimens ranged in age from 6 to 11 years. Personnel and equipment to remove the piles and assist in the inspection were provided by the AFS.

## Geologic and Climatic Conditions at AFS

The CRREL Alaska Field Station is located about 2 1/2 miles (4.0 km) northeast of Fairbanks, Alaska. The mean annual temperature is about +26 F (-3 C) with a mean normal high temperature of 70 F (21 C) and yearly normal low temperature of -20 F (-29 C). The freezing season usually begins in early October and the thawing season about the middle of April. The annual rain is about 11 in (0.3 m). The annual snowfall is about 60 in (1.5 m).

The terrain is gently sloping. Geologically, the area is located on the colluvial slopes above the valley fill. The soil at the AFS is mainly silt with some peat, fine sand and clayey silt of low plasticity.

Under natural surface conditions the maximum depth of seasonal thaw varies from 2 to 6 ft (0.6 to 1.8 m). The permafrost layer in the area ranges from 100 to 150 ft (30 to 45 m) in thickness. Permafrost temperatures in the upper 30 ft (9.1 m) may vary from 29 F to 31.5 F (-2 C to 0 C) depending on surface cover.

Test piles have been installed in 3 sites at AFS which are designated as Sites A, B and C.

## Test Sites

Test Sites A and B were constructed between April and August 1952. Each site consists of an area approximately 100 by 200 ft (30 x 61 m). Site A was cleared of trees and brush and the surface organic layer left essentially undisturbed during and after the installation of the test piles. Site B was cleared and stripped of the surface organic material about 2 years prior to selection of the area for the test site. The elevations at the ground surface and at the top of the permafrost layer at Site A are about 476 ft (145.1 m) and 472 ft (143.8 m), respectively. The active layer, which freezes and thaws annually, is between the ground line and the top of permanently frozen soil. At Site B, the elevations at the ground surface and the top of the permafrost layer are about 474 ft (144.5 m) and 468 ft (142.6 m), respectively. Typical soil borings at Sites A and B are given in Table 1.

Test Site C consists of an area approximately 200 ft (61 m) square. The site was initially undisturbed and clearing of trees and brush was accomplished prior to installing the test piles. The surface layer of organic material was preserved during the pile installation period and during the subsequent years. The elevations at the ground surface and the top of the permafrost layer at this site are about 497 ft (151.4 m) and 493 ft (150.3 m), respectively. A typical soil boring at Site C is given in Table 2.

TABLE 1 – Typical Soil Borings at Test Sites A and B

| Group Symbols[1] | Soil Description | Depth Below Ground Line[2] ft | m |
|---|---|---|---|
| ML | Gray-brown silt with organic matter . . . . . . . . . | 0 to 5 | 0 to 1.5 |
| ML | Gray silt with high organic content . . . . . . . . | 5 to 14 | 1.5 to 4.3 |
| Pt | Brown organic layer . . . . | 14.0 to 14.5 | 4.3 to 4.4 |
| ML | Gray silt with little organic matter . . . . . . . . | 14.5 to 20 | 4.4 to 6.1 |
| ML, CL | Clayey silt . . . . . . . . | 20 to 21 | 6.1 to 6.4 |

[1]Classified according to: Unified Soil Classification System for Roads, Airfields, Embankments and Foundations. Military Standard MIL-STD 619A (March 20, 1962), Department of Defense, Washington, D. C.
[2]Ground line elevations at Sites A and B are about 476 and 474 ft (145 and 144 m) mean sea level, respectively.

TABLE 2 – Typical Soil Boring at Site C

| Group Symbols[1] | Soil Description | Depth Below Ground Line[2] ft | m |
|---|---|---|---|
| Pt | Organic matter . . . . . . . | 0 to 0.5 | 0 to 0.15 |
| OL | Organic silt . . . . . . . . . | 0.5 to 4.0 | 0.15 to 1.2 |
| ML | Silt with high organic content . | 4.0 to 4.5 | 1.2 to 1.4 |
| Pt | Organic layer . . . . . . . | 4.5 to 4.8 | 1.4 to 1.5 |
| ML | Gray silt . . . . . . . . . . | 4.8 to 7.5 | 1.5 to 2.3 |
| OL | Organic silt . . . . . . . . . | 7.5 to 8.0 | 2.3 to 2.4 |
| ML, OL, Pt | Layers of silt with varying amounts of organic matter . | 8.0 to 11 | 2.4 to 3.3 |
| ML | Gray silt with clayey silt . . . . | 11 to 21 | 3.3 to 6.4 |
| OH | Organic clay . . . . . . . . | 21 to 22 | 6.4 to 6.7 |

[1]Classified according to: Unified Soil Classification System for Roads, Airfields, Embankments and Foundations. Military Standard MIL-STD 619A (March 20, 1962), Department of Defense, Washington, D. C.
[2]Ground line elevation about 497 ft (151 m) mean sea level.

## Installation of Test Specimens

A total of 32 test piles was installed to depths of 13 to 23 ft (4.0 to 7.0 m) below the ground surface, in each of Sites A and B between April and August 1952. During April 1957, 93 test piles were installed from 8 to 22 ft (2.4 to 6.7 m) below ground surface in Site C. The steel piles[1] consisted of pipe and H-piles. The H-piles consisted of the following sections: 8B15 (light beam), 6WF25 (wide flange) and 10BP42. Timber and pre-cast reinforced concrete-piles also were included among test piles at sites for load-settlement and other tests conducted by CRREL.

The piles were installed by different methods, as follows:

(1) in holes formed by steam thawing;
(2) in holes formed by dry augering; and
(3) driving with a pile hammer powered by compressed air.

In the steam-thawed holes, the piles were installed directly in the silt-water slurry resulting from the steaming process and little or no additional backfill was required. In the dry-augered holes, the pile backfills consisted of silt-water slurry or clay-water slurry, manually or machine mixed. The slurry was rodded and vibrated during placement. Soil for the silt-water slurry consisted of the cuttings removed from the particular pile hole during the augering operation. Soil for the clay-water slurry was procured from the coal mining area near Healy, Alaska. The water used for slurry was obtained from a local well located near the Chena River, Fairbanks.

During subsequent years after installation, load-settlement tests were performed on some piles to determine possible failures in the bond between the soil and pile.

[1]The steel piles conform to the requirements of ASTM Standard Specifications for Steel for Bridges and Buildings, ASTM Designation A7.

## Piles Removed for Corrosion Studies

Nine steel test piles were extracted during July 1963. Five piles were removed from Site A, one from Site B and three from Site C. The piles were extracted from the sites by a thawing operation. A steam point, 90 psi (63 kgf/mm$^2$) steam pressure was advanced adjacent to and down to the depth of the pile until the pile heaved up. The pile was then lifted out of the thawed soil with a crane (Figure 1).

After removal of the piles from the 3 sites, they were assembled in one area where they were steam cleaned (Figure 2).

The piles were then examined for corrosion. After the examination was completed, 6-ft (1.8 m) sections were cut from pile specimens A17, A25, A32, B7D, C9 and C81 and shipped to the Corrosion Laboratory at the National Bureau of Standards for further study. The samples cut from the pile specimens were from zones exposed about 6 in (0.2 m) above ground surface to below the top of the permafrost, that is, in the active layer which thaws and freezes annually.

Soil and slurry samples collected at the time of pulling each test pile also were forwarded to the NBS Corrosion Laboratory. Soil resistivities and pH of the samples are given in Table 3.

The types of piles, methods of installation, exposure times, condition of the piles and other pertinent information follow:

### Site A

*Pile No.* A17
*Date pile driven:* April 21, 1952
*Date pile pulled:* July 22, 1963
*Age of piling:* 11 years
*Type of piling:* Steel pipe pile, 8-in (0.20 m) diameter, 0.272 in (6.9 mm) wall thickness, 25 lb/ft (37 kg/m).

*Method of installation:* A cone-shaped steel plate was welded over one end of the pipe and the pile installed with closed end down. Pile installed in 12 in (0.3 m) diameter dry-augered hole and backfilled with silt-water slurry. The slurry was mixed manually using soil cuttings removed from the hole.

| Exposure Data | ft | m |
|---|---|---|
| Overall pile length .................. | 23.8 | 7.2 |
| Total embedment below ground surface .. | 21.0 | 6.4 |
| Embedment in permafrost ............ | 16.4 | 5.0 |
| Above ground line .................. | 2.8 | 0.8 |

Condition of Pile:

*Above ground – 2.8 ft (0.8 m):* light film of rust, no metal attack or pitting visible.

*Active Region – Ground line to 4.6 ft (1.4 m) below:* Slight metal attack and pitting in localized areas. No pits measured greater than 20 mils (0.5 mm) in depth, except 2 pits at 4 ft (1.2 m) depth which measured 22 and 28 mils (0.6 and 0.7 mm). About 60 percent mill scale intact.

*Permafrost Region – 4.6 ft (1.4 m) to bottom of pile:* Mill scale 100 percent intact. No metal attack or pitting. Welds on the pipe at 3 ft (0.9 m) from the bottom and at the bottom of the pile were unaffected by corrosion.

Photographs of pile A17 are shown in Figures 3 and 4.

*Pile No.* A23
*Date pile driven:* July 1, 1952
*Date pile pulled:* July 23, 1963
*Age of piling:* 11 years
*Type of piling:* Steel pipe, 8 in (0.20 m) diameter, 0.272 in (6.9 mm) wall thickness, 25 lb/ft (37 kg/m).
*Method of installation:* Installed in 12 in (0.30 m) diameter steam thawed hole formed by advancing a steam point to full specified pile depth and continuing the steaming until a hole of adequate

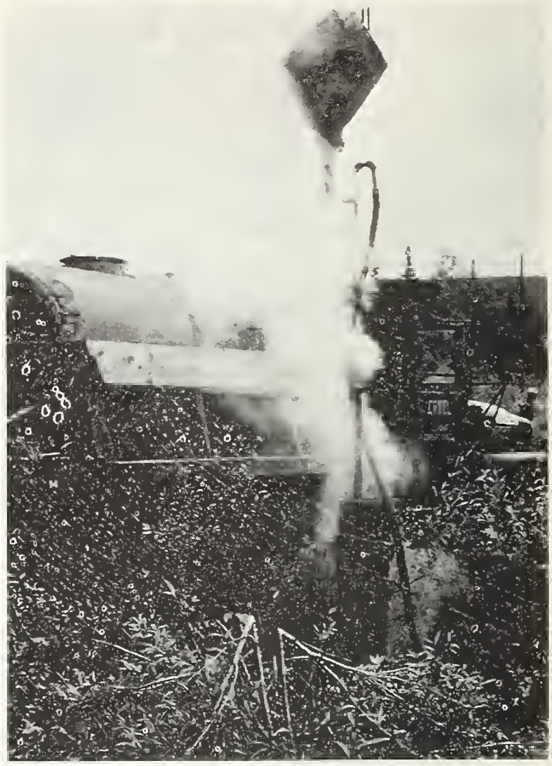

FIGURE 1 – Extraction of steel pile in permafrost at Fairbanks, Alaska. Soil was thawed by advancing a steam jet adjacent to and down to the depth of the pile until the pile heaved up.

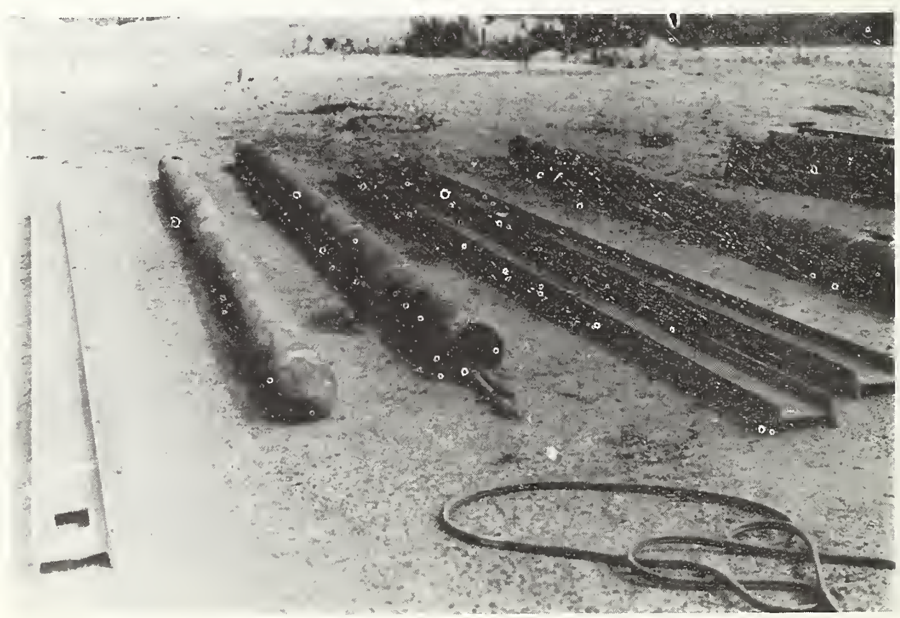

FIGURE 2 – Test piles prepared for inspection after cleaning. Left to right: Specimen A25, A17, A23, A31, A32, B7D and C9.

TABLE 3 – Data on Soil Samples Removed from Specimens During Extraction

| Site | Test Pile | Location of Soil Sample | Soil Group Symbol[1] | Soil Type | pH | Resistivity at 60 F ohm-cm |
|---|---|---|---|---|---|---|
| A | A17 | 17 ft (5.2 m) below ground surface | ML | Brown, silty clay | 6.1 | 3,000 |
| A | A23 | Surface | ML | Dark-brown, silty clay with organic matter | 7.0 | 4,200 |
| | | 3 ft (0.9 m) below ground surface | ML | Gray silt | 6.8 | 3,850 |
| | | Slurry | ML | Gray silt | 6.9 | 1,350 |
| A | A25 | Surface | ML | Brown, silty clay | 5.4 | 5,210 |
| | | 3 ft (0.9 m) below ground surface | CL | Brown, silty clay | 6.1 | 4,500 |
| | | Slurry | CL | Tan, silty clay | 6.9 | 2,410 |
| A | A31 | 11 ft (3.3 m) below ground surface | ML | Brown, silty clay with organic matter | 6.7 | 1,420 |
| A | A32 | 20 ft (6.1 m) below ground surface | ML | Gray silt | 6.1 | 11,500 |
| B | B7D | 15 ft (4.6 m) below ground surface | ML, Pt | Gray, silty clay with high peat content | 5.6 | 7,700 |
| C | C9 | Surface | OL | Black organic silt | 5.8 | 3,510 |
| | | Slurry | ML | Tan, silty clay | 6.5 | 1,440 |
| C | C61 | 3 ft (0.9 m) below ground surface | OL | Black organic silt | 5.6 | 4,700 |
| C | C81 | 1 ft (0.3 m) below ground surface | OL | Black organic silt | 7.6 | 2,540 |
| | | 5 ft (1.5 m) below ground surface | ML | Silt with high organic content | 7.2 | 3,850 |
| | | Slurry | ML | Gray silt | 6.9 | 1,970 |
| | | Slurry | CL | Gray clay | 6.7 | 1,890 |

(1) Classified according to: Unified Soil Classification System for Roads, Airfields, Embankments and Foundations. Military Standard MIL-STD 619A (March 20, 1962), Department of Defense, Washington, D. C.

diameter was formed. A cone-shaped steel plate was welded over one end of the pipe and the pile installed closed end down. The pile was installed in the existing silt-water slurry in the pipe hole resulting from the steaming process. Additional slurry backfill was added near the top of the pile hole as needed.

| Exposure Data | ft | m |
|---|---|---|
| Overall pile length | 24.6 | 7.5 |
| Total embedment below ground surface | 21.0 | 6.4 |
| Embedment in permafrost | 17.0 | 5.2 |
| Above ground line | 3.6 | 1.1 |

Condition of Pile:

*Above ground – 3.6 ft (1.1 m):* Thin uniform film of rust, no measurable pits.

*Active region – ground line to 4.0 ft (1.2 m) below:* Mill scale about 70 percent intact. Slight metal attack and pitting in isolated areas. No measurable pits beyond the thickness of mill scale (maximum scale thickness 20 mils).

*Permafrost region – 4.0 ft (1.2 m) to bottom of pile:* Mill scale 100 percent intact. No visible metal attack or pitting.

FIGURE 3 – Pipe pile specimen No. A17 prepared for inspection in the field after steam cleaning.

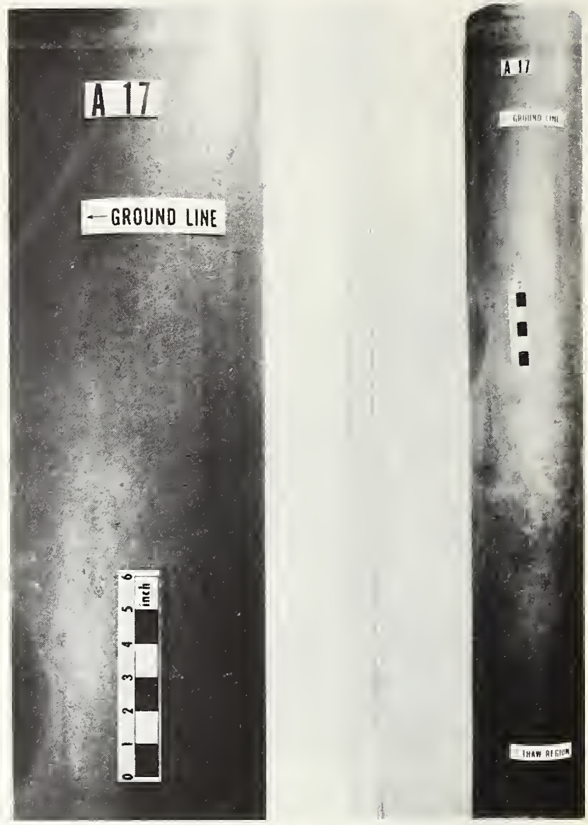


FIGURE 4 – Conditions of sections of pipe pile A17 exposed above the ground line and in the active (thaw) region. Final inspections of these sections were made in the laboratory.

*Pile No.* A25
*Date pile driven:* April 22, 1952
*Date pile pulled:* July 23, 1963
*Age of pile:* 11 years
*Type of piling:* Light beam, 8B15, 8 in (0.20 m) x 4 in (0.10 m), 15 lb/ft (22 kg/m).
*Method of installation:* Installed in 12 in (0.30 m) diameter hole dry-augered and backfilled with silt-water slurry, mixed manually using soil cuttings removed from the hole.

| Exposure Data | ft | m |
|---|---|---|
| Overall pile length | 23.4 | 7.1 |
| Total embedment below ground surface | 20.8 | 6.3 |
| Embedment in permafrost | 16.0 | 4.9 |
| Above ground line | 2.6 | 0.8 |

Condition of Pile:

*Above ground – 2.6 ft (0.8 m):* Thin uniform film of rust over entire surface. No pitting.
*Active region – 4.8 ft (1.5 m) below surface:* Mill scale about 75 percent intact. Metal attack with some pits up to 18 mils (0.4 mm) in the area between 3 to 5 ft (0.9 to 1.5 m) below the ground line. Other pits measured less than 10 mils (0.2 mm) in depth.
*Permafrost region – 4.8 ft (1.5 m) to bottom of pile:* Mill scale 100 percent intact. No evidence of pitting or metal attack.

