

INSITU DETECTION OF PILE CORROSION

Final Report

April 6, 1992

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JHR 92-207

Project 89-2

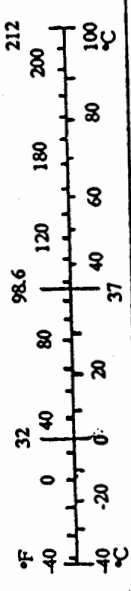
This research was sponsored by the Joint Highway Research Advisory Council (JHRAC) of the University of Connecticut and the Connecticut Department of Transportation and was carried out in the Civil Engineering Department of the University of Connecticut.

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1. Report No. JHR 92-207		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle INSITU DETECTION OF PILE CORROSION				5. Report Date April 6, 1992	
				6. Performing Organization Code	
				8. Performing Organization Report No. JHR 92-207	
7. Author(s) Richard P. Long & Shantanu Lele				10. Work Unit No. (TRAIS)	
9. Performing Organization Name and Address The University of Connecticut Department of Civil Engineering 191 Auditorium Road, U-37TI Storrs, CT 02629				11. Contract or Grant No.	
				13. Type of Report and Period Covered Final Report	
12. Sponsoring Agency Name and Address Connecticut Department of Transportation 280 West Street Rocky Hill, CT 06067-0207				14. Sponsoring Agency Code	
15. Supplementary Notes NONE					
16. Abstract <p>Severe corrosion of steel piles was discovered during the reconstruction of I-91 to I-84 interchange in Hartford, CT. The worst losses occurred at distinct elevations. This corrosion was traced to the development of electrochemical macro cells at the locations of the losses in miscellaneous fills. The conditions that caused this metal loss from the piles are probably present at many other locations in the State of Connecticut as well as the other states. The research described here is a systematic study of the conditions that caused this corrosion in situations that were previously thought safe from corrosion. It was found that the severe corrosion losses occurred at locations at or above the ground water table, where non-homogenous layers, capable of remaining moist for long periods of time, developed macro cells with contact potentials of at least 0.1 v between layers having resistivity of about 1000 ohm-cm or less. A field procedure involving an investigation taking these characteristics into account is described.</p>					
17. Key Words Corrosion, Steel Piles			18. Distribution Statement No Restrictions		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 82	22. Price

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				APPROXIMATE CONVERSIONS TO SI UNITS			
Symbol	When You Know	Multiply By	To Find	Symbol	When You Know	Multiply By	To Find
<u>LENGTH</u>							
in	inches	25.4	millimetres	mm	millimetres	0.039	inches
ft	feet	0.305	metres	m	metres	3.28	feet
yd	yards	0.914	metres	m	metres	1.09	yards
mi	miles	1.61	kilometres	km	kilometres	0.621	miles
<u>AREA</u>							
in ²	square inches	645.2	millimetres squared	mm ²	millimetres squared	0.0016	square inches
ft ²	square feet	0.093	metres squared	m ²	metres squared	10.764	square feet
yd ²	square yards	0.836	metres squared	m ²	hectares	2.47	acres
ac	acres	0.405	hectares	ha	kilometres squared	0.386	square miles
mi ²	square miles	2.59	kilometres squared	km ²			
<u>VOLUME</u>							
fl oz	fluid ounces	29.57	millilitres	mL	millilitres	0.034	fluid ounces
gal	gallons	3.785	Litres	L	litres	0.264	gallons
ft ³	cubic feet	0.028	metres cubed	m ³	metres cubed	35.315	cubic feet
yd ³	cubic yards	0.765	metres cubed	m ³			
NOTE: Volumes greater than 1000 L shall be shown in m ³ .							
<u>MASS</u>							
oz	ounces	28.35	grams	g	grams	0.035	ounces
lb	pounds	0.454	kilograms	kg	kilograms	2.205	pounds
T	short tons (2000 lb)	0.907	megagrams	Mg	megagrams	1.102	short tons (2000 lb)
<u>TEMPERATURE (exact)</u>							
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C	Celcius temperature	1.8C + 32	Fahrenheit temperature



*SI is the symbol for the International System of Measurement

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1. INTRODUCTION

A previous investigation focused on explaining the metal loss from steel piles beneath the original Piers 7 and 12 of the Southbound lane on I-91 in Hartford (1). These locations contained non-homogeneous, miscellaneous fills interspersed with layers of silts, clays, cinders, and construction rubble. At these locations, contiguous layers with a potential difference of at least 0.1 v and a resistivity below 1000 ohm-cm, developed a macro corrosion cell accounting for the observed loss of metal. All observed losses of metal occurred above the ground water table. The anodes developed in soil layers having low permeability capable of capillary retention of moisture.

The objective of the present project is to develop techniques that can identify fills that attack steel piles. To do this requires a method or methods of predicting the aggressiveness of various contiguous layers. The metal loss on the piles beneath the wingwall of Abutment 2 of the same lane, was substantially greater. The loss of cross-section on some of these piles was so great that the upper portions of several of the piles broke off while being extracted. It appeared therefore that additional techniques for predicting metal loss must be investigated.

2. BACKGROUND

Romanoff conducted the classic studies on metals in contact with earth materials (2)(3)(4). In the case of metals buried in disturbed soil he found that the corrosion is related to pH and soil resistivity and to the presence of chlorides and sulfates. A subsequent study on steel piles showed a completely different pattern. The losses due to corrosion on driven steel piles were small and did not relate to any of the characteristics of soil and pore water found to support corrosion in disturbed soils (3)(4). Based on these findings, Romanoff concluded that steel piles driven below fresh ground water tables develop a self-induced, weak, global cathodic protection (4). The soils surrounding the portion of the pile below the ground water table are oxygen deficient and become the anode to the oxygen rich portion of the pile in the fill above the ground water table. Subsequent investigators observed similar behavior, leading to little loss of metal (5).

Losses of metal from the steel piles as great as found beneath Pier 12, I-91 Southbound in Hartford had not been reported previously. These losses required an explanation relating the conditions of the fill, through which these piles were driven, to the amount of metal lost. Laboratory

investigations into electrical resistivity of the layers and the contact potential developed between contiguous layers in the miscellaneous fill, revealed conditions in the fills, similar to the macro cells developed by two different soils in contact with pipelines (6). The energy of these macro cells were sufficient to account for the current flow leading to the observed metal loss at Piers 7 and 12 (1). Beneath other piers, the fill conditions did not support the current flow because the macro cells had contact potentials that were too small, resistivities that were too great or both. Tests on field samples from beneath Pier 12 by PCA indicated that the observed corrosion occurred in the absence of chlorides and sulfides (7).

3. SITES INCLUDED IN PRESENT STUDY

There were pier locations near the southbound lane of I-91 in Hartford whose piles were not observed in time to be included in the previous report. These piers were part of Project 63-375-08. The piles beneath these piers showed minimal corrosion and measurements indicated the soil resistivity and contact potential could not support large metal losses.

There was substantial loss of cross-section on a few piles from beneath the old bridge supporting structure on the reconstruction of Route I-91 in Windsor, CT under Project 63-358-08. The worst corrosion was found beneath Structure 9. The sources of this metal loss were found to be stray currents.

The piles beneath the wingwall of Abutment 2 under the southbound lane of I-91 were scheduled for removal as part of Project 63-375. The metal loss was so great on some of the piles that they could not be removed by conventional techniques. Several piles were so weakened that they snapped off when a tension force was applied. This metal loss appeared to be greater than could be accounted for by a macro cell alone, so that additional sources of corrosion loss had to be investigated.

The corrosion problems uncovered in pile foundations in Connecticut are not unique. The New York Department of Transportation has discovered severe metal loss at several locations (8)(9). Samples of slag recovered from the abutment site in Lockport, N.Y. were tested in our laboratory to compare results of resistivity and contact potential to the values found in Connecticut.

4. RESEARCH APPROACH

The fundamental phenomenon causing the observed metal loss appears to be the development of the macro cell between layers of different materials in miscellaneous fills. The macro cell is usually an aeration cell, in which the electrical potential is due to a difference in oxygen or a concentration cell in which differing quantities of chemicals are present in adjacent layers. This effect has been described in the literature by several authors, only one of whom reported any measurements (10)(11)(12). The macro cell is sometimes described in the literature as STEEL/Soil 1/Soil 2/STEEL CELL (11).

The objective of the present work is to demonstrate a means of measuring and predicting corrosion loss from steel piles, and reflects the present state of the art. Based on observations and measurements to date, it is postulated that macro cells develop in non-homogeneous fills. The observed cells in Connecticut were above the ground water table; the losses observed in New York State were at or near the ground water table. The threshold properties of the macro cell are: a contact potential between contiguous layers of 0.1 v and a resistivity of layers below 1000 ohm-cm. At greater contact potentials and lower resistivities, corrosion loss from pile flanges by the local galvanic cell can be significant over a period years.

The corrosion observed on the piles beneath the wingwall of Abutment 2 produced greater metal loss than can be accounted for by the macro cell alone. This required a corollary to the macro cell hypothesis, i.e. the development of the local macro cell neutralizes the global cell that cathodically protects the upper part of the pile in homogeneous fills as described by Romanoff (4). With the usual global protection neutralized, many of the factors found to support the corrosion of buried metals accelerate the metal loss from steel fills where the pH is low and chlorides and sulfates are present.

To check this hypothesis the soils from the most aggressive areas were checked for chlorides and sulfates and the polarization potential of available soil samples against steel were measured. In addition long term laboratory tests of the metal loss from three STEEL/SOIL 1/SOIL 2/STEEL cells were made and compared to theoretical predictions.