Photographs of pile specimen A25 are shown in Figure 5.

*Pile No.* A31
*Date pile driven:* August 3, 1952
*Date pile pulled:* July 23, 1963
*Age of pile:* 11 years
*Type of piling:* Light beam, 8B15, 8 in (0.20 m) x 4 in (0.10 m), 15 lb/ft (22 kg/m).
*Method of installation:* Installed in 12 in (0.3 m) diameter steam thawed hole formed by advancing a steam point to full specified pile depth and continuing the steaming until adequate diameter hole was formed. The pile was installed in the existing silt-water slurry in the pile hole resulting from the steaming process. Additional silt-water slurry backfill added near the top of the pile hole as needed.

| Exposure Data | ft | m |
|---|---|---|
| Overall pile length | 23.5 | 7.2 |
| Total embedment below ground surface | 20.4 | 6.2 |
| Embedment in permafrost | 16.0 | 4.9 |
| Above ground line | 3.1 | 0.9 |

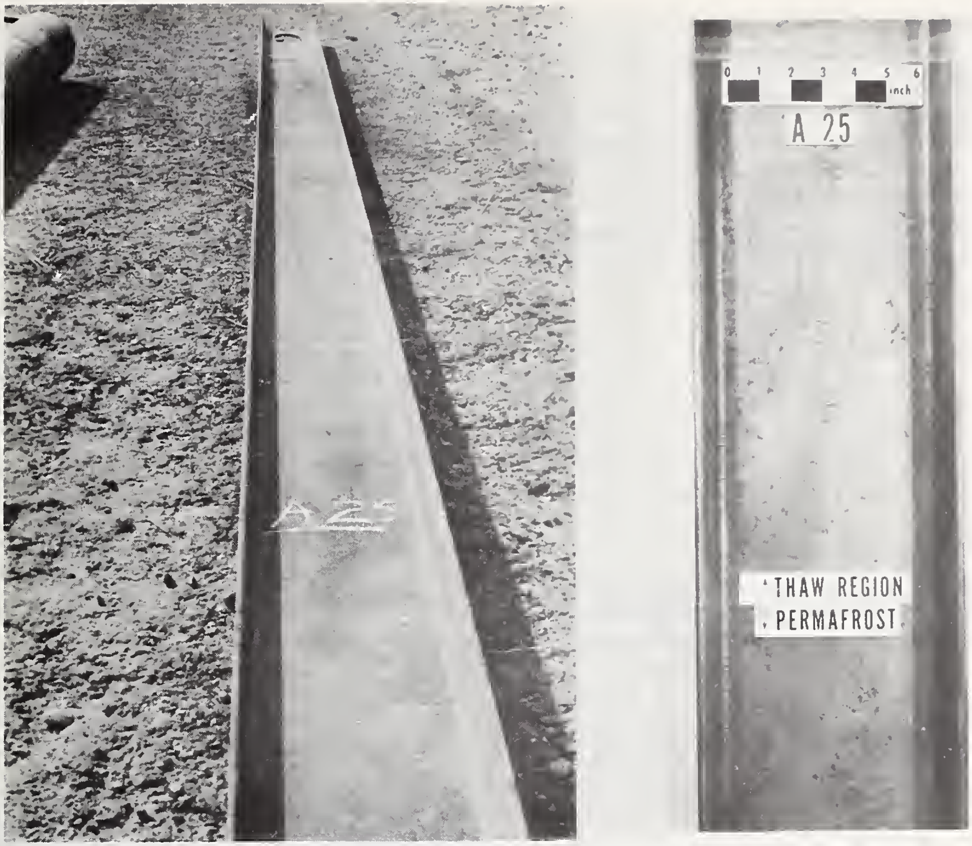


**FIGURE 5 – Pile A25 prepared for inspection in the field (left) and section prepared for inspection in the laboratory (right).**

**Condition of Pile:**

*Above ground – 3.1 ft (0.9 m):* Surface completely covered with thin film of rust. Numerous pits not exceeding 20 mils (0.5 mm) in depth.

*Active region – 4.4 ft (1.3 m) below ground:* Mill scale about 50 percent intact. Slight metal attack in areas where mill scale was removed. No measurable pits greater than 10 mils (0.2 mm) in depth.

*Permafrost regions – 4.4 ft (1.3 m) to bottom of pile:* This section was unaffected by corrosion. Mill scale 100 percent intact.

*Pile No.* A32
*Date pile driven:* July 3, 1952
*Date pile pulled:* July 23, 1963
*Age of pile:* 11 years
*Type of piling:* Light beam, 8B15, 8 in (0.20 m) x 4 in (0.10 m), 15 lb/ft (22 kg/m).
*Method of installation:* Installed in 12 in (0.3 m) diameter steam thawed hole and backfilled exactly as Pile A31.

| Exposure Data | ft | m |
|---|---|---|
| Overall pile length .................... | 23.9 | 7.3 |
| Total embedment below ground surface .. | 20.1 | 6.1 |
| Embedment in permafrost ............ | 15.7 | 4.8 |
| Above ground line .................. | 3.8 | 1.2 |

Condition of Pile:

*Above ground – 3.8 ft (1.2 m):* The entire surface was covered with a thin uniform layer of rust. Isolated shallow pits had a maximum depth of 20 mils (0.5 mm).

There was a weld in the beam at the ground line. Although the weld was rusted, there were no measurable pits.

*Active region – 4.4 ft (1.3 m) below ground:* Mill scale about 60 percent intact. Metal attack and shallow pits present. Pits were less than 20 mils (0.5 mm) in depth.

*Permafrost region – 4.4 ft (1.3 m) to bottom of pile:* Mill scale intact over the entire surface. No evidence of corrosion.

## Site B

*Pile No.* B7D
*Date pile driven:* October 27, 1955
*Date pile pulled:* July 24, 1963
*Age of pile:* 8 years
*Type of piling:* Steel pile, 8 in (0.20 m) diameter, 0.272 in (6.9 mm) wall thickness, 25 lb/ft (37 kg/m).
*Method of installation:* Installed by driving with a No. 7 pile hammer powered by compressed air. The bottom of the pipe pile was open.

| Exposure Data | ft | m |
|---|---|---|
| Overall pile length .................. | 22.5 | 6.8 |
| Total embedment below ground surface .. | 19.5 | 5.9 |
| Embedment in permafrost ............ | 13.0 | 4.0 |
| Above ground line .................. | 3.0 | 0.9 |

Condition of Pile:

*Above ground –3.0 ft (0.9 m):* Surface covered with thin uniform film of rust. There were no measurable pits.

*Active region – 6.5 ft (2.0 m) below ground:* Mill scale about 50 percent intact on the surface. Metal attack and isolated pitting present. Four pits measured between 22 and 27 mils (0.6 and 0.7 mm) in depth. Many pits measured up to 20 mils (0.5 mm) in depth.

*Permafrost region – 6.5 ft (2.0 m) to bottom of pile:* Mill scale intact over entire surface. Surface of pile unaffected by corrosion.

## Site C

*Pile No.* C9
*Date pile driven:* April 23, 1957
*Date pile pulled:* July 24, 1963
*Age of pile:* 6 years
*Type of piling:* Steel H-pile, 10BP42, 10 in x 10 in (0.25 m x 0.25 m), 42 lb/ft (62 kg/m).
*Method of installation:* Installed in 18 in (0.5 m) diameter hole, augered dry and backfilled with machine mixed silt-water slurry using soil cuttings removed from the hole during augering.

| Exposure Data | ft | m |
|---|---|---|
| Overall pile length .................. | 13.8 | 4.2 |
| Total embedment below ground surface .. | 12.3 | 3.7 |
| Embedment in permafrost ............ | 7.3 | 2.2 |
| Above ground line .................. | 1.5 | 0.5 |

Condition of Pile:

*Above ground – 1.5 ft (0.5 m):* Mill scale about 25 percent intact over surface. Rust present on the rest of the surface. No measurable pits visible.

*Active region – 5.0 ft (1.5 m) below ground:* Mill scale about 70 percent intact on the surface. Pit depth, maximum 12 mils (0.3 mm), did not exceed the thickness of the mill scale.

*Permafrost region – 5.0 ft (1.5 m) to bottom of pile:* Surface unaffected by corrosion. Mill scale intact over entire surface. Markings in white paint made on the pile prior to installation were still present and legible.

*Pile No.* C61
*Date pile driven:* April 17, 1957
*Date pile pulled:* July 24, 1963
*Age of pile:* 6 years
*Type of piling:* Steel pile, 8 in (0.20 m) diameter, 0.375 in (9.5 mm) wall thickness, 36 lb/ft (54 kg/m).
*Method of installation:* Installed in 14 in (0.36 m) diameter hole, augered dry and backfilled with machine mixed silt-water slurry using soil cuttings removed from the hole during augering. A flat steel plate was welded over one end of the pipe and the pile installed closed end down.

| Exposure Data | ft | m |
|---|---|---|
| Overall pile length .................. | 21.0 | 6.4 |
| Total embedment below ground surface .. | 20.1 | 6.1 |
| Embedment in permafrost ............ | 15.6 | 4.8 |
| Above ground line .................. | 0.9 | 0.3 |

Condition of Pile:

*Above ground – 0.9 ft (0.3 m):* Mill scale present over 25 percent of surface. No measurable pit depths present.

*Active region – 4.5 ft (0.3 m) below ground:* Mill scale, which was broken in localized area was intact over 75 percent of the surface. No measurable pit depths greater than 10 mils (0.2 mm).

*Permafrost region – 4.5 ft (1.3 m) to bottom of pile:* Mill scale about 90 percent intact over surface. The steel was bright in the areas where the mill scale was broken. No evidence of metal attack or pitting was visible.

*Pile No.* C81
*Date pile driven:* April 26, 1957
*Date pile pulled:* July 24, 1963
*Age of pile:* 6 years
*Type of piling:* Steel H-pile, 6WF25, 6 x 6 in (0.15 m x 0.15 m), 25 lb/ft (37 kg/m).
*Method of installation:* Installed in 14 in (0.36 m) diameter hole, augered dry. Backfilled to 5.5 ft (1.7 m) from ground surface with machine mixed clay-water slurry. Considerable vibrating and rodding was required for placement of the clay-water slurry. Upper 5.5 ft (1.7 m) of pile backfill consisted of silt-water slurry.

| Exposure Data | ft | m |
|---|---|---|
| Overall pile length .................. | 16.9 | 5.1 |
| Total embedment below ground surface .. | 15.5 | 4.7 |
| Embedment in permafrost ............ | 11.5 | 3.5 |
| Above ground line .................. | 1.4 | 0.4 |

Condition of Pile:

*Above ground – 1.4 ft (0.4 m):* Uniform rust over 50 percent of the surface. Mill scale intact over the remaining half of the surface. No measurable pits present.

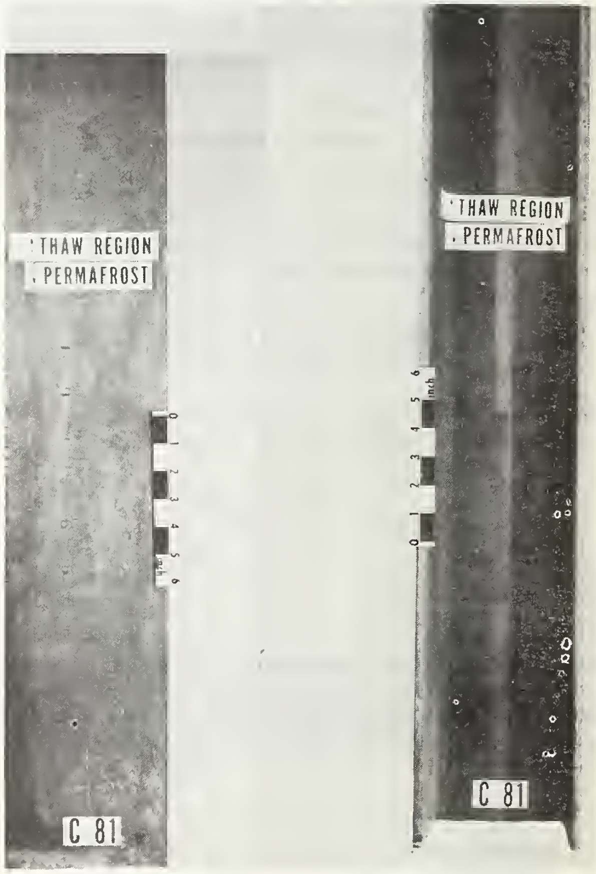


**FIGURE 6 – Condition of flange (left) and web (right) sections from H-pile specimen C81 exposed in the thaw and permafrost regions.**

*Active region – 4.0 ft (1.2 m) below ground:* With the exception of a few pits about 2 ft (0.6 m) below the ground line, which measured up to 18 mils (0.5 mm) in depth, there were no measurable pits greater than 10 mils (0.2 mm) in depth. Mill scale intact over 90 percent of the surface.

*Permafrost region – 4.0 ft (1.2 m) to bottom of pile:* Pile surface unaffected by corrosion. Mill scale intact over entire surface.

Figure 6 shows web and flange views of sections of H-pile C81 exposed in the thaw and permafrost regions.

## Summary

Nine steel test piles exposed in 3 soil sites at the Alaska Field Station of the U. S. Army Regions Research and Engineering Laboratory at Fairbanks, Alaska, were extracted to investigate the extent of corrosion on the piles. Each of the pipe and H-pile specimens was exposed underground for 6, 8 or 11 years in an active horizon in which the soil thaws and freezes annually to a depth of approximately 5 ft (1.5 m) and in permanently frozen soil beneath the active layer.

Test piles were installed to depths of 21 ft (6.4 m) below ground surface by several different methods in soils which varied in texture from silt to clay. The pH of the soils ranged from 5.4 to 7.6. The soil resistivities ranged from 1,350 to 11,500 ohm-cm (Table 3).

Inspections showed that the steel piles were unaffected by corrosion in the permafrost regions. The original mill scale on the test piles was intact over the entire surface in this region.

Although mill scale was removed from as much as 50 percent and as little as 10 percent of test pile surfaces in the active or thaw regions, the extent of corrosion as indicated by metal attack and pitting was insignificant. Except for a few maximum pit depths which ranged up to 28 mils deep (0.7 mm) on two pile specimens (A17 and B7D), pit depths on test piles in the active region did not exceed 20 mils (0.5 mm). This is about the thickness of the original mill scale on the steel surfaces.

There was no evidence of significant corrosion on the test piles at the ground line or at the boundary between the thaw and permafrost regions. Data from these inspections on the performance of steel pilings in permafrost soils are in agreement with those previously published on steel pilings which have been exposed up to 40 years in various underground structures under a wide variety of soil conditions.[1] In the earlier investigation, it was observed in general, that no appreciable corrosion of steel pilings occurred in undisturbed soils 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.

## Acknowledgments

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# PERFORMANCE OF STEEL PILINGS IN SOILS

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Washington, D. C.

## Introduction

The magnitude of corrosion that occurs on steel piling exposed underground is being investigated at the National Bureau of Standards (NBS) with the cooperation of the U. S. Corps of Engineers and the American Iron and Steel Institute.

The results of the first phase of the investigation were published in NBS Monograph 58.[1] Since then, additional data have been obtained from inspections of steel piles after exposure from 6 to 50 years in a wider variety of soil environments in different geographic locations. This paper gives a summary of the results of the inspections made since publication of Monograph 58. It is intended to publish more detailed information on the inspections in the near future to supplement the data in Monograph 58.

## Background on Investigation

Data obtained by the National Bureau of Standards on the corrosion performance of steel piles driven into the ground in a wide variety of soil environments show that the strength and useful life of steel piles are not significantly affected by corrosion.[1] These findings are in sharp contrast to those of earlier corrosion studies in which iron and steel specimens, such as pipe, that are buried under "disturbed" soil conditions exhibit varying amounts of corrosion.[2]

Previous studies of the corrosivity of soils toward metals have been restricted to the behavior of specimens in "disturbed" soils, that is, in trenches or excavations which were dug and backfilled after installation. These studies[2] revealed that the corrosion of ferrous metals varied from negligible to severe in different soil environments. In such instances, the major cause of corrosion was attributed to a nonuniform distribution of oxygen and moisture along the surfaces of the buried metallic structures, which resulted in the formation of oxygen-concentration cells that initiated an electrochemical corrosion process.

The earlier investigations conducted in "disturbed" soils also revealed at least a rough correlation between corrosion and soil properties, such as pH, resistivity and chemical composition. The investigation on steel piles in soils was initiated to determine whether these soil properties also affected the corrosion behavior of steel piling. Steel piles are frequently driven in soils to resist lateral pressures from earth and water, or to transmit loads to lower levels.

To permit examination of entire lengths of piling, some of which had been exposed from 32 to 40 years, H-piling used as load-bearing foundations and sheet piling used as structural members of dams, floodwalls and bulkheads were extracted from eight locations (Table 1). At seven floodwall

TABLE 1 – Steel Piles Extracted from Structures in Prior Inspections[1]

| Structure | Location | Age of Piling yr | Type of Piling | Length of Piling Exposed Below Ground Line ft | m |
|---|---|---|---|---|---|
| Bonnet Carre Spillway | New Orleans, La. | 17 | H | 122 | 37.2 |
| Test piling | Sparrows Point, Md. | 18 | H | 135 | 41.4 |
| Corps of Engineers Lock and Dam No. 8 | Ouachita River, Ark. | 40 | Sheet | 15 | 4.6 |
| Grenada Dam Spillway | Grenada, Miss. | 12 | Sheet | 14 | 4.3 |
| Sardis Dam Outlet | Sardis, Miss. | 20 | Sheet | 3.5 | 1.1 |
| Simpson-Long Bridge, retaining wall | New Orleans, La. | 32 | Sheet | 33 | 10.1 |
| Wilmington Marine Terminal, pile jetty | Wilmington, Del. | 23 | Sheet | 100 | 30.5 |
| Lumber River Bridge, Cofferdam | Boardman, N. C. | 37 | Sheet | 17.5 | 5.3 |

and dam installations where existing structures could not be disturbed, test holes were excavated adjacent to the sheet steel pilings, to expose about an 8-ft (2.4 m) width of piling, for inspection of piling in service in various environments (Table 2). Small pile sections and samples of the soils collected at different levels during the excavations were forwarded to the laboratory for further study.

The inspections listed in Tables 1 and 2 provided information on the behavior of steel piling over a wide range of conditions. For example, backfill material varied in content from riprap, cinders and slag to combinations of sand, silt, loam and clay. Undisturbed natural soils varied from well-drained sands to impervious clays. Soil resistivities ranged from 300 ohm-cm (indicating the presence of large quantities of soluble salts, normally corrosive under "disturbed" soil conditions) to over 50,000 ohm-cm (indicating the absence of soluble salts). The pH of the soils ranged from 2.3 to 8.6.

Results of the inspections[1] disclosed that limited corrosion in the form of highly localized pitting occurred on a few occasions below the water table zone. Laboratory measurements revealed only small or negligible reductions in wall thickness of the pile specimens. The pitting type of corrosion is, of course, of major importance in pipelines or other metal structures designed to carry fluids. But, in piling structures, the depth of scattered pitting is not particularly significant; a uniform reduction in thickness from corrosion of a considerable area of structural surface is much more serious.