5. CORROSION RATES IN SOILS

Several investigators measured the instantaneous corrosion rate of steel in contact with soil using a

"polarization" technique. Electrical current, conducted by the soil-water, is applied to the steel soil system using a power source. This approach has been applied to steel piles in homogeneous soils in the field, where small rates were measured and to soil-steel systems in the laboratory. Polarization methods can result in the calculation of an accurate parameter called the "corrosion current density" when additional parameters called Tafel slopes are known. The corrosion current density is usually expressed in amperes per square centimeter and is then converted, using Faraday's Law, (13) to a corrosion rate. Faraday's Law relates the amount of current passed through a metal to the weight loss of that metal at the anode. Corrosion currents vary with both time and water content (14).

The polarization resistance represents the change in potential of a steel electrode from its steady-state potential divided by the current applied to the electrode that caused the change in potential. The measurement is made by placing the soil between two electrodes in a small cell. The current is applied to the steel electrode through the soils to be tested. The polarization resistance of a particular steel-soil system is inversely proportional to the corrosion current for that system.

The classic equation relating the polarization resistance to the corrosion current was derived by Stearn and Geary (17) and is presented in the next section, along with specific details concerning polarization measurements. Stearn's equation is usually reduced to $i_{\text{corr}} = 0.026/R_p$ when used in relation to soils. The constant 0.026 represents approximate Tafel slopes. In this expression R_p is expressed in ohm/sq.cm. whereas i_{corr} is expressed in amps/sq.cm.

In 1971, Schwerdtfeger (18), conducted field polarization measurements on 2 piles twelve years after they were driven into natural soils. Corrosion currents were determined for both piles to be approximately 0.9 microamps/sq cm. This corrosion rate results in an estimated metal loss of only 0.12 mm of thickness over 12 years. One of the piles was exposed and found to be in very good condition which correlated well to the low corrosion rates.

In 1972, Schwerdtfeger and Romanoff (19) presented a paper dealing with the corrosion rates of underground steel piles, in place for about three years, in Canada. Bare, epoxy coated, and concrete coated piles were studied. The soil strata included natural soils as well as some cinders. Polarization curves, were determined for these three types of pile installations which did not differ greatly. Corrosion currents were typically low, approximately 0.9 micro amps/sq.cm. The researchers found the greatest corrosion on

When this type of reaction, called a "redox reaction", takes place with the emission of electrons (goes to the left), we refer to it as "oxidation." If the reaction takes place with the consumption of electrons (goes to the right), then it is termed "reduction."

Electrons cannot exist free in a solution in any significant concentration. The electrons emitted in an oxidation reaction must therefore be used up via a simultaneous reduction reaction.

The reaction may take place in an "electrochemical cell" shown schematically in Figure 1 from Mattsson (21).

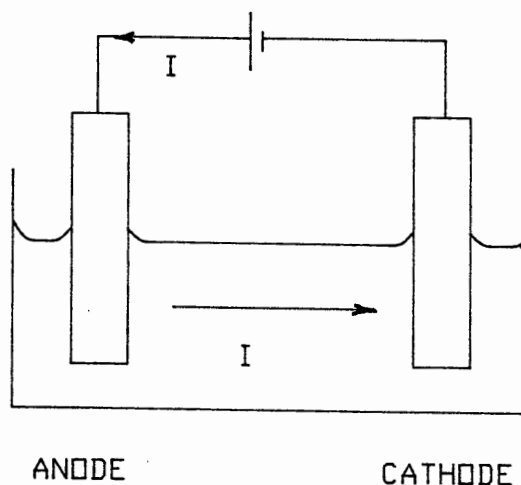


Figure 1: An Electrochemical Cell
(From Mattsson, 21)

An electrochemical cell consists of two "electrodes" connected by an "electrolyte." The electrodes are metals in contact with an electrolyte. The electrolyte is an aqueous solution that conducts electricity through the transfer of ions. The electrode from which the positive electric current enters the electrolyte is called the "anode." The other electrode, through which the electric current leaves the electrolyte, is called the "cathode".

When the electric current passes through an electrode surface, an electrochemical reaction always takes place at the electrode. The electrode reaction at the anode is always an oxidation. The cathode reaction is always a reduction.

An electrochemical cell in which current flow is forced by an external source is called an "electrolytic cell." An electrochemical cell which can itself produce an electric current is called a "galvanic cell," shown in Figure 2.

The electrical potential difference between the electrodes in a galvanic cell is called terminal voltage, which can be measured with a high resistance voltmeter.

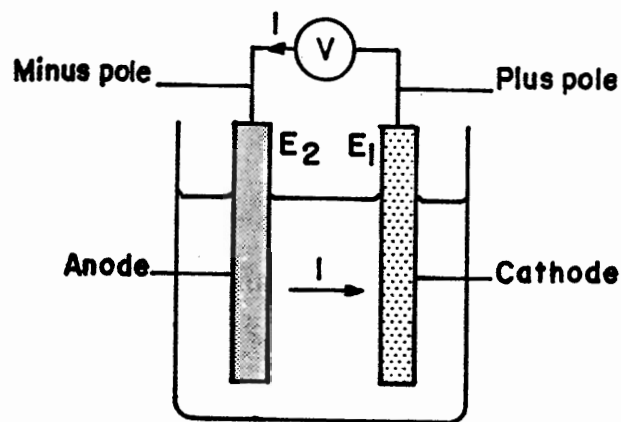


Figure 2: A Galvanic Cell
(From Mattsson, 21)

B. Faraday's Law

The quantities of chemicals converted during electrode reactions are proportional to the amount of current which passes through the electrode surface. This concept is expressed in Faraday's law. Faraday's law states that the passage of current through a non-noble metal will result in a weight loss in that metal, which is corrosion. The passage of 1 Faraday or 96,500 coulombs of charge through a metal will result in a weight loss of one gram equivalent weight in that metal. The gram equivalent weight is the atomic weight of the metal divided by the valence of its disassociated ion.

Although Faraday's law provides the basis for computing metal loss, it can not always be applied in practice because the current responsible for the corrosion is often difficult to locate and measure while it is occurring. Instead an

caused by the difference in concentration between the layer of electrolyte nearest the electrode surface and the rest of the electrolyte.

The polarization of an anode always results in overvoltages positive to the equilibrium electrode potential of the metal surface. Polarization of the cathode results in overvoltages negative to the equilibrium potential. The overvoltages resulting from applied currents are displayed in polarization curves which are sometimes called overvoltage or overpotential curves.

It is often the case that two or more electrode reactions can take place simultaneously at an electrode; a cathode reaction whose equilibrium potential is E_{01} , and an anode reaction, whose equilibrium potential is E_{02} , this can be seen in Figure 4.

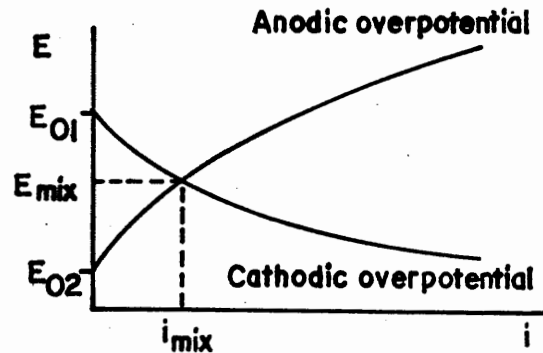


Figure 4: Overpotential Curves for 2 Electrode Reactions
(From C.F. Mattsson, 21)

When there is no net current applied to the electrode surface, the anodic and cathodic current densities are the same and equal to i_{mix} , which is the exchange current responsible for corrosion of the electrode. The electrode shows a mixed potential, E_{mix} , equivalent to the point of intersection of the anodic and cathodic polarization curves. The change in electrode potential which takes place when current is applied to such an electrode is also due to polarization with respect to this equilibrium condition.

Activation polarization below 30 millivolts is directly proportional to the current density. At polarization values from approximately 30 to 50 millivolts there is, on the other hand, a linear relationship between activation polarization

potential difference is measured in the laboratory by placing two different soils, in contact, in a soil "box" having steel plates at each end. The electrical potential difference between the steel plates is measured with a volt meter and called the contact potential. In effect, the voltage generated by the galvanic cell of the type STEEL/SOIL1/SOIL2/STEEL is measured. Contact potentials indicate combinations of contiguous soil layers that form macro cells capable of driving direct current.

8. CORROSION CURRENT

Instantaneous corrosion rates for a given soil-steel system can be determined using two different, but related, "polarization" techniques in which current, conducted by the soil water, is applied to the steel specimen and the resulting overvoltages are measured. These techniques are known as Tafel Extrapolation and Linear Polarization. Both of these methods involve the determination of the corrosion current, i_{corr} , the current which is responsible for the dissociation of the ferrous ions. The corrosion current is converted to a corrosion rate using Faraday's Law. The corrosion rates obtained can be compared for different soil-steel systems to judge the degree of corrosiveness of a given soil-steel system. It is important to note that the corrosion current has been found to vary with the amount of time that the steel is exposed to the soil, and the water content of the soil in contact with the steel (14).

The theoretical basis behind the determination of the corrosion current involves electrode kinetics; a branch of electrochemistry dealing with reaction rates at metal surfaces in solutions. The fundamental terms are polarization and overvoltage.

Polarization accompanying the flow of direct current can be viewed as the deposition of immobile ions on the metal surface that resists current flow and thus corrosion. The electrical resistance of this shield is termed the polarization resistance, R_p .