Sections of piling exposed to fill soil alone or in the water-table zone appeared to be the most vulnerable to corrosion. However, only localized pitting was generally found and these sections were readily accessible for protection, if necessary.

The survey showed that soil environments which are normally corrosive toward steel specimens buried in "disturbed" soils are not corrosive to steel piling driven into "undisturbed" soils. The difference in corrosion was attributed to differences in oxygen concentration. Apparently, "undisturbed" soils are so deficient in oxygen a few feet below the ground line or below the water-table zone that steel piling is not appreciably affected by corrosion, regardless of soil properties.

It was, therefore, concluded that information on the type, drainage, resistivity, pH, or chemical composition of soils is of no practical value in determining the corrosiveness of soils toward steel piling driven into the ground. Hence, such data should not be used to estimate the corrosion of piling installed in this manner.

## New Inspections Provide More Data

Since publication of NBS Monograph 58,[1] additional data have been obtained from inspections of steel piles exposed underground in a wide variety of soil environments. The inspections were conducted by the same procedures as described elsewhere.

At 18 locations the piles were pulled from the soil for inspection. Data pertaining to 8 of these piles are given in Table 3. Nine piles were pulled from permanently frozen soils, the data for which are presented in another paper.[3] Results of an inspection of a test pile extracted by the Philadelphia Electric Company, in which the writer participated, has been previously published.[4]

TABLE 2 – Steel Sheet Piles Exposed in Excavated Test Holes in Prior Inspections[1]

| Structure | Location | Age of Piling yr | Length of Piling Exposed Below Ground Line ft | m |
|---|---|---|---|---|
| Memphis Floodwall . . | .Memphis, Tenn. | 7 | 9.0 | 2.7 |
| Vicksburg Floodwall . . | .Vicksburg, Miss. | 7 | 8.5 | 2.6 |
| Sardis Dam Spillway . . | .Sardis, Miss. | 20 | 5.0 | 1.5 |
| Grenada Dam Spillway . | .Grenada, Miss. | 11 | 5.5 | 1.7 |
| Berwick Lock . . . . | .Berwick, La. | 11 | 5.0 | 1.5 |
| Algiers Lock . . . . | .New Orleans, La. | 12 | 2.5 | 0.8 |
| Enid Dam . . . . . | .Enid, Miss. | 12 | 5.5 | 1.7 |

At 17 locations, where it was not possible to pull the piles without disturbance to the existing structures, test holes were excavated adjacent to the sheet steel piles to expose a width of piling at each location to a depth below the ground surface which was usually determined by the water table. The soil and corrosion products were removed from the exposed pilings by wire brushing and scraping and the condition of the pile surfaces was determined by visual examination and pit depth measurements.

A portion of the pile web, approximately 1 ft by 2 ft (0.3 m x 0.6 m), was cut from one or more areas of the exposed pile at each location. During excavation of the test holes, soil samples were collected at different depths. The pile specimens and soil samples were shipped to the laboratory for further examination.

Data pertaining to the soil type, resistivity and pH are given with the inspection results for each location in Tables 4 and 5.

Results of the inspections made on bare steel pilings in 13 excavated test holes are given in Table 4, and the results of inspections which were made on steel piles coated with a coal-tar enamel in 4 test holes are given in Table 5.

## Results of Inspections

Tables 3, 4 and 5 show wide variations in the characteristics and properties of the soils at the locations where the steel piles were exposed. The soil types ranged from porous sands to silts and impervious clays and combinations of these types. The soil resistivities ranged from 78 to 45,000 ohm-cm and the pH from 4.1 to 8.8. At many locations the natural "undisturbed" soils were covered by an overlay of fill material which consisted of combinations of materials, such as sand, silt, clay, gravel, cinders, oyster shells and various riprap and rubble.

At most sites the piles were subjected to different soil types in the different horizons which varied in resistivity and pH. Such differences in soil properties at the same location can be expected to promote galvanic-type corrosion by differential aeration or the formation of oxygen concentration cells.

A summary of the condition of the steel piles is given in Tables 3, 4 and 5. Table 3 gives data for 8 piles which were extracted from different structures after exposures from 21 to 50 years. It is interesting to note the absence of significant corrosion on the steel piles, especially on the pile sections exposed in the low-resistivity soils. For example, a maximum pit of only 50 mils (1.3 mm) was measured on the 31-ft (9.4 m) length of pile exposed for 21 years in the stoplog dam structure at Freeport, Texas, in silty clay and clay soils which had a maximum soil resistivity of 350 ohm-cm.

The three 27- to 29-year-old piles pulled from the Mississippi River Lock and Dams Nos. 5, 5A and 7 were exposed to depths of 30 to 40 ft (9.1 to 12.2 m) in soils which varied from sands to clays and ranged in pH from 4.7 to 7.7 and in soil resistivity from 1750 to over 40,000 ohm-cm. Water tables at the 3 sites were located from 2 to 6 ft (0.6 to 1.8 m) below the ground line. Inspection results show that only minor corrosion in the form of slight metal attack and isolated pitting occurred on the sections of the piles exposed in and above the water table zone.[1] The maximum pit depth measured on the three piles was 55 mils (1.4 mm) and the average reductions in wall thickness of the piles were negligible. Below the water table zone the piles were practically unaffected by corrosion, the original mill scale being almost entirely intact over the steel surfaces.

Figure 1 shows the condition of pile sections cut from areas at the water table zone and near the bottom of the pile that was pulled from the Mississippi Lock and Dam No. 5.

The data from the inspections of the remaining four piles which were extracted from structures at Olcott, N. Y., Buffalo, N. Y., Erie, Pa. and Fairport, Ohio (Table 3) show performance similar to that noted for the above piles. The

[1]The water table zone includes 2 ft above and below the mean water table.

**TABLE 3 – Steel Piles Extracted from Structures for Inspection**

| Structure and Location | Age of Piling yr | Type of Piling | Length of Piling Below Ground Inspected ft | m | Depth Below Ground Line ft | m | Soil Characteristics and Properties: Soil Type[1] | pH | Soil Resistivity ohm-cm | Condition of Piling: Maximum Pit Depth[2] mils | mm | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stoplog Dam - Freeport, Tex. | 21 | Sheet | 31.5 | 9.6 | 0-6.5 | 0-2.0 | Silty clay (CL) – water table at 4.5 ft | 7.5 | 150-350 | 50 | 1.3 | Isolated pitting at ground line and water table. |
| | | | | | 6.5-24.5 | 2.0-7.5 | Clay (CH) and silty clay (CL). | 7.2-7.3 | 100-160 | U | — | Unaffected by corrosion. |
| | | | | | 24.5-28.0 | 7.5-8.5 | Clay (CH) and silty clay (CL). | 7.3-7.5 | 78-130 | U | — | Shallow metal attack. |
| | | | | | 28.0-31.5 | 8.5-9.6 | Silty clay (CL). | — | — | U | — | Unaffected by corrosion. |
| Cutoff wall – Mississippi River Lock and Dam No. 5, Minnesota City, Minn. | 29 | Sheet | 35.3 | 10.8 | 1-13 | 0.3-4.0 | Fine to medium sand (SP) – water table at 2 ft | 7.2-7.3 | 36,000 | 10 | 0.2 | Few isolated pits and slight metal attack at water table. |
| | | | | | 13-36 | 4.0-11.0 | Silty sand (SM), fine to medium sand (SP). | 4.7-5.4 | 1860-3400 | U | — | Unaffected by corrosion. |
| Cutoff wall – Mississippi River Lock and Dam No. 5A, Winona, Minn. | 28 | Sheet | 40 | 12.2 | 0-14 | 0-4.3 | Sand, fine to medium (SP) – water table at 6 ft | 7.5-7.7 | 41,000 | 55 | 1.4 | Some pitting in water table zone. Few pit depths measured 28 to 55 mils. Other pits were less than 20 mils. |
| | | | | | 14-20 | 4.3-6.1 | Silty sand (SC). | 6.8-7.2 | 2,660 | U | — | Unaffected by corrosion |
| | | | | | 20-42 | 6.1-12.8 | Sand, fine to medium (SP). | 4.8-5.6 | 14,700 | U | — | Unaffected by corrosion. |
| | | | | | 42-44 | 12.8-13.4 | Sandy silt mixed with clay (ML). | 6.2-7.3 | 1,880 | U | — | Unaffected by corrosion |
| Cutoff wall - Mississippi River Lock and Dam No. 7, Dresback, Minn. | 27 | Sheet | 30.3 | 9.2 | 0-2 | 0-0.6 | Sand, fine to medium (SP) – water table at 2 ft | 7.5-7.6 | 44,000 | 30 | 0.8 | Scattered metal attack and few isolated pits. |
| | | | | | 2-10 | 0.6-3.0 | Sand, cinder-like (SP). | 5.4-6.9 | 1750-8700 | U | — | Unaffected by corrosion. |
| | | | | | 10-22 | 3.0-6.7 | Sandy silt (ML). | 6.8-7.4 | 3100-4000 | 10 | 0.2 | Many small pits not exceeding 10 mils in depth at 10-12 ft and 19-22 ft. |
| | | | | | 22-23 | 6.7-7.0 | Gray gumbo clay (CH). | – – | – – | U | — | Unaffected by corrosion. |
| | | | | | 23-30 | 7.0-9.1 | Sandy silt and silty clay (CL). | 6.7 – | 3400-5000 | U | — | Unaffected by corrosion. |
| Pier-Lake Ontario, Olcott, N. Y. | 50 | I-Beam | 4[3] | 1.2 | 0-0.5 | 0-0.2 | Soil sample not available | – – | – – | 45 | 1.1 | Isolated pits at mud line. |
| | | | | | 0.5-4.0 | 0.2-1.2 | Soil sample not available | – – | – – | U | — | Slight metal attack, no measurable pits. |
| Engineers Slip - Niagara River, Buffalo, N. Y. | 36 | Sheet | 5.5[4] | 1.7 | 0-6 | 0-1.8 | Silty sand (SC) | 7.7-7.8 | 1540-2820 | U | — | Top of pile exposed 3 ft below ground line. No measurable pits. |
| | | | | | 6-8.5 | 1.8-2.6 | Silty sand (SC) with lumps of silty clay (CL) – water table at 8.5 ft | 7.8-8.1 | 1610-1920 | 50 | 1.3 | Uniform metal attack; one pit, 50 mils in depth; other pits did not exceed mill scale thickness. |
| State Groin No 8 – Presque Isle, Erie, Pa. | 32 | Sheet | 3.2[5] | 1.0 | 0-3.2 | 0-1.0 | Sand, fine to medium – water table at 3.2 ft | 7.9 – | 23,000 | 65 | 1.6 | Many pits between 30 and 65 mils in depth near ground line. Few pits up to 45 mils at water table. Uniform rust and metal attack over rest of surface. |
| Coast Guard Slip – Grand River, Fairport, Ohio | 30 | Sheet | 22.3 | 6.8 | 0-5 | 0-1.5 | Fill soil – silty sand with boulders and gravel (SC) | 8.0 – | 4,200 | <20 | <0.5 | Metal attack over most of surface with isolated pit depths. |
| | | | | | 5-8 | 1.5-2.4 | Clay loam (CL) – water table at 8 ft | 7.6 – | 3,500 | <20 | <0.5 | Same as above. |
| | | | | | 8-22.3 | 2.4-6.8 | Fine silt with sand and gravel (SC), blue clay (CH), silty clay with gravel (CL). | 7.2-7.7 | 1120-6000 | U | — | Unaffected by corrosion. Mill scale almost 100% intact. |

[1]Letters in parentheses are the group symbols for classifying soil types according to the Unified Soil Classification System for Roads, Airfields, Embankments and Foundations. Military Standard MIL-STD 619 A (March 20, 1962). Department of Defense, Washington, D. C.

[2]U, indicates that there were no pits of measurable depth.

[3]A 10-ft (3.0 m) length of the pile was extracted. The top 2 ft (0.6 m) was exposed to the atmosphere, 4 ft (1.2 m) exposed in water and 4 ft (1.2 m) exposed below the mud line. The section in the atmosphere had uniform metal attack and isolated pits up to 40 mils (1.0 mm) in depth. The section in water was severely corroded, causing perforation of the wall thickness of the pile.

[4]Attempts to pull this pile were unsuccessful. An excavation was made down to the water table and the upper 5.5 ft (1.7 m) section of the pile was removed by cutting.

[5]Attempts to pull this pile were unsuccessful. An excavation was made down to the water table and the upper 6.7 ft (2.0 m) section of the pile was removed by cutting. The upper 3.5 ft (1.1 m) of the pile was exposed to the atmosphere.

TABLE 4 - Bare Sheet Piles Inspected in Excavated Test Holes

| Structure and Location | Age of Piling Yr | Length of Piling Exposed Below Ground ft | m | Depth Below Ground Line ft | m | Soil Type(1) | pH | Soil Resistivity ohm-cm | Maximum Pit Depth(2) mils | mm | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Floodwall - Harrisburg, Ill. | 22 | 5 | 1.5 | 0-5 | 0-1.5 | Fill soil-silty clay mixed with gray silt (CL). | 7.8-7.9 | 1800-3000 | - | - | Piling in concrete cap. |
| | | | | 5-10 | 1.5-3.0 | Silty clay (CL)-water table at 5 ft. | 7.9-8.0 | 1800-2770 | <10 | <0.2 | Scattered pits did not exceed the thickness of the mill scale which was about 90% intact. |
| Floodwall - Louisville, Ky. | 13 | 6 | 1.8 | 0-6 | 0-1.8 | Brown firm clay and organic silty clay (CL,OH). | 4.3-4.7 | 6500-8800 | <10 | <0.2 | Top 5-ft of piling encased in concrete. No pits beyond thickness of mill scale which was about 80% intact. |
| | | | | 7-11 | 2.1-3.3 | Stiff clay (CH) - water table below 11 ft. | 4.1-6.4 | 1420-2560 | <10 | <0.2 | Same as above. |
| Floodwall - Jeffersonville, Ind. | 20 | 4.5 | 1.4 | 0-3 | 0-0.9 | Fill soil-clay, cinders and gravel. | - - | 10,000+ | - | - | Piling capped with concrete from 0 to 7 ft. |
| | | | | 3-11.5 | 0.9-3.5 | Brown firm clay with tan organic matter (CH); tan firm silty clay (CL). | 4.3-5.2 | 4810-7620 | <10 | <0.2 | No pits beyond thickness of mill scale which was about 70% intact. |
| Guidewall, Colorado River Locks - Matagorda, Tex. | 16 | 16 | 4.9 | 0-1 | 0-0.3 | Fill, top soil-silty clay (CL). | 7.6 | 1810-1920 | <20 | <0.5 | Slight metal attack; depth of pits penetrated slightly beyond mill scale thickness. |
| | | | | 1-12 | 0.3-3.7 | Fill consisting entirely of broken oyster shells. | - - | - - | 70 | 1.8 | Uniform corrosion with many pits up to 70 mils in depth. |
| | | | | 12-16 | 3.7-4.9 | Natural soil-silty clay (CL) with considerable line-water table at 16 ft. | 7.3-7.8 | 600-1540 | <10 | <0.2 | Few pits not exceeding the thickness of mill scale. |
| Guidewall, Brazos River Floodgates - Freeport, Tex. | 16 | 14 | 4.3 | 0-1 | 0-0.3 | Silty clay (CL) and organic silt clay (OL). | 7.8-8.4 | 600-980 | 20 | 0.5 | General metal attack with isolated pits. |
| | | | | 1-8 | 0.3-2.4 | Fill consisting of clay (CH) mixed with broken shells-water table at 8 ft. | 7.9 | 485-750 | 90 | 2.3 | Metal attack over most of surface with scattered pitting. Deepest pits (90 mils max.) occur about 2 ft from surface. |
| | | | | 8-14 | 2.4-4.3 | Same as above. | - - | - - | <10 | <0.2 | Slight metal attack and shallow pitting. |
| Drain outlet, Clinton River Flood Control Project - McComb County, Mich. | 11 | 10 | 3.0 | 0-5 | 0-1.5 | Silty clay (CL) with organic matter and clayey sand (ML). | 7.2-7.6 | 1350-3300 | 15 | 0.4 | Mill scale intact over 90% of surface. Few isolated pits not exceeding mill scale thickness. |
| | | | | 5-10 | 1.5-3.0 | Stiff clay (CH)-water table below 10 ft. | 7.2-7.4 | 940-3000 | U | - | Mill scale intact over entire pile surface. No corrosion. |
| Floodwall - North Little Rock, Ark. | 24 | 10 | 3.0 | 0-4 | 0-1.2 | Fill-very fine silty sand (SC) with beads of clay (CH) dispersed throughout. | .3 | 9500 | 30 | 0.8 | Top 2 ft of pile capped with concrete. Isolated pitting. Mill scale 90% intact. |
| | | | | 4-5 | 1.2-1.5 | Clay(CH). | 7.4 | 1800-1890 | 50 | 1.3 | Isolated pitting; mill scale 70% intact. |
| | | | | 5-12 | 1.5-3.7 | Very fine silty sand (SC)-water table below 12 ft. | 8.2 | 9800-11,000 | 20 | 0.5 | Mill scale about 90% intact. Scattered pits not exceeding 20 mils in depth. |
| Seawall - Charleston, S. C. | 24 | 15 | 4.6 | 0-8 | 0-2.4 | Fill-sand (SP) with clay lumps. | 8.3 | 750-2500 | 95 | 2.4 | Scattered pitting most prevalent between 2 to 4 ft from surface. Many pits between 40-75 mils. Few pits between 75-95 mils in depth. |
| | | | | 8-15 | 2.4-4.6 | Clay (CH)-water table at 12 ft. | 7.2 | 325-400 | U | - | Mill scale practically entirely intact. No corrosion. |
| Diversion Dam, Jemez River - San Ysidro, N. M. | 27 | 10 | 3.0 | 0-8 | 0-2.4 | Fill-fine to coarse sand (SP) with gravel-water table at 7 ft. | 7.8-8.8 | 1855-40,000 | U | - | Limelike crust over entire surface of steel. Slight metal attack in some areas. No measurable pits. |
| | | | | 8-10 | 2.4-3.0 | Sandy silt (ML) | 7.6-7.7 | 1650-2310 | U | - | No corrosion. |
| Bridge abutment retaining wall - Lamar, Colo. | 14 | 9.5 | 2.9 | 0-2 | 0-0.6 | Fill-clayey silt (ML) with gravel and lime concretions. | 7.2-7.6 | 1160-1475 | 25 | 0.6 | Metal attack over most of surface and scattered pitting. |
| | | | | 2-6 | 0.6-1.8 | Silty sand (SM) and gravelly sand (SP)-water table fluctuates seasonly between 2 to 11 ft. | 7.9-8.3 | 31500 | 110 | 2.8 | Shallow metal attack over most of surface. Many pits up to 30 mils in depth. Three pits between 90 and 110 mils. |
| | | | | 6-9.5 | 1.8-2.9 | Gravelly sand (SP) | 8.2 | 10100 | <10 | <0.2 | No pit beyond thickness of mill scale which was about 75% intact. |
| Gate structure Hartford Dike, Hartford, Conn. | 23 | 10 | 3.0 | 0-10 | 0-3.0 | Fill soil. | - | - | - | - | Piling capped with concrete. |
| | | | | 10-14 | 3.0-4.3 | Fill-clayey silt (ML). | 6.2 | 23000 | 40 | 1.0 | Shallow metal attack. Few pits up to 40 mils in depth. |
| | | | | 14-16 | 4.3-4.9 | Fill-sandy silt (ML) with clay (CL) and cinders | 7.8 | 2090-3500 | 170 | 4.3 | Scattered pitting up to 170 mils over 15% of surface. |
| | | | | 16-20 | 4.9-6.1 | Fill-sand and sandy silt (SP) and much cinders. Water table-varies with river stage up to top of pile | 7.6 | 4600 | 220 | 5.6 | Scattered deep pits up to 220 mils over 10% of surface. |
| Seawall jetty-Snake River - Nome, Alaska | 30 | 5 | 1.5 | 0-5 | 0-1.5 | Fill-clay silt (ML), sandy silt (ML), sand (SP) and cinders-water table below 5 ft. | 6.2-7.8 | 600-4800 | 80 | 2.0 | Shallow isolated pits less than 20 mils over about 30% of surface. Many pits between 22 and 80 mils in depth |
| Floodwall-Omaha, Neb. | 14 | 3 | 0.9 | 15-18 | 4.6-5.5 | Clayey silt (ML) and silty clay (CL)-water table at 20 ft. | 6.9-8.0 | 700-1500 | 50 | 1.3 | Many shallow pits did not exceed the thickness of the mill scale which was 40% intact. Few pits between 20 to 50 mils in depth. |

(1) Letters in parentheses are the group symbols for classifying soil types according to the Unified Soil Classification System for Roads, Airfields, Embankments and Foundations, Military Standard MIL-STD 619 A (March 20, 1962), Department of Defense, Washington, D. C.

(2) U, indicates that there were no pits of measurable depth.

**TABLE 5 – Coated Steel Sheet Piles(1) Inspected in Excavated Test Holes**

| Structure and Location | Age of Piling yr | Length of Piling Inspected Below Ground ft | m | Depth Below Ground Line ft | m | Soil Type(2) | pH | Soil Resistivity ohm-cm | Maximum Pit Depth(3) mils | mm | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Floodwall – Memphis, Tenn. | 8 | 15 | 4.6 | 0-12.5 | 0-3.8 | Fill soil – clayey silt (ML) with cinders, glass, brick, decomposed wood and metallic waste – water table at 12.5 ft. | 6.8-7.5 | 850-1470 | 60 | 1.5 | Mill scale on steel surface was about 90% intact. Scattered areas of metal attack and pitting. Many pits between 40-60 mils in depth. |
| | | | | 12.5-15 | 3.8-4.6 | Similar to above. | 7.3-7.6 | 780-1440 | U | – | Unaffected by corrosion. |
| Chamber wall, Pearl River Lock No. 1 – Pearl River, La. | 16 | 20 | 6.1 | 0-17 | 0-5.2 | Sand with gravel (SP) – water table fluctuates between 0-17 ft. | 5.1-7.2 | 30000-45000 | 40 | 1.0 | Scattered small pits between 15 to 40 mils in depth. |
| | | | | 17-20 | 5.2-6.1 | Sand with gravel (SP). | 5.1-6.6 | 30000-40000 | – | – | Unaffected by corrosion. |
| Floodwall – Newport, Ark. | 24 | 6 | 1.8 | 0-5 | 0-1.5 | Fill – silt and friable clay (ML, CL) with organic matter and cinders. | – – | 5000-9000 | – | – | Top 6 ft of pile capped with concrete. |
| | | | | 5-11 | 1.5-3.3 | Friable clay (CL) – water table at 9 ft. | 5.9-6.1 | 2800-3870 | U | – | Mill scale practically 100% intact. No corrosion. |
| | | | | 11-12 | 3.3-3.6 | Stiff clay (CH). | 6.9-7.1 | 1650-2040 | U | – | No corrosion. |
| Wingwall, St. Lucie Canal – Stuart, Fla. | 24 | 12.5 | 3.8 | 0-5.5 | 0-1.7 | Fill – sand (SP) and silty sand (SC) with shells and lumps of clay. | 7.8-8.1 | 10700-19000 | 72 | 1.8 | Isolated pits up to 72 mils in depth. Mill scale about 80% intact. |
| | | | | 5.5-8.0 | 1.7-2.4 | Silty sand (SC) and sandy clay (CL). | 7.4-7.9 | 1550-3860 | 10 | 0.2 | Mill scale about 95% intact. Coating peeled in many areas. No pits greater than 10 mils in depth. |
| | | | | 8.0-12.5 | 2.4-3.8 | Silty sand (SC) and clay (CH) – water table at 12.5 ft. | 7.2-7.7 | 480-3600 | 10 | 0.2 | Same as above. |

(1) Steel piles coated with coal-tar enamel before installation.
(2) Letters in parentheses are the group symbols for classifying soil types according to the Unified Soil Classification System for Roads, Airfields, Embankments and Foundations, Military Standard MIL-STD 619 A (March 20, 1962), Department of Defense, Washington, D. C.
(3) U, indicates that there were no pits of measurable depth.

maximum pit found on all the piles listed in Table 3 was 65 mils (1.7 mm) in depth.

Figure 2 shows a section of a 50-year-old I-beam that was extracted from a pier in Lake Ontario at Olcott, N. Y. The photograph shows part of the 4-ft (1.2 m) section of the pile which was exposed below the mud line. No measurable pits were found in this section, except for the few isolated pits (maximum depth 45 mils) which occurred at the mud line. The 4-ft (1.2 m) section of the same pile exposed in the water above the mud line was severely corroded.

The condition of sections cut from piles which were pulled from a 36-year-old structure at Buffalo, N. Y. and a 30-year-old structure at Fairport, Ohio, are shown in Figures 3 and 4, respectively.

DeMarco[4] reported the results of an inspection in which the author participated of a test H-pile pulled at the Eddystone Generating Station in Philadelphia, after exposure for 5 1/2 years in a location where acid leachings from a coal pile caused severe contamination of the subsoil. The 45-ft (12.7 m) H-pile was exposed in a porous river sand to a depth of 37 ft (11.3 m) below the ground line, which was underlain by silt. The pH of the soils from the ground line to the bottom of the pile ranged between 4.6 and 6.4; the soil resistivity ranged between 1600 and 17,500 ohm-cm. The water table was at approximately 15 ft (4.6 m) below the ground line.

DeMarco concluded that, generally, the pile was only mildly corroded with minor pitting in the water table area. The maximum pit measured was 55 mils (1.4 mm), while the average reduction in wall thickness was estimated at less than 10 mils (0.2 mm). From the examination of the test pile removed and other measurements made throughout the station, it is anticipated that the service life of the structural piles will not be impaired by corrosion in the existing soil environments, even in contaminated material below the coal pile.

In another paper,[3] the writer reported the results of inspections to investigate the corrosion of steel pilings in permanently frozen soils. Nine steel test piles exposed in 3 soil sites at the Alaska Field Station of the U. S. Army Cold Regions Research and Engineering Laboratory at Fairbanks, Alaska, were extracted to investigate the extent of corrosion on the piles. The pipe and H-pile specimens were exposed underground for 6, 8 or 11 years in an active horizon in which the soil thaws and freezes annually to a depth of approximately 5 ft (1.4 m) and in permanently frozen soil beneath the active layer. Test piles were installed to depths of 21 ft (6.4 m) below ground surface by several different methods. Inspections show that the steel piles are unaffected by corrosion in the permafrost regions and that there was no evidence of significant corrosion at the ground line either in the active or thaw region or at the boundary between the thaw and permafrost regions.

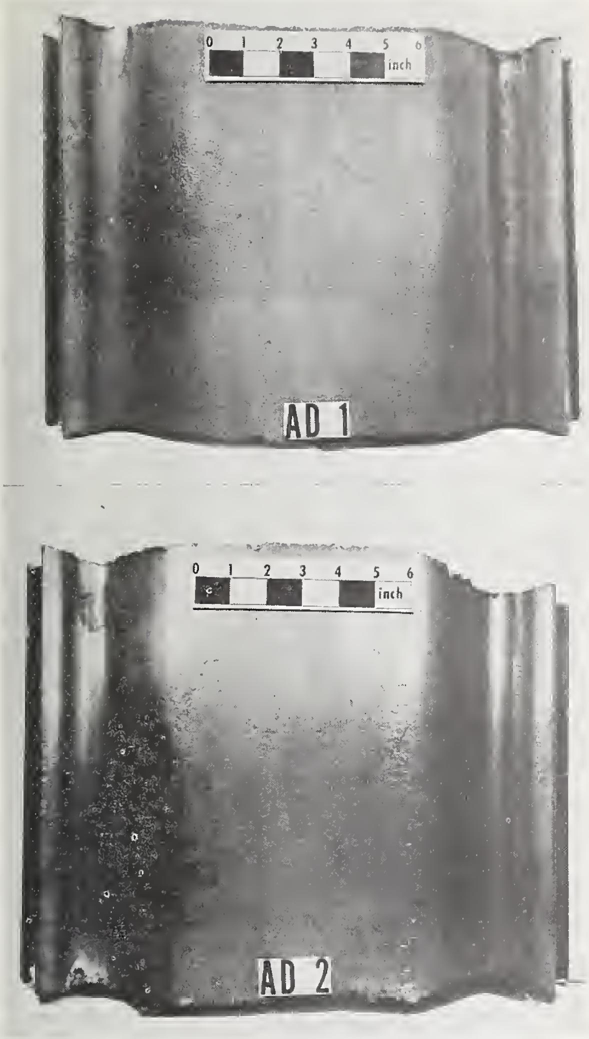


**FIGURE 1 — Sections from the 29-year-old sheet piling pulled from a cut off wall in the Mississippi River Lock and Dam No. 5 near Winona, Minn. Top—Section exposed about 2 to 4 ft below the ground line in the water table zone. Bottom—Section exposed about 33 ft below the ground line.**


**FIGURE 2 — Section of steel I-beam pulled from a pier on Lake Ontario at Olcott, N. Y., after exposure for 50 years. The section was exposed about 2 ft below the mud line and was practically unaffected by corrosion.**


**FIGURE 3 — Section of steel sheet-pile pulled from an engineer's slip on the Niagara River at Buffalo, N. Y., after exposure for 36 years. The section was exposed about 8 ft below the ground line in the water table zone.**

## Results of Other Tests

Tables 4 and 5 give the results of inspections performed on 13 bare steel piles and 4 coated steel piles exposed in excavated test holes after exposures up to 30 years. Here again it will be noted that there are large differences in the soil types and properties at the different locations and at different horizons at the same location. At all but three locations (Louisville Floodwall, McComb County Drain Outlet and Omaha Floodwall), where the bare steel piles were examined in excavations, the "undisturbed" natural soil was overlain by fill material (Table 4).

At three locations (Freeport Guidewall, Hartford Dike and the Nome Seawall), the bare pile specimens inspected were completely embedded in fill material.

The data from the examinations of the bare pile specimens show, with one exception, that corrosion was limited to shallow metal attack and isolated pitting on


**FIGURE 4 – Sections from the 30-year-old sheet pile extracted from a Coast Guard slip on Grand River at Fairport, Ohio. Top–Section exposed between 4 to 7 ft below the ground line in fill soil and in the water table zone, showing slight metal attack over most of the surface. Bottom–Section cut from bottom of pile about 22 ft below the ground line, unaffected by corrosion.**

surfaces of the pile sections that were exposed in fill material, above the water table, or in the water table zone. The corrosion was generally confined in the upper portions of the piles. At 5 locations, the pits on the bare piles did not exceed the thickness of the mill scale on the steel surfaces. Although pits between 70 and 110 mils (1.8 and 2.8 mm) in depth were found on five of the piles, the extent of corrosion cannot be considered appreciable with respect to the useful life of the structures. The isolated or localized pits resulted in only negligible or small reductions in wall thickness of the pile specimens.

The exception occurred on the 23-year-old sheet piling exposed in the Hartford Dike in connection with construction of a gate structure at the South Meadows Power Station. The structure was embedded entirely in fill soil


**FIGURE 5 – Section of steel-sheet pile cut from an underground gate structure of the Hartford Dike at Hartford, Conn., after exposure for 23 years. There were deep pits over the entire steel structure which was exposed in fill soil, containing a considerable amount of cinders. The water table at this location fluctuated from the bottom to the top of the pile with the river stage.**

which contained up to 90 percent cinders. Severe metal attack and deep pitting up to 220 mils (5.6 mm) in depth occurred over large areas of the pile surfaces. The deepest pits were observed below the 14 ft (4.3 m) level. During the period of one year, the 10-ft (3.0 m) length of piling examined was subjected to a water table at all levels because the water table at this location fluctuates considerably with the river stage.

Figure 5 shows the extent of corrosion on a section cut from the piling in the Hartford Dike.

A section of bare steel piling removed from the Jeffersonville Floodwall after exposure for 20 years is shown in Figure 6. The pit depths did not exceed 10 mils (0.2 mm) on this structure.

Figure 7 shows the corrosion on a section of pile cut from the 27-year-old floodwall at North Little Rock, which occurred in the transition layer between the fill and natural soils. The maximum depth of pitting was 50 mils (1.3 mm) on this structure.

Figure 8 shows a section of piling after exposure in fill soil containing cinders for 30 years in the seawall jetty at the mouth of the Snake River at Nome, Alaska.

The only corrosion observed on the 4 coated piles which were inspected in the excavated holes (Table 5) occurred in the upper sections of the structures exposed in fill soil and in water table areas. The corrosion was limited to localized pits and shallow metal attack.

## Discussion and Conclusions

The observations reported in this paper are in agreement and substantiate the observations and conclusions based on the results of the previous examinations on steel pile structures which are published in NBS Monograph 58.[1]

The data show that, in general, steel pilings are not significantly affected by corrosion in undisturbed natural soils, regardless of the soil types and soil properties. Only minor or moderate corrosion in the form of shallow metal attack or localized pitting occurred on the upper portions of the pile structures which were exposed in fill or in soils above or in the water table zone. The average reduction in wall thickness on any of the piles examined was not of sufficient significance to impair the useful life of the structures.

Corrosion of any consequence which may possibly have an effect on a longer life of the structure was observed at only one location where the piling was exposed in a fill contaminated with cinders. Even at this site, despite the deep pitting observed, the structure was still serving its useful purpose after exposure in the environment for 23 years.

It will be observed from the data in Tables 3, 4 and 5 that soil environments which can be predicted to be severely corrosive to iron and steel under disturbed conditions in excavated trenches[2] were not corrosive to steel pilings driven in undisturbed soils. This observation was also made in the previous report[1] concerned with the earlier pile investigations. The difference in corrosion was attributed to the differences in oxygen concentration. It was indicated that undisturbed soils are so deficient in oxygen at levels a few feet below the ground line, or in and below the water table zone, that steel pilings are not appreciably affected by corrosion, regardless of the soil types or the soil properties.


**FIGURE 6 – Section cut from a steel sheet pile about 10 ft below the ground in a floodwall at Jeffersonville, Ind., after exposure for 20 years.**

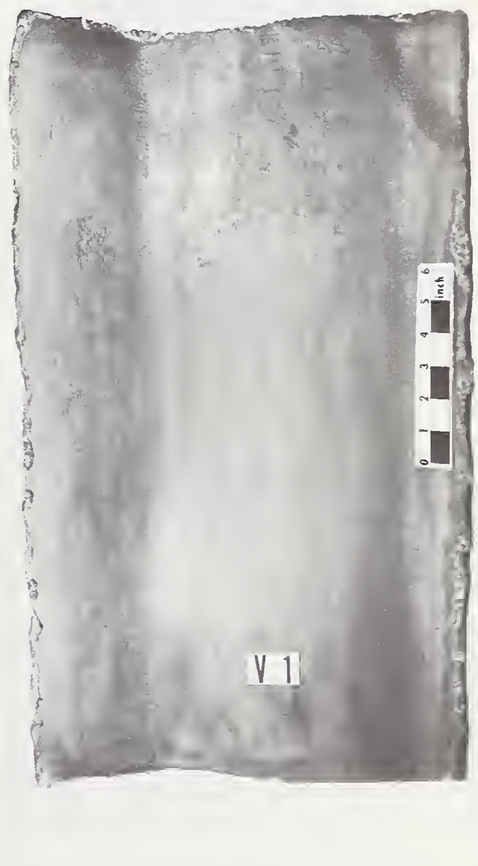


**FIGURE 7 – Steel sheet pile section cut from a floodwall at North Little Rock, Ark., after exposure for 24 years. The section was exposed between 3 to 5 ft below the ground line in fill soil underlain by natural clay soil. The depth of pitting did not exceed 50 mils.**

assumed that the oxygen concentration of the soil decreases with depth, especially below the water table.

In such a galvanic cell, the upper portion of the pile which is, in general, a much smaller part of the entire pile length will be cathodic to the much larger portion of the pile driven into the natural soil which is more deficient in oxygen. The resulting galvanic cell, therefore, consists of a small cathode (upper portion of pile) and a huge anode (lower portion of pile). The area relation between the anode and cathode would, of course, depend on the total length of the pile; the longer the pile, the greater the anode area. Because of the large differences in area between the cathode and anode, the amount of iron sacrificed by the anode in protecting the relatively small cathode is negligible.

To investigate this hypothesis, an installation of test piles was made during September 1966 in Montreal, Quebec. Steel H-pile specimens were driven about 35 ft (10.7 m) to bedrock through 8 ft (2.4 m) of a sand-silt-cinder fill which is underlain by natural soil layers consisting of sand, peat, marl, clay, silt and gravel. The soil resistivities at the sites range from 400 to 5000 ohm-cm. It is expected that the data to be obtained from periodic inspections will provide valuable information to supplement the data obtained on the performance of steel piles in soils.

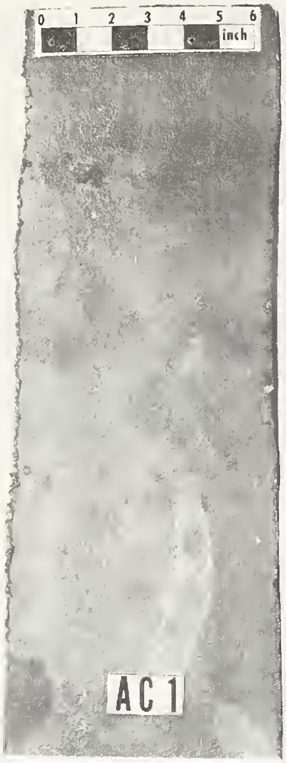


**FIGURE 8 — Underground section of sheet pile cut from a seawall jetty at the mouth of the Snake River at Nome, Alaska, after exposure for 30 years. The section was exposed in fill and cinder soil just above the water table.**

This reasoning does not seem to fully explain the presence of only minor or moderate corrosion or the absence of high corrosion rates on the upper portions of steel piling exposed in low resistivity fill or natural soils near the surface, in or above the water table zones. It is possible that the little corrosion observed on these portions of the piles occurred during the early exposure periods due to the corrosive environment. In time, a large galvanic corrosion cell is created between the upper portion of the pile structure, which lies in the fill or above the water table, and the lower portion of the pile structure. It can be

## Acknowledgment

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# Polarization Measurements as Related to Corrosion of Underground Steel Piling

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Most of this paper is devoted to the author's evaluation of polarization measurements made by the Corps of Engineers (Lower Mississippi Valley Division) on steel pipe specimens exposed to the soil at four dam sites as related to the corrosion of steel piling (underground) observed at the sites. As the polarization measurements were made periodically on weighed specimens for periods as long as seven years, the Corps' data offered an excellent opportunity for evaluating the accuracy and practicability of a polarization technique for measuring corrosion rates. Reasonable agreement between calculated and actual corrosion on the specimens made it possible to estimate maximum anticipated corrosion on the piling after 50 years of exposure.