Before the metal (or electrode) is polarized by the application of current, it exists at a distinct electrode potential with respect to a reference electrode placed in the soil solution. This electrode potential is termed the equilibrium or corrosion potential because it represents the potential at equilibrium leading to the flow of current between the soil and the steel electrode. Polarization of an electrode results in an overvoltage at the electrode. Overvoltage is a measure of polarization with respect to the

Figure 5 schematically illustrates the relationship between the oxidation and reduction rates and the exchange current at the equilibrium potential and the effect of overvoltage on these rates. When the electrode equilibrium is

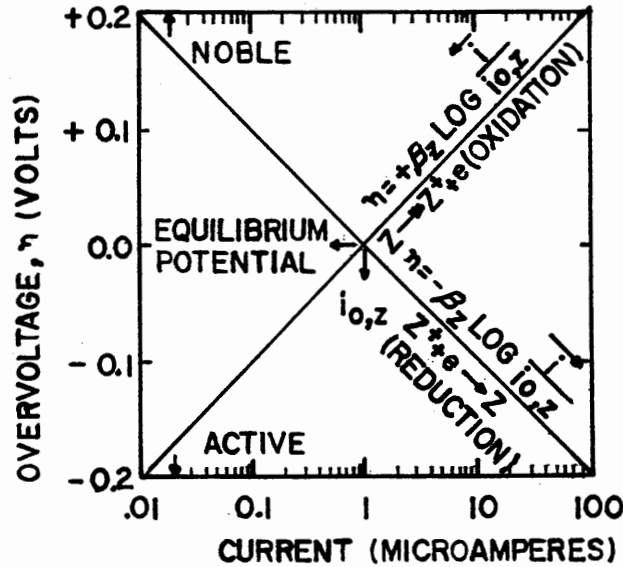


Figure 5: Relationship between overvoltage and current (From Stern and Geary, 17)

disturbed by the application of current, the reaction rates change as shown schematically by curves in Figure 5. Experimentally, however, the individual oxidation and reduction rates cannot be measured. The external current used for polarization actually is a measure of the difference between the two rates. For example, if the electrode under discussion (Fig. 5) is cathodically polarized from its equilibrium potential to an overvoltage of -0.10 volts, the rate of reduction is equivalent to $10 \mu\text{a}$ while the rate of oxidation is $.1 \mu\text{a}$. The external current required to polarize to this potential is the difference between i_1 and i_2 , or $9.9 \mu\text{a}$. If the absolute difference between the forward and reverse reaction currents is defined as i_x so that

$$i_{z,c} - i_{z,a} = i_{x,c} \quad \dots \dots \dots 11$$

then $i_{x,c}$ is the external cathodic current when the electrode is polarized to some overvoltage value, η . It is evident that $i_{x,c}$ approaches $i_{z,c}$ at overvoltage values sufficiently removed from the reversible potential. It is important to emphasize

again that experimentally the only factors measured directly are η and $i_{x,c}$ or $i_{x,a}$. The individual rate of oxidation or reduction cannot be measured. Although theory shows that there is a linear (Tafel) relationship between η and $\log i_{z,c}$ or $\log i_{z,a}$, only η vs. $\log i_{x,c}$ is measured and plotted. By substituting equation 11 into equation 9, the theoretical relationship between overvoltage and the logarithm of the external cathodic current is obtained as:

$$\eta = -\beta_z \log(i_{x,c} + i_{z,a})/i_{o,z} \quad 12$$

Using the previous values for the constants β_z and $i_{o,z}$ and knowing the relation between η and i_z , a plot of the variation on η with i_x may be constructed. This is shown in Fig. 6.

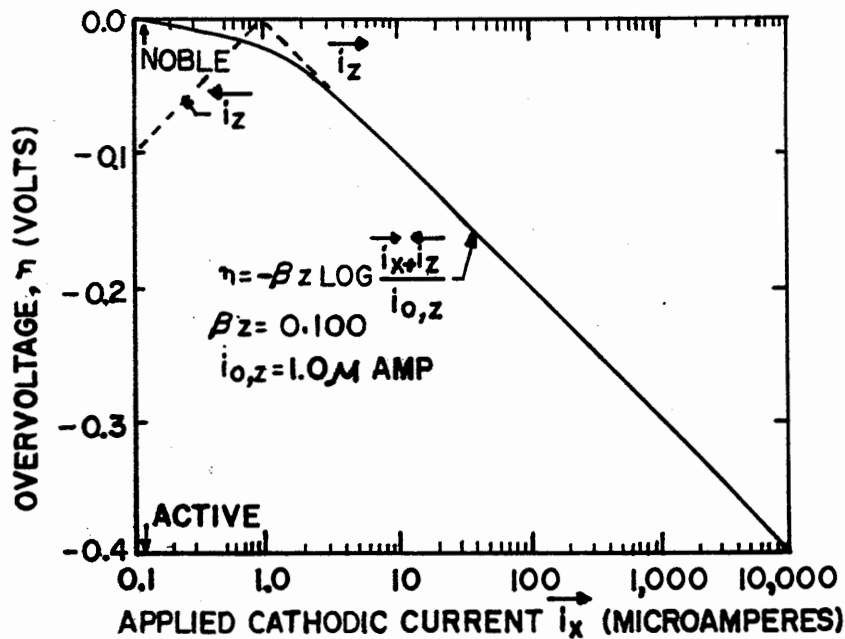


Figure 6: Relationship between overvoltage and applied cathodic current (From Stearn and Geary, 17)