Confidence gained in the value of polarization measurements made on short length pipe specimens led the author to make measurements on actual piling. Instantaneous corrosion rates were measured on two driven pipe piles, 72 ft (22 m) and 19 ft (5.8 m) in length, both of which had been exposed for 12 years. One month later, the short pile was extracted and examined. Relatively low corrosion rates calculated from the polarization data were verified by the appearance of the pile and by the limited extent of the pitting.

Key words: Corrosion; corrosion rate; disturbed soil; instantaneous rate; pit depth; pitting factor; polarization; steel piling; undisturbed soil; weight loss.

## 1. Introduction

Corrosion observed on structural steel piling exposed to underground environments based on visual inspection and measurements of pit depth has been described by Romanoff [1].[1] His inspections were made in cooperation with the Corps of Engineers (Lower Mississippi Valley Division) and the American Iron and Steel Institute. During the course of an investigation at four dam sites, where piling had been examined, Romanoff decided to expose steel pipe specimens, arranged in groups of four, to the same underground environments nearby. One specimen of each group was wired to enable periodic monitoring of instantaneous rates of corrosion by polarization measurements. The groups of specimens were removed from each site at intervals of 1, 2, 4, and 7 years.

The buried specimens, exposed to back-filled trenches, served a two-fold purpose. Romanoff [1] reported that steel exposed to excavated soils was subject to more severe corrosion than that which he observed on driven piling for a given environment. Thus, the steel specimens would provide the opportunity for comparing corrosion under the two conditions of exposure (driven or buried). Secondly, they offered an excellent chance for evaluating the accuracy and practicability of a polarization technique for measuring corrosion. The method was evaluated by comparing the cumulative metal losses (based on Faraday's law) of the wired specimens with their actual weight losses.

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

Past work has demonstrated that instantaneous rates of corrosion on pipe specimens in situ can be measured by a polarization technique and averaged for periodic intervals in calculating metal losses resulting from corrosion for a given period of exposure [2]. As exposure time for some of the Corps of Engineers' specimens extended over a period of 7 years, an excellent opportunity prevailed for a further evaluation of the technique as applied to underground corrosion. Furthermore, it became possible to monitor corrosion rates at each of the four sites over a period of 7 years. By thus monitoring corrosion rates, the length of exposure time required to obtain reliable performance data of metals exposed to a given environment can be estimated.

Romanoff [1] concluded, based primarily on visual observation and experience, that iron exposed to soil in backfilled trenches is more severely corroded than when exposed to the same soil (undisturbed). Romanoff referred to undisturbed soil as that soil adjacent to driven piling below the backfilled soil. In order to further substantiate this conclusion, Romanoff exposed iron pipe specimens to excavated trenches in the same areas where driven piling had previously been visually examined. The Corps of Engineers, responsible for making the polarization measurements, also exposed iron rods, limited in number, by driving some of them into the soil and by exposing other identical rods to excavated soil nearby. The National Bureau of Standards prepared weighed pipe specimens for the burial program. The rod specimens were prepared by the Corps of Engineers. The Corps furnished the Bureau with copies of the polarization curves obtained at the periodic intervals. During the period of 7 years, all specimens involved in four removals were sent to the Bureau for cleaning and determination of metal losses.

In a recent report [3] by the Corps of Engineers on the corrosion of underground steel piling, the results of measurements made on the pipe and rod specimens are included. Included in that report are the weight losses and maximum pit depths on all specimens, pipe and rod, unwired and wired. Estimated weight losses based on electrical measurements are summarized and discussed in relation to what was observed on nearby piling.

In this paper, the polarization curves submitted to NBS by the Corps of Engineers are evaluated by the Bureau. This accounts for any differences (averaging 9%) between the Corps estimated weight losses and the calculated weight losses tabulated herein. Stabilized corrosion rates, based on polarization measurements made on the wired seven-year pipe specimens in back-filled trenches, are expressed as average penetration and compared with the maximum corrosion observed on piling at the same sites exposed from 11 to 20 years.

Recently, the writer became aware of some isolated steel pipe piles located on the grounds of a sewage disposal plant. It was suggested that it might be of interest to make polarization measurements on one or more of the driven piles which were exposed to the soil for 12 years. The results of measurements and calculated rates of corrosion for two 12.75 in (32.5 cm) diam piles 72 ft (22 m) and 19 ft (5.8 m) long are described.

## 2. Experimental Procedure

### 2.1. Preparation of Pipe and Rod Specimens

Sixteen pipe specimens were prepared for burial at each of four sites. The specimens were cut from standard black iron pipe 1.5 in (3.8 cm) diam to lengths of 14 in (35.5 cm). Loose mill scale was removed and the specimens were deburred, degreased and weighed to the nearest 50 mg. The inside of the pipe was coated with heavy grease and rubber caps were placed over the open ends so as to confine corrosion to the outer surface area 0.5 $ft^2$ (4.6 $dm^2$) approx. One of each set of four specimens, constituting a set for removal, was equipped with an insulated copper wire soldered to the inside of the pipe and brought through a hole in the center of one of the rubber caps. The pipes were placed laterally in the trench about 12 in (30.5 cm) apart and buried horizontally about 3 ft (0.92 m) below the earth's surface. The wires to specimens terminated above ground in boxes mounted on wooden posts.

The number of rod specimens was limited to two at each of the four sites. One of the rods was exposed vertically positioned in back-filled soil and the other rod was driven off to the side about 18 in (46 cm) away. The rods were cut from hot-rolled steel 0.75 in (1.9 cm) diam to 3 ft. (0.92 m) lengths. They were cleaned and weighed as previously mentioned for the pipe specimens. Both rods were equipped with insulated copper wires terminating above ground. The top 5 in (12.7 cm) of each rod, including the wire connection, was coated with coal tar. This again left about 0.5 $ft^2$ (4.6 $dm^2$) of bare surface for exposure to the soil, the same as for the pipe specimens.

### 2.2. Polarization Measurements — Pipe and Rod Specimens

A galvanized steel pipe 1 in (2.54 cm) diam and five ft (1.5 m) long was driven at each site for use as an auxiliary electrode. Polarization measurements were made by the Corps of Engineers [3] at intervals of from 3 to 7 months approximately. When making polarization measurements in soil environments, it is usually necessary to use a bridge circuit because changes in measured potential caused by the IR drop through the soil may be sufficient to obscure changes due to actual polarization. The Holler bridge circuit, originally described by Holler [4] and more recently by Schwerdtfeger [5], was used by the Corps of Engineers at the test sites. For running the polarization curves, equal increments of current were applied at one minute intervals.

### 2.3. Removal of Corrosion Products from the Specimens

The pipe and rod specimens were returned to the Bureau for cleaning after exposure to the soils. They were scrubbed under hot running water to remove soil and loose corrosion products. The rubber caps were removed from the pipe specimens and grease inside the pipes was melted out by applying heat from a torch flame. Following degreasing, the specimens were immersed in a hot solution (150 °F) of 10 percent ammonium citrate neutralized with ammonium hydroxide. Length of immersion time varied with the degree of corrosion, being usually not over five hours. Ammonium hydroxide was added as required to keep the solution on the neutral to alkaline side. Specimens were intermittently scrubbed with a steel-bristle brush to remove corrosion products down to bare metal. The rod specimens were freed of corrosion products in the same way. Solder was melted and scraped from those specimens which had wire leads. Finally, all specimens were again weighed to the nearest 50 mg.

### 2.4. Polarization Measurements on Pipe Piling in Situ

Polarization curves were obtained on bare pipe piling driven 12 years previously on property of the Hiawatha Treatment Plant at Syracuse, N. Y. Measurements were made on two 12 in diam (30.5 cm) pipe piles, 72 ft (22 m) and 19 ft (5.8 m) in length. The auxiliary anode was a third pipe pile driven to a depth of 122 ft (37 m). The piles were separated by a distance of about 5 ft (1.5 m). The reference electrode was copper-copper sulfate placed on the earth's surface at a distance of about 50 ft (15.2 m) from the top of the pile being measured.

An adaptation of the Holler bridge (fig. 1) was used by the Bureau to obtain the polarization curves. It will be noted that terminals are provided for inserting other control resistors, $R_s$ and $R_x$, should specimen size or environmental conditions make that necessary. For running the curves on the piling, the 0.5 Ω balancing resistor $R_x$ was used and the other balancing resistors were set at zero. A 12-volt storage battery supplied the polarizing

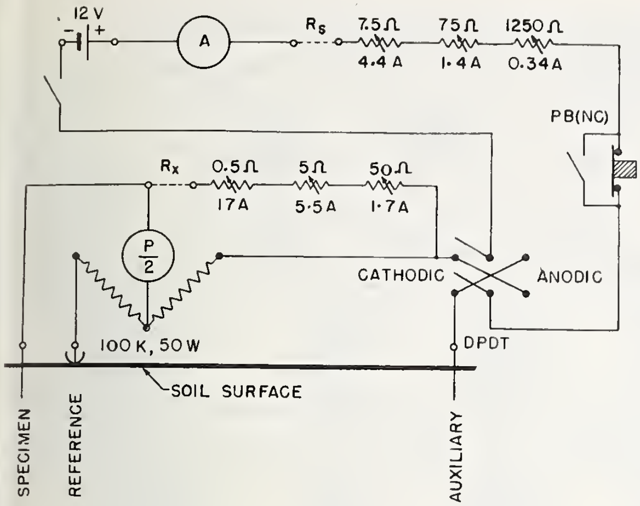


FIGURE 1. *Circuit used for obtaining polarization curves on piling.*

current. A potentiometer was used in the bridge circuit for measuring potentials. The polarization curves were obtained by applying equal increments of current at one minute intervals. The increments were previously determined by the applied current necessary to change the potential from 2 to 10 m*V*.

In addition to polarization, soil resistivity in the vicinity of the piling was measured at depths of 3, 12, and 30 ft (0.91, 3.7, 9.1 m) using the 4-pin Wenner method.

The 19 ft (5.8 m) pile was extracted for examination and measurement of depth of pits.

## 3. Results and Discussion

### 3.1. Corrosion Rates of Pipe Specimens in Back-Filled Trenches

In figure 2 are shown typical polarization curves obtained at periodic intervals on the seven-year pipe specimen at Sardis Dam. Corrosion rates at Sardis Dam were the lowest of the 4 sites. The cathodic curves are those having breaks indicated by $I_p$, while breaks in the anodic curves are shown by the currents $I_q$. Anodic curves are omitted for data obtained 8-10-60 and 5-1-61 because there was relatively little or no polarization, indicating a value for the current $I_q$ several times that of the current $I_p$. Typical polarization curves obtained on four-year pipe specimens at the 4 test sites are shown in figure 3. The curves were obtained a few months prior to removal of the specimens.

All electrical data obtained on the pipe specimens at the 4 sites are shown in tables 1 through 4. The method used in calculating corrosion currents and metal losses is described in the footnotes of the table. Actual weight losses, after chemical removal of corrosion products, are also shown for comparison. Agreement between actual and calculated values is reasonably good. The calculated values are based on the electrochemical equivalent for ferrous iron. With the exception of the Sardis site which is poorly aerated, where corrosion probably continues in

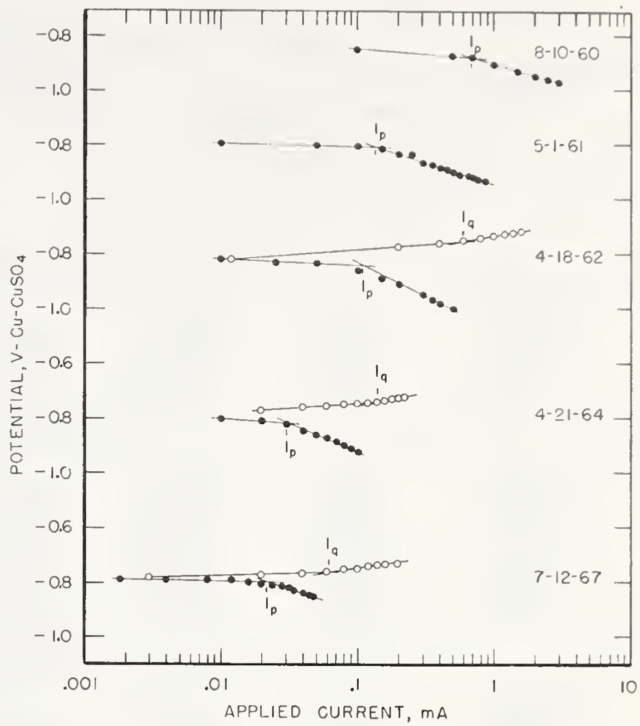


FIGURE 2. *Typical polarization curves of underground steel specimen (C8) during seven years of exposure at Sardis Dam site.*
● Cathodic ○ Anodic

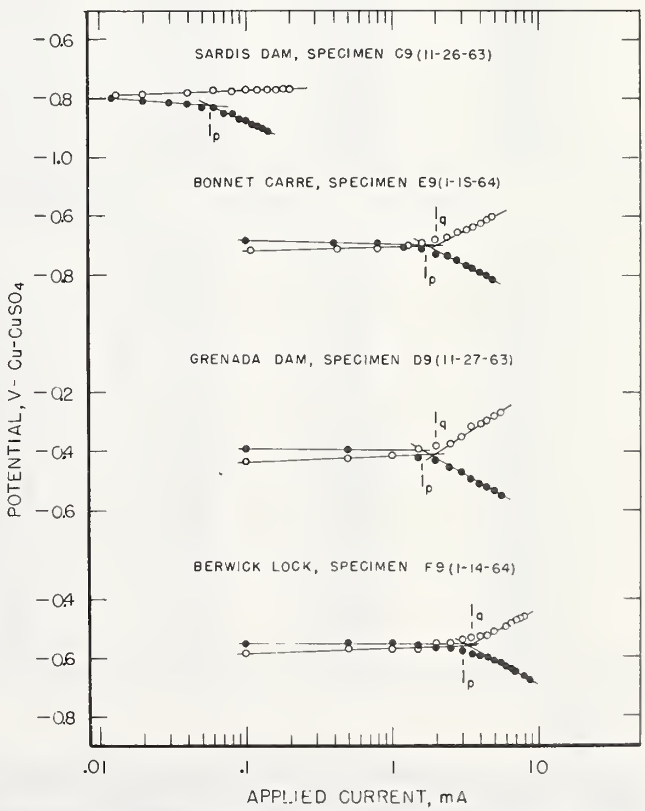


FIGURE 3. *Polarization curves of underground specimens Nos. 9 after 45 months of exposure at four soil sites.*
● Cathodic ○ Anodic

TABLE 1. *Total corrosion (weight loss) calculated from polarization curves of ferrous pipe specimens exposed up to 7 years in back-filled trenches at Berwick Lock*

| Date | Exposure time cumulative | Corrosion potential Ref-Cu-CuSO$_4$ | Polarizing Current[a] at break in curve | | Corrosion current | Weight loss | |
|---|---|---|---|---|---|---|---|
| | | | Cathodic $I_p$ | Anodic $I_q$ | $i_0$[b] | Calculated[c] cumulative | Actual |
| | days | V | mA | mA | mA | g | g |
| **Specimen F4** | | | | | | | |
| 4-05-60 | 0 | | | | | | |
| 8-23-60 | 140 | −0.780 | 4.2 | $2I_p$[d] | 2.8 | 10 | |
| 11-16-60 | 225 | .735 | 2.7 | 4.2 | 1.6 | 15 | |
| 2-07-61 | 308 | .772 | 2.8 | 2.8 | 1.4 | 18 | |
| 5-10-61 | 400 | .762 | 2.9 | 4.1 | 1.7 | 21 | 19 |
| **Specimen F13** | | | | | | | |
| 4-05-60 | 0 | | | | | | |
| 8-23-60 | 140 | −0.630 | 6.0 | $2I_p$[d] | 4.0 | 14 | |
| 11-16-60 | 225 | .640 | 3.0 | 3.6 | 1.6 | 20 | |
| 2-07-61 | 308 | .657 | 3.6 | 4.5 | 2.0 | 24 | |
| 5-10-61 | 400 | .580 | 5.4 | 7.4 | 3.1 | 30 | |
| 9-19-61 | 532 | .655 | 9.0 | 11.0 | 4.9 | 43 | |
| 1-17-62 | 652 | .625 | 10.0 | 14.0 | 5.8 | 59 | |
| 4-25-62 | 750 | .580 | 6.5 | 7.6 | 3.5 | 70 | 49 |
| **Specimen F9** | | | | | | | |
| 4-05-60 | 0 | | | | | | |
| 8-23-60 | 140 | −0.718 | 5.6 | $2I_p$[d] | 3.7 | 13 | |
| 11-16-60 | 225 | .630 | 3.6 | 3.6 | 1.8 | 19 | |
| 2-07-61 | 308 | .700 | 3.1 | 4.4 | 1.8 | 23 | |
| 5-10-61 | 400 | .645 | 7.0 | 8.0 | 3.7 | 29 | |
| 9-19-61 | 532 | .665 | 6.8 | 7.5 | 3.6 | 40 | |
| 1-17-62 | 652 | .642 | 8.0 | 11.0 | 4.6 | 53 | |
| 4-25-62 | 750 | .577 | 8.0 | 9.4 | 4.3 | 64 | |
| 8-29-62 | 876 | .564 | 7.6 | 9.6 | 4.2 | 78 | |
| 1-16-63 | 1016 | .620 | 9.0 | 9.0 | 4.5 | 93 | |
| 5-15-63 | 1135 | .415 | 6.0 | 4.5 | 2.6 | 103 | |
| 9-18-63 | 1261 | .552 | 3.5 | 3.5 | 1.7 | 110 | |
| 1-14-64 | 1379 | .575 | 2.7 | 3.2 | 1.5 | 115 | |
| 4-28-64 | 1483 | .533 | 4.0 | 4.0 | 2.0 | 119 | 67 |
| **Specimen F8** | | | | | | | |
| 4-05-60 | 0 | | | | | | |
| 8-23-60 | 140 | −0.628 | 7.4 | $2I_p$[d] | 4.9 | 17 | |
| 11-16-60 | 225 | .638 | 3.0 | 3.7 | 1.7 | 24 | |
| 2-07-61 | 308 | .635 | 5.2 | 4.3 | 2.3 | 28 | |
| 5-10-61 | 400 | .635 | 11.5 | 10.0 | 5.3 | 37 | |
| 9-19-61 | 532 | .660 | 7.5 | 6.5 | 3.5 | 51 | |
| 1-17-62 | 652 | .553 | 10.0 | 10.0 | 5.0 | 64 | |
| 4-25-62 | 751 | .578 | 6.8 | 6.6 | 3.3 | 74 | |
| 8-29-62 | 877 | .587 | 13.0 | 13.0 | 6.5 | 90 | |
| 1-16-63 | 1017 | .613 | 13.0 | 12.0 | 6.2 | 112 | |
| 5-15-63 | 1136 | .417 | 4.5 | 4.0 | 2.1 | 124 | |
| 9-18-63 | 1262 | .560 | 4.5 | 5.2 | 2.4 | 131 | |
| 1-14-64 | 1380 | .553 | 3.7 | 5.0 | 2.1 | 138 | |
| 4-28-64 | 1484 | .500 | 4.5 | 4.5 | 2.2 | 143 | |
| 9-09-64 | 1618 | .337 | 3.4 | 3.4 | 1.7 | 150 | |
| 12-17-64 | 1717 | .556 | 2.0 | 2.0 | 1.0 | 153 | |
| 5-04-65 | 1856 | .450 | 1.2 | 2.4 | 0.8 | 156 | |
| 1-11-66 | 2180 | .531 | 1.2 | 1.4 | 0.6 | 161 | |
| 5-17-66 | 2235 | .530 | 0.6 | 1.0 | 0.4 | 162 | |
| 10-25-66 | 2396 | .545 | 0.7 | 1.4 | 0.5 | 164 | |
| 7-25-67 | 2669 | .328 | 0.9 | 0.7 | 0.4 | 167 | 125 |

[a] See figure 2.

[b] $i_0 = \frac{I_p I_q}{I_p + I_q}$.

[c] From Faraday's law, Weight loss (grams) $= Kti_0$, where $K$ = electrochemical equivalent $2.8938 \times 10^{-4}$ g/c, $t$ = time (s) for the period between successive readings, $i_0$ = average current (amperes) for a period. Approximately, weight loss (mg) = 25 $t$ $i_0$, where $t$ = days between successive measurements, $i_0$ = average current (mA) between successive measurements. The values of $i_0$ at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

[d] Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of $I_q$ before or after.

Table 2. *Total corrosion (weight loss) calculated from polarization curves of ferrous pipe specimens exposed up to 7 years in back-filled trenches at Bonnet Carre Spillway*

| Date | Exposure time cumulative | Corrosion potential Ref-Cu-$CuSO_4$ | Polarizing Current[a] at break in curve | | Corrosion current | Weight loss | |
|---|---|---|---|---|---|---|---|
| | | | Cathodic $I_p$ | Anodic $I_q$ | $i_0$[b] | Calculated[c] cumulative | Actual |
| | days | V | mA | mA | mA | g | g |
| | | | **Specimen E4** | | | | |
| 4-06-60 | 0 | | | | | | |
| 8-24-60 | 140 | −0.800 | 3.0 | 7.0 | 2.0 | 7 | |
| 11-17-60 | 225 | .780 | 2.9 | 7.3 | 2.1 | 11 | |
| 2-08-61 | 308 | .770 | 2.6 | 2.5 $I_p$[d] | 1.9 | 15 | |
| 5-11-61 | 400 | .780 | 3.0 | 2.5 $I_p$ | 2.1 | 20 | 12 |
| | | | **Specimen E13** | | | | |
| 4-06-60 | 0 | | | | | | |
| 8-24-60 | 140 | −0.822 | 2.7 | 2 $I_p$[d] | 1.8 | 6 | |
| 11-17-60 | 225 | .786 | 2.3 | 2.5 $I_p$[d] | 1.7 | 10 | |
| 2-08-61 | 308 | .775 | 2.8 | 2.5 $I_p$ | 2.0 | 14 | |
| 5-11-61 | 400 | .790 | 2.8 | 2.5 $I_p$ | 2.0 | 18 | |
| 9-20-61 | 532 | .790 | 2.8 | 2.5 $I_p$ | 2.0 | 25 | |
| 1-18-62 | 652 | .777 | 2.7 | 6.7 | 1.9 | 31 | |
| 4-26-62 | 750 | .770 | 3.0 | 8.5 | 2.2 | 36 | 21 |
| | | | **Specimen E9** | | | | |
| 4-06-60 | 0 | | | | | | |
| 8-24-60 | 140 | −0.806 | 2.8 | 2 $I_p$[d] | 1.9 | 7 | |
| 11-17-60 | 225 | .790 | 3.2 | 2.5 $I_p$[d] | 2.3 | 11 | |
| 2-08-61 | 308 | .780 | 2.9 | 2.5 $I_p$ | 2.1 | 16 | |
| 5-11-61 | 400 | .800 | 3.5 | 2.5 $I_p$ | 2.5 | 21 | |
| 9-20-61 | 532 | .799 | 3.1 | 2.5 $I_p$ | 2.2 | 29 | |
| 1-18-62 | 652 | .790 | 3.1 | 7.8 | 2.2 | 35 | |
| 4-26-62 | 750 | .800 | 3.0 | 8.4 | 2.2 | 41 | |
| 8-30-62 | 876 | .771 | 6.4 | 7.2 | 3.4 | 50 | |
| 1-17-63 | 1016 | .750 | 4.4 | 5.7 | 2.5 | 60 | |
| 5-16-63 | 1135 | .545 | 3.0 | 3.0 | 1.5 | 66 | |
| 9-17-63 | 1259 | .650 | 2.4 | 2.5 | 1.2 | 70 | |
| 1-15-64 | 1379 | .710 | 1.7 | 2.0 | 0.92 | 73 | |
| 4-29-64 | 1483 | .690 | 2.1 | 2.8 | 1.2 | 76 | 41 |
| | | | **Specimen E8** | | | | |
| 4-06-60 | 0 | | | | | | |
| 8-24-60 | 140 | −0.812 | 2.8 | 2 $I_p$[d] | 1.9 | 7 | |
| 11-17-60 | 225 | .790 | 3.2 | 2 $I_p$ | 2.1 | 11 | |
| 2-08-61 | 308 | .775 | 3.6 | 9.0 | 2.6 | 10 | |
| 5-11-61 | 400 | .795 | 4.6 | 2 $I_p$[d] | 3.1 | 22 | |
| 9-20-61 | 532 | .790 | 3.5 | 9.0 | 2.5 | 32 | |
| 1-18-62 | 652 | .787 | 3.4 | 8.0 | 2.4 | 39 | |
| 4-26-62 | 751 | .780 | 4.2 | 12.0 | 3.1 | 45 | |
| 8-30-62 | 877 | .684 | 8.6 | 9.0 | 4.4 | 57 | |
| 1-17-63 | 1016 | .680 | 4.9 | 5.6 | 2.6 | 69 | |
| 5-16-63 | 1135 | .565 | 1.7 | 3.5 | 1.1 | 74 | |
| 9-17-63 | 1259 | .628 | 1.5 | 3.1 | 1.0 | 77 | |
| 1-15-64 | 1379 | .640 | 1.6 | 1.9 | 0.9 | 80 | |
| 4-29-64 | 1483 | .620 | 2.0 | 2.0 | 1.0 | 83 | |
| 9-10-64 | 1617 | .600 | 1.9 | 2.1 | 1.0 | 86 | |
| 12-18-64 | 1716 | .559 | 1.4 | 1.9 | 0.8 | 88 | |
| 5-05-65 | 1855 | .488 | 1.3 | 1.9 | 0.8 | 91 | |
| 1-12-66 | 2107 | .638 | 1.1 | 0.8 | 0.5 | 95 | |
| 5-18-66 | 2234 | .600 | 0.8 | 1.4 | 0.5 | 96 | |
| 10-26-66 | 2395 | .563 | 0.9 | 1.2 | 0.5 | 98 | |
| 7-26-67 | 2668 | .530 | 1.1 | 1.1 | 0.6 | 102 | 71 |

[a] See figure 2.

[b] $i_0 = \frac{I_p I_q}{I_p + I_q}$.

[c] From Faraday's law, Weight loss (grams) $= K\,t\,i_0$, where $K =$ electrochemical equivalent $2.8938 \times 10^{-4}$ g/c, $t =$ time (s) for the period between successive readings, $i_0 =$ average current (amperes) for a period. Approximately, weight loss (mg) $= 25\,t\,i_0$, here $t =$ days between successive measurements, $i_0 =$ average current (mA) between successive measurements. The values of $i_0$ at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

[d] Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of $I_q$ before or after.

TABLE 3. *Total corrosion (weight loss) calculated from polarization curves of ferrous pipe specimens exposed up to 7 years in back-filled trenches at Grenada Dam*

| Date | Exposure time cumulative | Corrosion potential Ref-Cu-$CuSO_4$ | Polarizing Current[a] at break in curve | | Corrosion current[b] $i_0$ | Weight loss | |
|---|---|---|---|---|---|---|---|
| | | | Cathodic $I_p$ | Anodic $I_q$ | | Calculated[c] cumulative | Actual |
| | days | V | mA | mA | mA | g | g |
| | | | Specimen D4 | | | | |
| 3-30-60 | 0 | | | | | | |
| 8-11-60 | 134 | −0.408 | 1.9 | 2.9 | 1.1 | 3.7 | |
| 11-02-60 | 217 | .403 | 2.0 | 2.2 | 1.0 | 5.9 | |
| 2-16-61 | 323 | .444 | 3.3 | 4.1 | 1.8 | 9.6 | |
| 5-03-61 | 399 | .437 | 4.0 | 8.3 | 2.7 | 14 | 17 |
| | | | Specimen D13 | | | | |
| 3-30-60 | 0 | | | | | | |
| 8-11-60 | 134 | −0.452 | 4.0 | 4.5 | 2.1 | 7 | |
| 11-02-60 | 217 | .483 | 2.2 | 4.0 | 1.4 | 11 | |
| 2-16-61 | 323 | .588 | 7.0 | 13.0 | 4.5 | 18 | |
| 5-03-61 | 399 | .560 | 7.5 | 9.7 | 4.2 | 27 | |
| 9-07-61 | 526 | .457 | 4.5 | 5.6 | 2.5 | 37 | |
| 1-26-62 | 667 | .473 | 5.0 | 6.4 | 2.8 | 47 | |
| 4-19-62 | 750 | .500 | 6.0 | 6.6 | 3.1 | 53 | 40 |
| | | | Specimen D9 | | | | |
| 3-30-60 | 0 | | | | | | |
| 8-11-60 | 134 | −0.467 | 2.6 | 2.7 | 1.3 | 4 | |
| 11-02-60 | 217 | .433 | 2.7 | 3.9 | 1.6 | 7 | |
| 2-16-61 | 323 | .630 | 4.3 | 6.0 | 2.5 | 13 | |
| 5-03-61 | 399 | .662 | 4.3 | 4.3 | 2.2 | 17 | |
| 9-07-61 | 526 | .495 | 4.8 | 5.6 | 2.6 | 25 | |
| 1-26-62 | 667 | .725 | 3.1 | 3.5 | 1.6 | 32 | |
| 4-19-62 | 750 | .725 | 2.4 | 2.6 | 1.2 | 35 | |
| 9-06-62 | 890 | .265 | 4.2 | 5.9 | 2.4 | 42 | |
| 12-12-62 | 987 | .169 | 2.4 | 2.5 | 1.2 | 46 | |
| 4-04-63 | 1100 | .501 | 4.2 | 4.2 | 2.1 | 51 | |
| 8-29-63 | 1247 | .550 | — | — | — | — | |
| 11-27-63 | 1337 | .425 | 2.5 | 2.1 | 1.1 | 60 | |
| 4-22-64 | 1483 | .610 | 2.0 | 2.0 | 1.0 | 64 | 63 |
| | | | Specimen D8 | | | | |
| 3-30-60 | 0 | | | | | | |
| 8-11-60 | 134 | −0.388 | 1.9 | 3.0 | 1.2 | 4 | |
| 11-02-60 | 217 | .390 | 2.2 | 2.5 | 1.2 | 6 | |
| 2-16-61 | 323 | .447 | 3.5 | 3.9 | 1.8 | 10 | |
| 5-03-61 | 400 | .457 | 4.6 | 5.2 | 2.4 | 14 | |
| 9-07-61 | 528 | .387 | 3.0 | 8.0 | 2.2 | 22 | |
| 1-26-62 | 669 | .437 | 3.8 | 5.5 | 2.2 | 30 | |
| 4-19-62 | 752 | .465 | 2.7 | 5.2 | 1.8 | 34 | |
| 9-06-62 | 892 | .230 | 3.0 | 4.0 | 1.7 | 40 | |
| 12-12-62 | 989 | .132 | 1.7 | 2.6 | 1.0 | 43 | |
| 4-04-63 | 1102 | .358 | 3.0 | 4.3 | 1.8 | 47 | |
| 8-29-63 | 1249 | .384 | 2.0 | 2.2 | 1.0 | 53 | |
| 11-27-63 | 1339 | .403 | 1.3 | 1.9 | 0.8 | 55 | |
| 4-22-64 | 1485 | .379 | 1.2 | 1.1 | 0.6 | 57 | |
| 8-26-64 | 1611 | .382 | 0.8 | 1.2 | 0.5 | 59 | |
| 1-13-65 | 1751 | .366 | 0.5 | 0.8 | 0.3 | 60 | |
| 4-29-65 | 1858 | .359 | 0.5 | 0.7 | 0.3 | 61 | |
| 12-08-65 | 2081 | .390 | 0.3 | 0.4 | 0.2 | 62 | |
| 5-11-66 | 2235 | .373 | 0.3 | 0.5 | 0.2 | 63 | |
| 10-12-66 | 2389 | .127 | 0.2 | 0.3 | 0.1 | 63 | |
| 7-13-67 | 2663 | .406 | 0.4 | 0.4 | 0.2 | 64 | 55 |

[a] See figure 2.

[b] $i_0 = \frac{I_p \quad Iq}{I_p + Iq}$.

[c] From Faraday's law, Weight loss (grams) $= K\ t\ i_0$, where $K$ = electrochemical equivalent $2.8938 \times 10^{-4}$ g/c, $t$ = time (s) for the period between successive readings, $i_0$ = average current (amperes) for a period. Approximately, weight loss (mg) $= 25\ t\ i_0$, where $t$ = days between successive measurements, $i_0$ = average current (mA) between successive measurements. The values of $i_0$ at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

TABLE 4. *Total corrosion (weight loss) calculated from polarization curves of ferrous pipe specimens exposed up to 7 years in back-filled trenches at Sardis Dam*

| Date | Exposure time cumulative | Corrosion potential Ref-Cu-CuSO$_4$ | Polarizing Current[a] at break in curve | | Corrosion current $i_0$[b] | Weight loss | |
|---|---|---|---|---|---|---|---|
| | | | Cathodic $I_p$ | Anodic $I_q$ | | Calculated[c] cumulative | Actual |
| | days | V | mA | mA | mA | g | g |
| | | | **Specimen C4** | | | | |
| 3-29-60 | 0 | | | | | | |
| 8-10-60 | 134 | −0.821 | 0.54 | ⩾ $I_p$[d] | 0.54 | 1.8 | |
| 11-01-60 | 217 | .802 | .16 | 9 $I_p$[d] | .14 | 2.5 | |
| 2-15-61 | 323 | .800 | .11 | 9 $I_p$ | .10 | 2.8 | |
| 5-01-61 | 398 | .795 | .09 | 9 $I_p$ | .08 | 3.0 | 4.3 |
| | | | **Specimen C13** | | | | |
| 3-29-60 | 0 | | | | | | |
| 8-10-60 | 134 | −0.815 | 0.86 | ⩾ $I_p$[d] | 0.86 | 2.9 | |
| 11-01-60 | 217 | .806 | .35 | 9 $I_p$[d] | .31 | 4.1 | |
| 2-15-61 | 323 | .800 | .25 | 9 $I_p$ | .22 | 4.8 | |
| 5-01-61 | 398 | .795 | .22 | 9 $I_p$ | .20 | 5.2 | |
| 9-06-61 | 526 | .799 | .32 | 9 $I_p$ | .29 | 6.0 | |
| 1-25-62 | 667 | .803 | .16 | 9 $I_p$ | .14 | 6.7 | |
| 4-18-62 | 750 | .800 | .20 | 9 $I_p$ | .18 | 7.1 | 6.0 |
| | | | **Specimen C9** | | | | |
| 3-29-60 | 0 | | | | | | |
| 8-10-60 | 134 | −0.815 | 0.58 | ⩾ $I_p$[d] | 0.58 | 1.9 | |
| 11-01-60 | 217 | .808 | .28 | 9 $I_p$[d] | .25 | 2.8 | |
| 2-15-61 | 323 | .805 | .11 | 9 $I_p$ | .1 | 3.3 | |
| 5-01-61 | 398 | .800 | .11 | 9 $I_p$ | .1 | 3.5 | |
| 9-06-61 | 526 | .800 | .09 | 9 $I_p$ | .08 | 3.7 | |
| 1-25-62 | 667 | .806 | .10 | 9 $I_p$ | .09 | 4.0 | |
| 4-18-62 | 750 | .812 | .10 | 9 $I_p$ | .09 | 4.2 | |
| 9-05-62 | 890 | .800 | .08 | 9 $I_p$ | .08 | 4.5 | |
| 12-11-62 | 987 | .770 | .13 | 9 $I_p$ | .12 | 4.8 | |
| 4-03-63 | 1100 | .804 | .09 | 9 $I_p$ | .08 | 5.0 | |
| 8-28-63 | 1247 | .830 | .06 | 9 $I_p$ | .06 | 5.3 | |
| 11-26-63 | 1337 | .797 | .06 | 9 $I_p$ | .05 | 5.4 | |
| 4-21-64 | 1483 | .800 | .04 | 9 $I_p$ | .03 | 5.6 | 4.6 |
| | | | **Specimen C8** | | | | |
| 3-29-60 | 0 | | | | | | |
| 8-10-60 | 133 | −0.828 | 0.68 | ⩾ $I_p$[d] | 0.68 | 2.3 | |
| 11-01-60 | 216 | .810 | .27 | 9 $I_p$[d] | .24 | 3.2 | |
| 2-15-61 | 322 | .810 | .14 | 9 $I_p$ | .13 | 3.7 | |
| 5-01-61 | 397 | .802 | .14 | 9 $I_p$ | .13 | 3.9 | |
| 9-06-61 | 525 | .805 | .13 | 0.4 | .10 | 4.3 | |
| 1-25-62 | 666 | .808 | .12 | .8 | .11 | 4.6 | |
| 4-18-62 | 749 | .808 | .11 | 1.2 | .10 | 4.8 | |
| 9-05-62 | 889 | .799 | .10 | 1.0 | .09 | 5.2 | |
| 12-11-62 | 986 | .782 | .08 | 0.8 | .07 | 5.4 | |
| 4-03-63 | 1099 | .790 | .05 | 0.3 | .04 | 5.6 | |
| 8-28-63 | 1246 | .830 | .04 | 9 $I_p$[d] | .04 | 5.7 | |
| 11-26-63 | 1336 | .792 | .04 | 0.1 | .03 | 5.8 | |
| 4-21-64 | 1481 | .790 | .03 | .1 | .02 | 5.9 | |
| 8-25-64 | 1607 | .799 | .03 | 3 $I_p$[d] | .02 | 5.9 | |
| 1-12-65 | 1747 | .790 | .02 | 0.1 | .02 | 6.0 | |
| 4-28-65 | 1854 | .800 | .02 | .6 | .02 | 6.1 | |
| 12-07-65 | 2078 | .787 | .01 | .4 | .01 | 6.1 | |
| 5-10-66 | 2232 | .790 | .02 | .5 | .01 | 6.2 | |
| 11-11-66 | 2417 | .790 | .02 | .5 | .01 | 6.2 | |
| 7-12-67 | 2660 | .797 | .02 | .6 | .02 | 6.3 | 4.8 |

[a] See figure 2.