Note that deviation from a Tafel slope exists at low values of applied current. Only when the reverse (oxidation) current i_z , becomes insignificant in comparison to the forward or reduction current can a true Tafel relation be expected. Further, Tafel slopes cannot be obtained until applied currents reach magnitudes of several times $i_{o,z}$. If it is assumed that experimental verification of a linear

Metal Reduction:

$$\eta = -.160 - \beta_m \log(i_{m,c}/i_{o,m}) = -.160 - .06 \log(i_{m,c}/.1) \quad .16$$

Metal Oxidation:

$$\eta = -.160 + \beta_m \log(i_{m,a}/i_{o,m}) = -.160 + .06 \log(i_{m,a}/.1) \quad .17$$

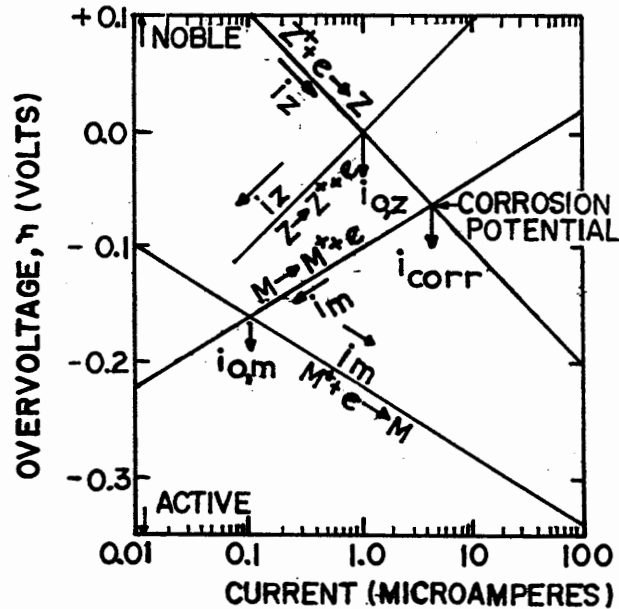


Figure 7: Relationship between overvoltage and current for a corroding mixed electrode system consisting of two coexisting electrochemical reactions. (From Stern and Geary, 17)

The constants are all arbitrary values. At any given potential, the rate of each reaction is indicated in Figure 7. As already discussed, the corrosion potential is closely approximated by the potential at which $i_{z,c} = i_{m,a}$. This potential is labeled i_{corr} in Figure 7.

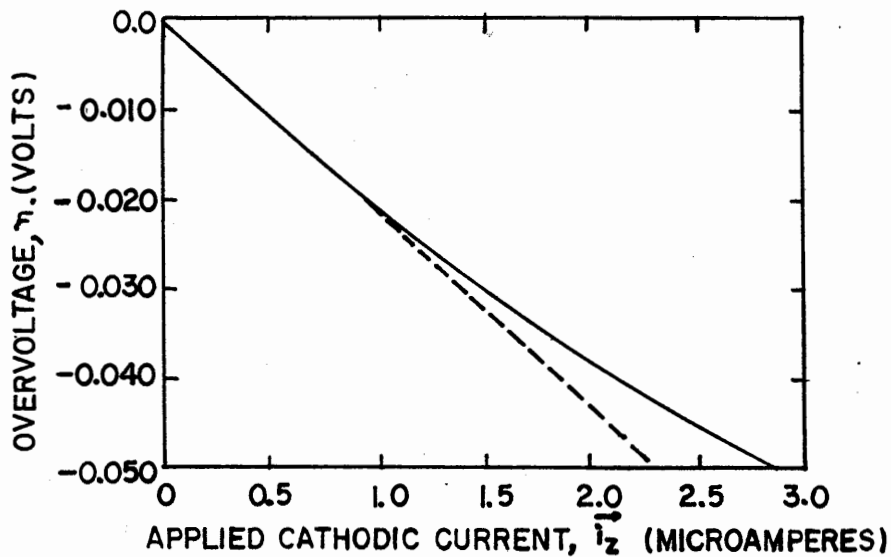


Figure 8: Linear relationship between overvoltage and applied current for a single electrode (non-corroding) system. (From Stern and Geary, 17)

B. A Corroding Electrode:

The same analysis may be applied to a corroding electrode where the corrosion potential is determined by the intersection of two logarithmic polarization curves. The corrosion current in this case is analogous to the exchange current of a non corroding electrode. Thus,

$$i_{x,c} = -2.3 i_{\text{corr}} \epsilon \frac{(\beta_z + \beta_m)}{(\beta_z \beta_m)} \text{ and } \dots \dots \dots 21$$

$$\left. \frac{\delta \epsilon}{\delta i_{x,c}} \right|_{\epsilon \rightarrow 0} = - \frac{\beta_z \beta_m}{2.3 i_{\text{corr}} (\beta_z + \beta_m)} \dots \dots \dots 22$$

For the mixed electrode system described earlier and illustrated in Figure 7:

$$\left. \frac{\delta \epsilon}{\delta i_{x,c}} \right|_{\epsilon \rightarrow 0} = -.0040 \text{ volts}/\mu\text{a} \dots \dots \dots 23$$

Figure 9, from Stearn and Geary, (17) is a plot of ϵ as a function of $i_{x,c}$ for small values of ϵ (overvoltage).