[b] $i_0 = \frac{I_p I_q}{I_p + I_q}$.

[c] From Faraday's law, Weight loss (grams) $= Kt\, i_0$, where $K$ = electrochemical equivalent $2.8938 \times 10^{-4}$ g/c, $t$ = time (s) for the period between successive readings, $i_0$ = average current (amperes) for a period. Approximately, weight loss (mg) $= 25\, t\, i_0$, where $t$ = days between successive measurements, $i_0$ = average current (mA) between successive measurements. The values of $i_0$ at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

[d] Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of $I_q$ before or after.

the ferrous state, the use of the ferric equivalent might be more valid. The use of the ferric equivalent would reduce the calculated weight losses by one-third.

The corrosion potentials at Sardis (table 4) were continuously around 0.8 V, while at other sites the potentials fluctuated and were generally more positive. The high water table at Sardis probably accounted for the relatively high electronegative potentials indicative of a deficiency in oxygen. Poor aeration could also account for the low corrosion rates at the Sardis site.

### 3.2. Comparison of Corrosion on Pipe Specimens and on Piling in the Same Soils

Cumulative weight losses based on polarization curves obtained on the seven-year specimens at the 4 sites are plotted against time in figure 4. These losses after 3.7 years of exposure are converted to corrosion rates expressed as weight loss and average penetration (reduction in cross section) for each site. Corrosion rates are tabulated in table 5 for comparison with corrosion observed on piling at the sites. The maximum reduction in thickness shown for the piling is not an overall average based on weight loss but is based on the average depth of the 25 deepest pits measured in the most corroded spots over an area 1 in$^2$ (6.5 cm$^2$) on the piles and includes both sides of the piling wall. Had the maximum reduction in thickness been based on metal loss for a larger area, such as that of the pipe specimen 72 in$^2$ (4.6 dm$^2$), the percentages shown in table 5 would be considerably lower.

The corrosion data (table 5) pertaining to the pipe specimens, under conditions conducive to maximum rates

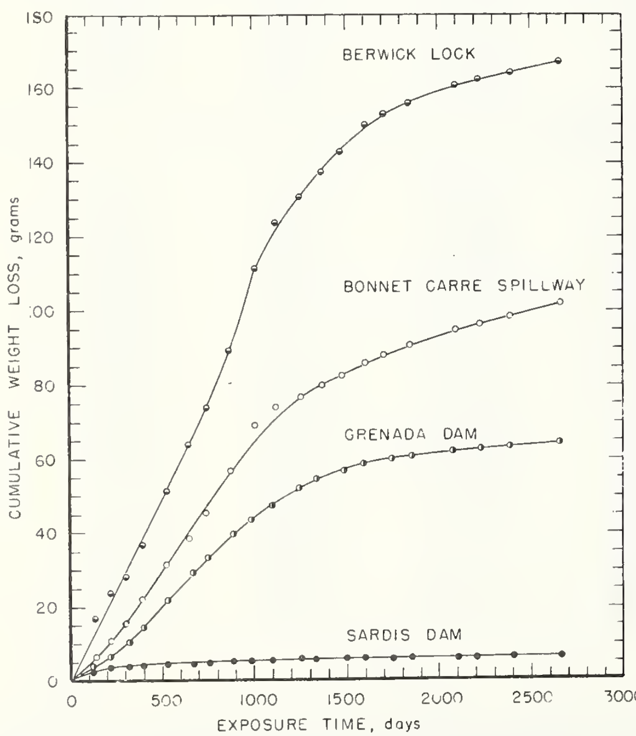


FIGURE 4. *Weight loss-time curves, based on polarization curves, obtained on iron specimens (Nos. 8) buried at four back-filled trench sites.*

of corrosion, show that corrosion is not a serious problem on piling in these particular locations. Pitting is not a limiting factor as it is on pipe lines. Thus, for example, at Berwick Lock (the most corrosive site) the average penetration on the pipe specimens after 3.7 years of exposure was at a rate of about 0.00078 in/yr (20 micrometers/yr). This means that on the piling of 0.375 in (0.95 cm) metal thickness, if corrosion were to occur on both sides in the same area at this rate only 10 percent of the metal thickness would be gone in 24 years. This corrosion would be in the area subject to the severest corrosion, that is, at the water table or in the excavated soil. In these areas on piling, the Corps of Engineers [3] considers a 35 percent reduction in cross section over a 50-year period as an acceptable maximum. At Berwick Lock, even taking into consideration the higher corrosion rate on specimens during the first 3.7 years, the average reduction in wall thickness over a 50-year period would still be under 30 percent, assuming that piling corroded at the same rate.

### 3.3. Polarization Measurements on Driven and on Buried Steel Rods

Electrical measurements on the rods are tabulated in tables 6 through 9. During early exposure, corrosion currents on the buried rods were larger than on the driven rods. As time went on, corrosion currents tended to equalize, except perhaps at Bonnet Carre and at Berwick Lock where corrosion rates on the buried rods appear to be significantly greater than those on the driven rods.

The potentials of the driven rods are apparently less affected by oxygen than are the potentials of the buried rods. A deficiency of oxygen tends to make the corrosion potentials more electronegative. It is interesting to correlate potential changes with pitting on the rods. As reported by the Corps of Engineers [3], except at Sardis Dam, it was observed that the pits were several times deeper on the buried rods than on the driven rods. Such differences were greatest at Bonnet Carre and at Berwick Lock where the differences in corrosion potentials between buried and driven rods was also greatest, the buried rods having potentials which fluctuated to more positive values. The data [3] indicate that the pitting factor (ratio of maximum pit-depth to average penetration) is greater on buried structures than on driven structures. At Sardis Dam this difference was negligible because of the high water table. The data suggest that future experiments along similar lines should be carried out with longer rods.

### 3.4. Corrosion Rates of Pipe Piles as Calculated from Polarization Curves

The Hiawatha Treatment Plant processes sewage for the area of metropolitan Syracuse, N. Y., where the water table is said to be about 10 ft (3 m) from the ground surface. Soil resistivities in the vicinity of the test piles as measured by the 4-pin method at pin spacings of 3 ft (0.91 m), 12 ft (3.7 m), and 30 ft (9.1 m) were respectively, 10,300, 3450 and 800 Ω-cm.

Preliminary polarization indicated that current increments of 40 mA would be satisfactory for obtaining the cathodic polarization curve on the 72 ft (22 m) pile (fig.

TABLE 5. *Comparison of maximum corrosion on driven steel piles with the normal corrosion on steel pipe specimens buried in nearby backfilled trenches*

| Location | Type of piling | Portion of pile inspected | | Exposure at time of inspection | Soil | | | Effect of soil on piling | | | | | | Effect of soil on pipe specimens. Corrosion rates from polarization curves based on the weight loss for the last 3.3 years of 7 years of exposure | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Surface with mill scale intact | | | Reduction in thickness in the most corroded spot [d] | | | | | | |
| | | Above water table | Below water table | | Type | Resistivity[a] | pH[b] | Above water table | In water table zone | Below water table | Above water table | In water table zone | Below water table | Weight loss | | Average penetration | |
| | | *ft* | *ft* | *yr* | | *Ω-cm* | | *percent* | *percent* | *percent* | *percent* | *percent* | *percent* | *oz/ft²/yr* | *mdd* [e] | *mpy* [f] | *micrometers/yr* |
| Berwick Lock, Berwick, La. (westside) | Arch sheet Width, 19.625 in. Thickness, 0.375 in. | 4 | 1 | 11 | Fill-silty clay over natural clay | 800-1500 | 8.1-8.5 | 60 | 60 | 60 | 8 | nil | nil | 0.51 | 4.3 | 0.78 | 20 |
| | | By excavation | | | | | | | | | | | | | | | |
| Berwick Lock (eastside) | Arch sheet Width, 19.625 in. Thickness, 0.375 in. | 2.5 | 1 | 11 | Fill-clay over natural clay | 750-1610 | 7.9-8.1 | 40 | 40 | 75 | 11 | 8 | nil | | | | |
| | | By excavation | | | | | | | | | | | | | | | |
| Bonnet Carre Spillway, New Orleans, La. | H, 12 in. Thickness, 0.607 in. | 2 | 120 | 17 | Sand, organic silt and clay mixture | 400-1050 | 6.7-8.1 | 95 | 0 | 95 | nil | nil | nil | 0.43 | 3,6 | 0.66 | 17 |
| | | Pile extracted | | | | | | | | | | | | | | | |
| Granada Dam, Granada Miss. (northside) | Arch sheet Width, 19.625 in. Thickness, 0.375 in. | 14 | 0 | 12 | Fill-sandy loam and silt over natural shale and organic clay | 4000-15,400 | 3.6-4.9 | 50 | (c) | (c) | 8 | (c) | (c) | | | | |
| | | Pile extracted | | | | | | | | | | | | | | | |
| Granada Dam (northside) | Arch sheet Width, 15 in. Thickness, 0.375 in. | 5.5 | 0 | 11 | Fill-clay, sand and silt loam mixture | 2300-16,500 | 4.0-4.4 | 20 | (c) | (c) | 16 | (c) | (c) | | | | |
| | | By excavation | | | | | | | | | | | | | | | |
| Granada Dam (southside) | Arch sheet Width, 15 in. Thickness, 0.375 in. | 5.5 | 0 | 11 | Fill-sandy loam over natural silty sand | 2400-8000 | 4.4-6.9 | 60 | (c) | (c) | 19 | (c) | (c) | 0.17 | 1.4 | 0.26 | 7 |
| | | By excavation | | | | | | | | | | | | | | | |
| Sardis Dam, Sardis, Miss. | Arch sheet Width, 15 in. Thickness, 0.375 in. | 2 | 3 | 20 | Fill-sandy loam over natural clay | 3000-50,000 | 5.4-6.0 | 90 | 90 | 90 | nil | nil | 4 | 0.021 | 0.18 | 0.032 | 0.8 |
| | | By excavation | | | | | | | | | | | | | | | |

[a] Resistivity varied with depth and water content. Maximum values shown were measured in situ by the Wenner 4-pin method and the minimum values are as measured in the laboratory under saturated conditilns.

[b] Removed from the site in sealed containers and measured in the laboratory.

[c] Entire piling was well above the water table.

[d] The reduction in thickness is based on the average of 25 measurements in the most severely corroded spot (area of spot, about 1 in²; 6.5 cm²) observed.

[e] mdd, milligrams per square decimeter per day.

[f] mpy, mils per year. One mil — .001 in (25 micrometers, approx.)

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TABLE 6. *Comparative corrosion (weight loss) on steel rods (driven and buried) exposed about 5 years at Berwick Lock*

Periodic corrosion rates are based on polarization measurements.

| Date | Exposure time cumulative | Corrosion potential Ref-Cu-CuSO4 | | Polarizing current at break in polarization curve[a] | | | | Corrosion[b] current | | Weight loss[c] calculated cumulative | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Driven No. 21 | Buried No. 22 | Driven | | Buried | | Driven No. 21 | Buried No. 22 | Driven No. 21 | Buried No. 22 |
| | | | | Cathodic $I_p$ | Anodic $I_q$ | Cathodic $I_p$ | Anodic $I_q$ | | | | |
| | days | V | V | mA | mA | mA | mA | mA | mA | g | g |
| 6-20-62 | 0 | −0.805 | −0.787 | 1.8 | $\geqslant I_p$[d] | 2.4 | $\geqslant I_p$[d] | 1.8 | 2.4 | | |
| 8-29-62 | 70 | .811 | .811 | 1.7 | 12 | 2.6 | 8.0 | 1.5 | 2.0 | 2.8 | 3.8 |
| 1-16-63 | 210 | .773 | .785 | 1.9 | 10 | 3.3 | 18 | 1.6 | 2.8 | 8.0 | 12 |
| 5-15-63 | 329 | .768 | .765 | 2.1 | 2.6 | 3.9 | $\geqslant I_p$[d] | 1.2 | 3.9 | 12 | 22 |
| 9-18-63 | 455 | .800 | .770 | 2.5 | 10 | 3.2 | 3.8 | 2.0 | 1.7 | 17 | 31 |
| 1-14-64 | 573 | .795 | .739 | 1.0 | 1.0 | 1.6 | 2.0 | 0.5 | 0.89 | 21 | 35 |
| 4-28-64 | 677 | .814 | .722 | 1.5 | 4.0 | 1.7 | 2.3 | 1.1 | .98 | 23 | 37 |
| 9-09-64 | 811 | .790 | .660 | 0.95 | 1.3 | 0.95 | 1.4 | 0.55 | .57 | 26 | 40 |
| 12-17-64 | 910 | .795 | .655 | .65 | 0.65 | .75 | 1.1 | .33 | .45 | 27 | 41 |
| 5-04-65 | 1049 | .777 | .610 | .70 | .90 | .70 | 0.90 | .39 | .39 | 28 | 42 |
| 9-01-65 | 1169 | .795 | .617 | | | | | | | | |
| 1-11-66 | 1301 | .790 | .603 | .43 | .43 | .65 | .78 | .22 | .35 | 30 | 45 |
| 5-17-66 | 1427 | .793 | .601 | .63 | .63 | .70 | .70 | .31 | .35 | 31 | 46 |
| 10-25-66 | 1588 | .790 | .595 | .37 | .40 | .60 | .45 | .19 | .26 | 32 | 47 |
| 7-25-67 | 1861 | .760 | .620 | .27 | .45 | .56 | .33 | .17 | .21 | 33 | 49 |
| Actual weight loss | | | | | | | | | | 20 | 28 |

[a] See figure 2.

[b] $i_0 = \frac{I_p I_q}{I_p + I_q}$.

[c] From Faraday's law, Weight loss (grams) $= K\,t\,i_0$, where $K$ = electrochemical equivalent $2.8938 \times 10^{-4}$ g/C, $t$ = time (s) for the period between successive readings, $i_0$ = average current (amperes) for a period. Approximately, weight loss (mg) $= 25\,t\,i_0$, where $t$ = days between successive measurements, $i_0$ = average current (mA) between successive measurements. The values of $i_0$ at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

[d] Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of $I_q$ before or after.

TABLE 7. *Comparative corrosion (weight loss) on steel rods (driven and buried) exposed about 5 years at Bonnet Carre Spillway*

Periodic corrosion rates are based on polarization measurements.

| Date | Exposure time cumulative | Corrosion potential, Ref-Cu-CuSO4 | | Polarizing current at break in polarization curve[a] | | | | Corrosion current[b] | | Weight loss calculated cumulative[c] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Driven No. 21 | Buried No. 22 | Driven | | Buried | | Driven No. 21 | Buried No. 22 | Driven No. 21 | Buried No. 22 |
| | | | | Cathodic $I_p$ | Anodic $I_q$ | Cathodic $I_p$ | Anodic $I_q$ | | | | |
| | days | V | V | mA | mA | mA | mA | mA | mA | g | g |
| 6-21-62 | 0 | −0.817 | −0.781 | 2.2 | $\geqslant I_p$[d] | 3.0 | $\geqslant I_p$[d] | 2.2 | 3.0 | | |
| 8-30-62 | 70 | .820 | .807 | 2.8 | 5 $I_p$[d] | 4.0 | 5 $I_p$[d] | 2.3 | 3.3 | 3.8 | 5.6 |
| 1-17-63 | 210 | .801 | .780 | 2.5 | 15 | 3.8 | 13 | 2.1 | 2.9 | 12 | 16 |
| 5-16-63 | 329 | .784 | .710 | 2.5 | 5 $I_p$[d] | 4.0 | 8.0 | 2.1 | 2.7 | 18 | 25 |
| 9-17-63 | 453 | .810 | .679 | 1.9 | 1.9 | 2.0 | 3.0 | 0.95 | 1.2 | 22 | 31 |
| 1-15-64 | 573 | .785 | .651 | 1.7 | 3.0 | 1.8 | 1.8 | 1.1 | 0.90 | 25 | 34 |
| 4-29-64 | 677 | .799 | .630 | 1.6 | 3.0 | 1.9 | 2.5 | 1.1 | 1.1 | 28 | 37 |
| 9-10-64 | 811 | .805 | .608 | 1.8 | 1.8 | 2.2 | 2.2 | 0.90 | 1.1 | 32 | 40 |
| 12-18-64 | 910 | .783 | .590 | 1.2 | 1.2 | 1.4 | 1.9 | .60 | 0.81 | 33 | 42 |
| 5-05-65 | 1049 | .780 | .529 | 1.6 | 3.0 | 1.1 | 1.8 | 1.1 | .68 | 36 | 45 |
| 9-02-65 | 1169 | .796 | .582 | - - - | - - - | - - - | - - - | - - - | - - - | - - - | - - - |
| 1-12-66 | 1301 | .792 | .563 | 1.0 | 0.80 | 0.70 | 0.70 | 0.44 | .35 | 41 | 48 |
| 5-18-66 | 1427 | .797 | .525 | 0.80 | 1.3 | 1.4 | 1.4 | .50 | .70 | 43 | 50 |
| 10-26-66 | 1588 | .785 | .503 | .70 | 0.70 | 0.85 | 0.60 | .35 | .35 | 44 | 52 |
| 7-26-67 | 1861 | .785 | .538 | .85 | .85 | 1.1 | 1.1 | .42 | .55 | 47 | 55 |
| Actual weight loss - - - | - - - | - - - | - - - | - - - | - - - | - - - | - - - | - - - | - - - | 27 | 48 |

[a] See figure 2.

[b] $i_0=\frac{I_p I_q}{I_p+I_q}$.

[c] From Faraday's law, Weight loss (grams) $=K\,t\,i_0$, where $K$=electrochemical equivalent $2.8938\times10^{-4}$ g/C, $t$=time (s) for the period between successive readings, $i_0$= average current (amperes) for a period. Approximately, weight loss (mg) $=25\,t\,i_0$, where $t$= days between successive measurements, $i_0$= average current (mA) between successive measurements. The values of $i_0$ at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

[d] Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of $I_q$ before or after.

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Table 8. *Comparative corrosion (weight loss) on steel rods (driven and buried) exposed about 5 years at Grenada dam*

Periodic corrosion rates are based on polarization measurements.

| Date | Exposure time cumulative | Corrosion potential, Ref-Cu-$CuSO_4$ | | Polarizing current at break in polarization curve[a] | | | | Corrosion current[b] | | Weight loss calculated cumulative[c] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Driven No. 21 | Buried No. 22 | Driven | | Buried | | Driven No. 21 | Buried No. 22 | Driven No. 21 | Buried No. 22 |
| | | | | Cathodic $I_p$ | Anodic $I_q$ | Cathodic $I_p$ | Anodic $I_q$ | | | | |
| | days | V | V | mA | mA | mA | mA | mA | mA | g | g |
| 5-15-62 | 0 | −0.821 | −0.665 | 2.5 | $\geqslant I_p$[d] | 7.4 | $\geqslant I_p$[d] | 2.5 | 7.4 | | |
| 9-06-62 | 114 | .710 | .502 | 4.7 | 7.0 | 6.0 | 7.0 | 2.8 | 3.2 | 7.6 | 15 |
| 12-12-62 | 211 | .603 | .550 | 5.8 | 6.6 | 5.0 | 5.6 | 3.1 | 2.7 | 14 | 22 |
| 4-04-63 | 324 | .735 | .635 | 6.6 | 10.0 | 6.3 | 6.7 | 4.0 | 3.3 | 24 | 31 |
| 8-29-63 | 471 | .695 | .568 | 3.0 | 3.0 | 4.0 | 4.0 | 1.5 | 2.0 | 34 | 40 |
| 11-27-63 | 561 | .651 | .515 | 1.9 | 1.9 | 1.9 | 1.3 | 1.0 | 0.74 | 37 | 43 |
| 4-22-64 | 707 | .770 | .717 | 1.9 | 23 | 1.7 | 1.7 | 1.0 | .85 | 41 | 46 |
| 8-26-64 | 833 | .670 | .440 | 1.8 | 3 $I_p$[d] | 2.0 | 2.0 | 1.4 | 1.0 | 44 | 49 |
| 1-13-65 | 973 | .691 | .499 | 1.4 | 1.4 | 1.4 | 1.4 | 0.70 | 0.70 | 48 | 52 |
| 4-29-65 | 1068 | .740 | .560 | 1.1 | 0.90 | 1.0 | 0.8 | .50 | .44 | 49 | 54 |
| 9-16-65 | 1208 | .546 | .325 | | | | | | | | |
| 12-08-65 | 1291 | .525 | .311 | 0.50 | .86 | 0.78 | .72 | .32 | .37 | 52 | 56 |
| 5-11-66 | 1445 | .595 | .450 | .90 | .50 | .80 | .75 | .32 | .39 | 53 | 57 |
| 10-12-66 | 1599 | .428 | .257 | .80 | .90 | .54 | .54 | .42 | .27 | 54 | 58 |
| 7-13-67 | 1873 | .543 | .480 | .65 | .65 | .45 | .70 | .32 | .27 | 57 | 60 |
| Actual weight loss | | | | | | | | | | 59 | 64 |

[a] See figure 2.

[b] $i_0=\dfrac{I_p\, I_q}{I_p+I_q}$.

[c] From Faraday's law, Weight loss (grams) $= K\, t\, i_0$, where $K$ = electrochemical equivalent $2.8938\times10^{-4}$ g/C, $t$ = time (s) for the period between successive readings, $i_0$ = average current (amperes) for a period. Approximately, weight loss (mg) $= 25\, t\, i_0$, where $t$ = days between successive measurements, $i_0$ = average current (mA) between successive measurements. The values of $i_0$ at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

[d] Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of $I_q$ before or after.

TABLE 9. *Comparative corrosion (weight loss) on steel rods (driven and buried) exposed about 5 years at Sardis Dam*

Periodic corrosion rates are based on polarization measurements.

| Date | Exposure time cumulative | Corrosion potential Ref-Cu-$CuSO_4$ | | Polarizing current at break in polarization curve[a] | | | | Corrosion current[b] | | Weight loss calculated cumulative[c] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Driven No. 21 | Buried No. 22 | Driven | | Buried | | Driven No. 21 | Buried No. 22 | Driven No. 21 | Buried No. 22 |
| | | | | Cathodic $I_p$ | Anodic $I_q$ | Cathodic $I_p$ | Anodic $I_q$ | | | | |
| | days | V | V | mA | mA | mA | mA | mA | mA | g | g |
| 5-16-62 | 0 | −0.791 | −0.797 | 0.91 | $\geqslant I_p$[d] | 1.1 | $\geqslant I_p$[d] | 0.91 | 1.1 | | |
| 9-05-62 | 112 | .773 | .772 | .60 | 9 $I_p$[d] | 1.0 | 9 $I_p$[d] | .54 | 0.9 | 2.0 | 2.8 |
| 12-11-62 | 209 | .767 | .765 | .52 | 9 $I_p$[d] | 0.52 | 9 $I_p$[d] | .47 | .47 | 3.3 | 4.4 |
| 4-03-63 | 322 | .790 | .787 | .50 | 9 $I_p$[d] | .48 | 9 $I_p$[d] | .45 | .43 | 4.6 | 5.7 |
| 8-28-63 | 469 | .772 | .716 | .70 | 9 $I_p$[d] | .50 | 9 $I_p$[d] | .63 | .45 | 6.6 | 7.3 |
| 11-26-63 | 559 | .760 | .740 | .54 | 1.5 | .44 | 0.52 | .40 | .24 | 7.8 | 8.1 |
| 4-21-64 | 705 | .778 | .770 | .47 | 1.4 | .38 | .56 | .35 | .23 | 9.1 | 9.0 |
| 8-25-64 | 831 | .645 | .620 | .40 | 0.45 | .52 | 1.0 | .21 | .34 | 10 | 9.9 |
| 1-12-65 | 971 | .763 | .762 | .35 | .35 | .29 | 0.20 | .18 | .12 | 11 | 11 |
| 4-28-65 | 1066 | .791 | .780 | .50 | .85 | .30 | .50 | .32 | .19 | 11 | 11 |
| 9-15-65 | 1206 | .610 | .624 | | | | | | | | |
| 12-07-65 | 1289 | .625 | .642 | .33 | .33 | .45 | .38 | .16 | .21 | 13 | 12 |
| 5-10-66 | 1443 | .755 | .721 | .35 | .40 | .42 | .68 | .19 | .26 | 13 | 13 |
| 10-11-66 | 1597 | .657 | .631 | .35 | .35 | .52 | .62 | .18 | .28 | 14 | 14 |
| 7-12-67 | 1871 | .745 | .637 | .25 | .25 | .32 | .32 | .13 | .16 | 15 | 16 |
| Actual weight loss | | | | | | | | | | 31 | 31 |

[a] See figure 2.

[b] $i_0=\frac{I_p I_q}{I_p+I_q}$.

[c] From Faraday's law, Weight loss (grams) $=K\,t\,i_0$, where $K$ = electrochemical equivalent $2.8938\times10^{-4}$ g/C, $t$ = time (s) for the period between successive readings, $i_0$ = average current (amperes) for a period. Approximately, weight loss (mg) $=25\,t\,i_0$, where $t$ = days between successive measurements, $i_0$ = average current (mA) between successive measurements. The values of $i_0$ at the beginning and at the end of exposure are taken as the initial and final values, respectively, as calculated.

[d] Breaks are indefinite. Values are based on relative cathodic and anodic polarization and/or values of $I_q$ before or after.

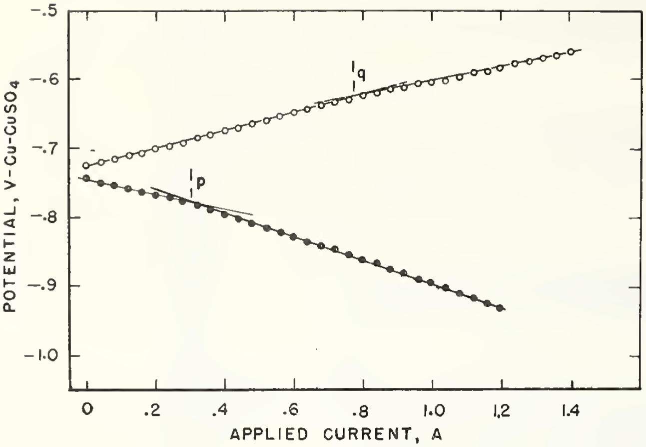


Figure 5. *Polarization curves of a bare pipe pile, 12.75 in O.D. × 72 ft. long (32.5 cm × 22m) after underground exposure for 12 years at the Hiawatha treatment plant, Syracuse, N. Y.*

5). The following day, the anodic curve was also obtained by using the same increments of applied current. Both curves are shown plotted on rectangular coordinates in order to verify changes-in-slope (breaks). Based on the Pearson equation [2], the total corrosion current on the bare metallic piling surface was calculated to be 215 mA, or a corrosion rate of 0.9 mA/ft$^2$ (0.097 mA/dm$^2$). Upon learning that one of the other piles in the vicinity (about 5 ft or 1.5 m away) was of the same diameter but only 19 ft (5.8 m) long, the thought occurred that the average corrosion rate of the shorter pile ought to be greater than that of the long pile because a larger percentage of the short one was probably exposed to excavated soil during installation. Time permitted running a cathodic curve on the 19 ft (5.8 m) pile, applied current increments (10 mA) being estimated in the same manner as previously (fig. 6). Time did not permit obtaining the anodic polarization curve; however, it seemed reasonable to assume that the $I_p/I_q$ ratio would be similar to what was previously observed for the long pile. Based on this assumption, the average corrosion current was calculated to be 79 mA and the corrosion rate 1.3 mA/ft$^2$ (0.14 mA/dm$^2$). Because of the limited data, it could be argued that the corrosion rates of the two piles might not be significantly different, and rightly so. Nevertheless, the second pile measurements add validity to the corrosion rate calculated for the long pile. Validation of the corrosion rate was further emphasized when the continuous application of 400 mA to the long pile for one hour caused a change in potential of 50 mV, confined strictly to polarization. This indicated that the pile (fig. 5) was being cathodically protected and that the current at the break, about 300 mA, was in excess of the corrosion current (calculated to be 215 mA).

On the basis of soil resistivity as measured in the area where the piles are located, it appears that the greater portion of the 72 ft (22 m) pile is driven into soil having a resistivity of 800 Ω-cm or less. To further validate the corrosion rate measurements made on the piling other information can be mentioned. The corrosion rates of plain ferrous pipe specimens, based on actual weight loss-time curves involving hundreds of specimens after five years of exposure in 28 soil sites having resistivities between 500 and 3000 Ω-cm, averaged 1.6 mA/ft$^2$ [6] (0.17 mA/dm$^2$). The specimens had been buried in back-filled trenches (disturbed soils).

One month after making the polarization measurements, the 19 ft (5.8 m) pile was extracted and cleaned for the measurement of pit depths. It was found that 40 to 50 percent of the pile surface was still covered by mill scale after 12 years of exposure. Pitting on the remaining surface was scattered. By far, most of the pitting was in the upper 9 ft (2.75 m). Thirty-four pits ranging in depth from 50 to 100 mils (1.3 to 2.6 mm) were found in the upper 9 ft (2.75 m), most of the other pits being less than 30 mils (0.77 mm). In the lower 10 ft (3.05 m) of the pile, ten pits ranging from 30 to 90 mils (0.77 to 2.3 mm) were observed. Pits less than 30 mils (0.77 mm) were not recorded.

Assuming that piling at the Syracuse Plant corrodes at the rate of 1.3 mA/ft$^2$ (0.14 mA/dm$^2$) for 50 years, the average reduction in metal thickness is of interest. A current density of 1.0 mA/ft$^2$ (0.11 mA/dm$^2$) is approximately equivalent to an overall reduction in wall thickness of 0.5 mils/yr (13 micrometers/yr). Thus, the corrosion current density of 1.3 mA/ft$^2$ (0.14 mA/dm$^2$) for 50 years would cause a reduction in pipe wall thickness of about 33 mils (0.85 mm). As the wall thickness of the pipe under discussion is 0.375 in (9.5 mm), the overall reduction in thickness for 50 years would be less than 9 percent. As previously mentioned, the Corps of Engineers [3] considered a 35 percent loss in cross section as the acceptable maximum for 50 years. Were a similar rate of corrosion taking place on two surfaces (for example on H piling), the reduction in wall thickness would still be within the acceptable maximum.

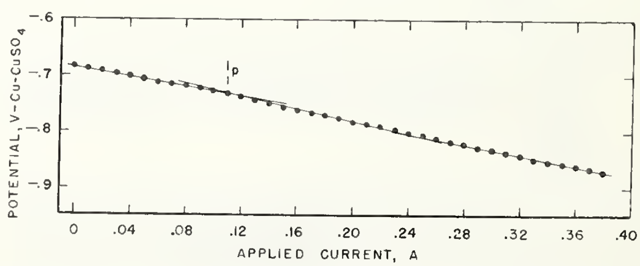


Figure 6. *Polarization curve of a bare pipe pile, 12.75 in O.D. × 19 ft. long (32.5 cm × 5.8 m), after exposure underground for 12 years at Hiawatha treatment plant, Syracuse, N. Y.*

## 4. Conclusions

Polarization curves obtained by the Corps of Engineers (Lower Mississippi Valley Division) on four wired pipe specimens at each of four underground test sites were evaluated by the National Bureau of Standards for accuracy in the calculation of metal loss attributable to corrosion and as a means of estimating corrosion on piling which had been previously examined and exposed to the same environments. At each test site one specimen (wired) along with three identical steel unwired specimens were removed after 1, 2, 4 and 7 years of exposure. The Corps of Engineers periodically had made cathodic and anodic polarization measurements on the wired specimens at intervals varying from 2 to 7 months. Using the changes-in-slope (breaks) in the curves plotted on semi-logarithmic coordinates, the calculated instantaneous rates of corrosion were converted to total metal losses by averaging rates for the intervals. The calculated metal losses were in reasonable agreement with the actual weight losses of the wired specimens and also with the weight losses of the unwired specimens.

The relatively stable rates of corrosion which were observed after about four years of exposure of the wired 7-year pipe specimens are expressed as average penetration (reduction in metal thickness) and compared with the corrosion visually observed on piling in the same area or soil environment. On the basis of a criterion mentioned by the Corps of Engineers and using average penetration rates at the most corrosive of the four sites it was concluded that the corrosion taking place on the bare piling was not a serious problem from the standpoint of loss in structural strength.

Corrosion which had taken place in five years on driven steel rods was compared with the corrosion on identical rods exposed concurrently in nearby excavated soil. The corrosion potentials, measured periodically on the rods in connection with polarization runs, seem to bear some relation to the maximum pit depths reported by the Corps of Engineers. Pits were several times deeper on the buried rods than on the driven rods at the two most corrosive sites where the buried rods fluctuated in corrosion potential to values more electropositive than those of the driven rods. While rod specimens were limited in number, one driven and one buried at each of the four sites, the data do indicate that pitting is deepest on the metal in contact with excavated soil above the water table. The differences in weight losses of driven and buried rods were not always significant; however, the metal losses on the driven rods were generally less.

Cathodic and anodic polarization curves were obtained on two 12 in (32.5 cm) diam pipe piles, 72 ft (22 m) and 19 ft (5.8 m) in length, driven 12 years previously at a sewage disposal plant. The 72 ft (22 m) pile was exposed to soil varying in resistivity from 800 Ω-cm for the greater part to 10,300 Ω-cm near the surface. Instantaneous corrosion rates were calculated from the curves. Based on the pipe wall thickness 0.375 in (0.95 cm) the average reduction in wall thickness of the short pile over a period of 50 years would be less than 9 percent. The polarization curves indicated that the long pile was corroding at a lower rate than the short one; however, as only two piles were involved, the difference may be insignificant. About one month later, the short pile was extracted and examined for general corrosion and pitting. It was found that about 40-50 percent of the surface was still covered with mill scale. Most of the pits under 30 mils (0.77 mm) in depth were in the upper 9 ft (2.75 m) of the pile with 34 pits ranging in depth from 50 to 100 mils (1.3 to 2.6 mm). Only two pits were 100 mils (2.6 mm) deep.

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The author is deeply indebted to his former associate Melvin Romanoff (deceased) who made the arrangements with the Corps of Engineers to carry out the visual inspection of piling at the dam sites and the electrical measurements on pipe specimens at the sites.

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Deserving special recognition is E. Harold Ardahl, U.S. Army Engineer District, Lower Mississippi Valley Division, Vicksburg, Miss., who carried out all electrical measurements on the pipe and rod specimens and together with Mr. Romanoff made physical inspections on excavated and extracted piles at the dam sites.

The author extends his thanks to O. W. Wade, Consultant, who instigated making polarization measurements on isolated piling at the Hiawatha Treatment Plant, Syracuse, N. Y. and for his assistance in performing the measurements. Mr. Wade later evaluated the corrosion on one of the extracted piles.

## 5. References

[1] Romanoff, Melvin, Corrosion of steel pilings in Soils, Nat. Bur. Stand. (U.S.), Monogr. 58, 23 pages (Oct. 1962).

[2] Schwerdtfeger, W. J., A study by polarization techniques of the corrosion rates of aluminum and steel underground for sixteen months, J. Res. Nat. Bur. Stand. (U.S.), **65C** (Eng. and Instr.), No. 4, 271–276 (Oct.-Dec. 1961).

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[4] Holler, H. D., Studies on galvanic couples 1. Measurement of electromotive force and internal resistance of cells during current flow, J. Electrochem. Soc. **97**, 271 (Sept. 1950); Corrosion **7**, 52 (Feb. 1951).

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(Paper 75C2–320)

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15. SUPPLEMENTARY NOTES

Supersedes NBS Monograph 58

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


This monograph is a collection of published papers on underground corrosion of steel piling. The papers are as follows:

(1) Romanoff, Melvin, Corrosion of Steel Pilings in Soils, Nat. Bur. Stand. (U.S.) Monogr. 58, (Oct. 1962).
(2) Romanoff, Melvin, Corrosion Evaluation of Steel Test Piles Exposed to Permafrost Soils, Proceedings 25th Conference, National Association of Corrosion Engineers, page 6 (March 1969).
(3) Romanoff, Melvin, Performance of Steel Pilings in Soils, Proceedings 25th Conference, National Association of Corrosion Engineers, page 14 (March 1969).
(4) Schwerdtfeger, W. J., Polarization Measurements as Related to Corrosion of Underground Steel Piling, J. Res. Nat. Bur. Stand. (U.S.), 75C (Eng. and Instr.) No. 2, 107-121 (April-June 1971).

The papers describe corrosion of various types of steel piling exposed underground in the United States under climatic conditions ranging from semi-tropical to frigid. Corrosion is described on driven piling above and below the water table after many years of exposure in soils having resistivities between 78 and 50,000 ohm-cm and ranging in pH from 2.3 to 8.8.

One of the papers demonstrates the value of a polarization technique in measuring corrosion. Polarization data were obtained on weighed steel pipe specimens exposed underground for seven years in backfilled soil trenches in the vicinity of driven sheet piling. The technique was evaluated by comparing calculated cumulative weight losses of specimens with their actual weight losses. The technique was also shown to be applicable to underground pipe piling.


17. KEY WORDS (Alphabetical order, separated by semicolons) Active region; aerated soil; corrosion; disturbed soil; excavated; extracted; H-piling; instantaneous corrosion rate; mill scale; permafrost region; pipe piling; pit depth; polarization; sheet piling; undisturbed soil; weight loss.

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