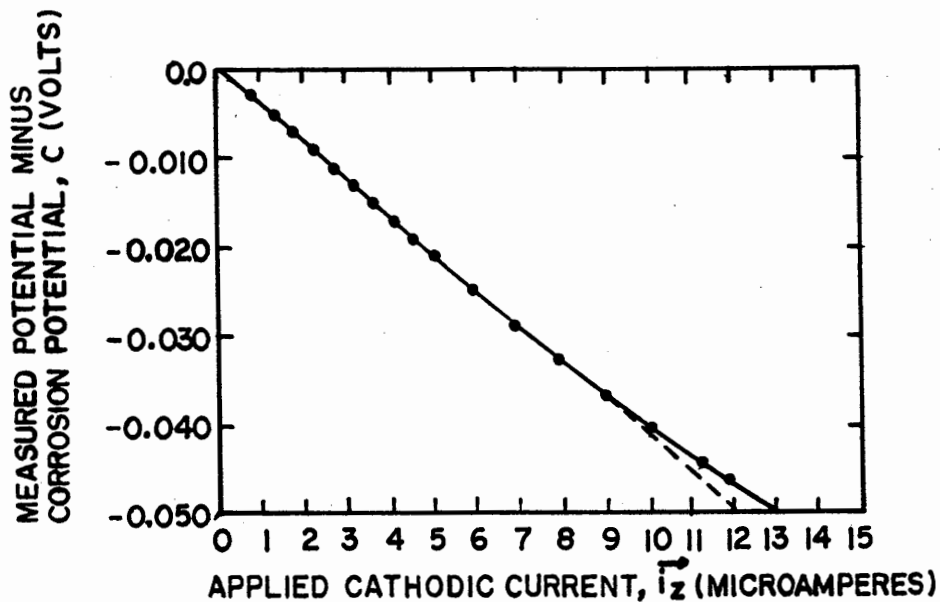


Figure 9: Linear relationship between potential and applied current at potentials only slightly removed from the corrosion potential. ϵ is the difference between the polarized potential and the corrosion potential. (From Stern and Geary, 17)

Here again a linear relation between electrode potential and applied current is found. It is important to note that the linear behavior extends to applied current values higher than the corrosion current. As stated previously, Tafel behavior would not be indicated until applied current values approximately ten times i_{corr} are reached.

Equation 22 is the equation of interest, used to calculate the corrosion current of steel-soil systems. The term $\delta\epsilon/\delta i_x$ is commonly referred to as the polarization resistance.

10. TAFEL EXTRAPOLATION

Tafel Extrapolation is a method which involves the use of polarization curves, such as the ones shown in the previous section, and results in the corrosion current directly. A schematic diagram for conducting a polarization measurement is shown in Figure 10 from Fontana and Green (23).

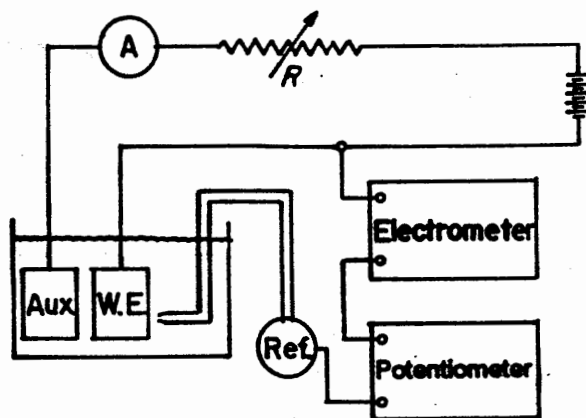


Figure 10: Electric circuit for polarization measurements.
(From Fontana and Greene, 21)

The metal sample is termed the "working electrode" (W.E) and current is supplied to it by means of an "auxiliary electrode" (AUX). Although the auxiliary, or counter electrode, has commonly been composed of a material such as copper, the working electrode and the auxiliary electrode may be composed of the same material (20). Current is measured by means of an ammeter, A, and the potential of the working electrode is measured with respect to a reference electrode (Ref.) by a potentiometer-electrometer circuit. In practice, the current may be increased by increasing the voltage output of the power source; the potential and current at various settings of voltage output are simultaneously measured. Cathodic or anodic current may be applied to the working electrode to obtain the values of applied current and corresponding potential. The application of cathodic current, or cathodic polarization means that the current is applied through the circuit so that the working electrode is the cathode. In anodic polarization the current is forced in the opposite direction so that the working electrode is the anode. Although both methods are acceptable some researchers prefer cathodic polarization due to the greater ease in obtaining data (23).

The results obtained during the cathodic polarization of a metal, M immersed in an air-free acid solution illustrative (23). Prior to the application of cathodic current, the voltmeter reads the corrosion potential, E_c , of the metal specimen (the working electrode) with respect to the reference electrode. If the potential of the electrode is plotted against the logarithm of applied current, a figure similar to that shown in Figure 11 is obtained (23).

The applied current polarization curve is indicated by points and a solid line. The region of linearity on the curve in Figure 11 is referred to as the Tafel region. In addition, the total anodic and cathodic polarization curves corresponding to hydrogen evolution and metal dissolution are superimposed as dotted lines in Fig. 11. To determine the corrosion rate from such polarization measurements, the Tafel region is extrapolated to the corrosion potential. At the corrosion potential, the rate of hydrogen evolution is equal to the rate of metal dissolution, and this point corresponds to the corrosion rate of the system expressed in terms of current density.

The use of Tafel extrapolation for soil-steel systems is illustrated by Jones (14) who used this method to find the corrosion current of a desert soil in contact with steel. As seen in Figure 12, which is a schematic of data from Abraham et. al. (16), $i_{\text{corr}} = 3.52$ micro amps/sq.cm.

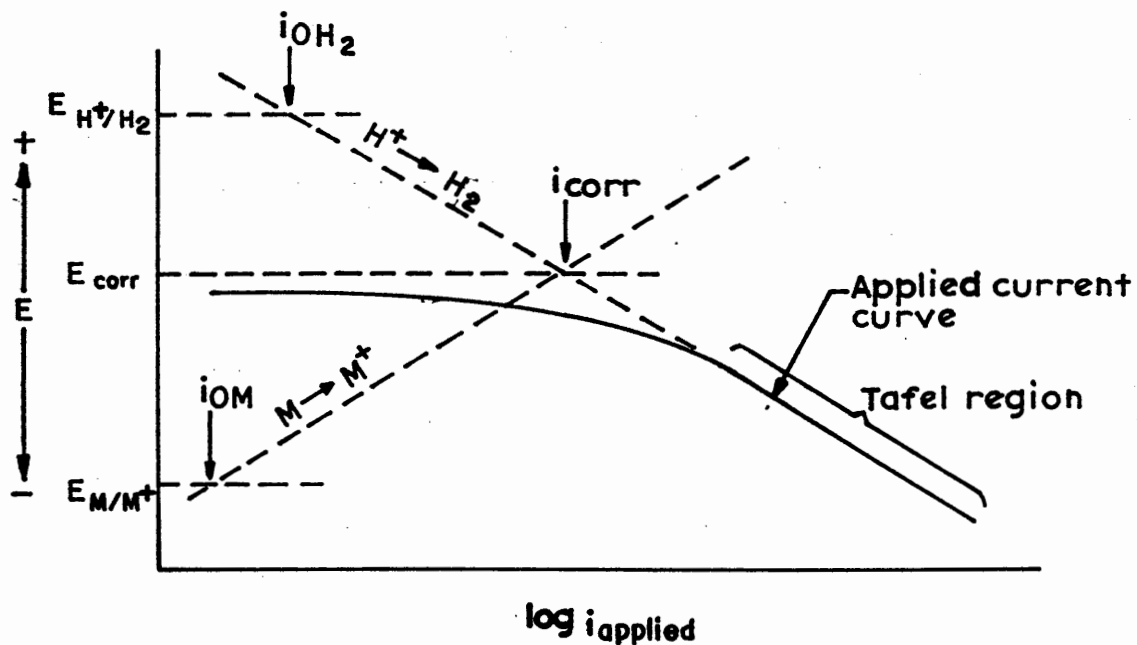


Figure 11: Applied current cathodic polarization curve of a corroding metal showing Tafel extrapolation. (From Fontanna and Greene, 23)

The Beta values have also been indicated as β_a and β_c which are equal to β_m and β_z in Stearn and Geary's (17) analysis, respectively.

The Tafel extrapolation technique allows one to measure extremely low corrosion rates accurately and rapidly, however there are a number of restrictions which must be met before this method can be used successfully. To ensure reasonable accuracy, the Tafel region must extend over a current range of at least one order of magnitude (23). In many systems (including the one used in this project) this cannot be achieved because of interference from concentration polarization and other extraneous effects such as multiple reduction processes. Indeed, Stearn and Geary (17) have shown that concentration polarization can distort the Tafel region which should be seen as a straight line on the polarization curve.

In summary, the Tafel extrapolation method is useful but can be used only in certain situations to measure the corrosion rate of a metal in a solution.

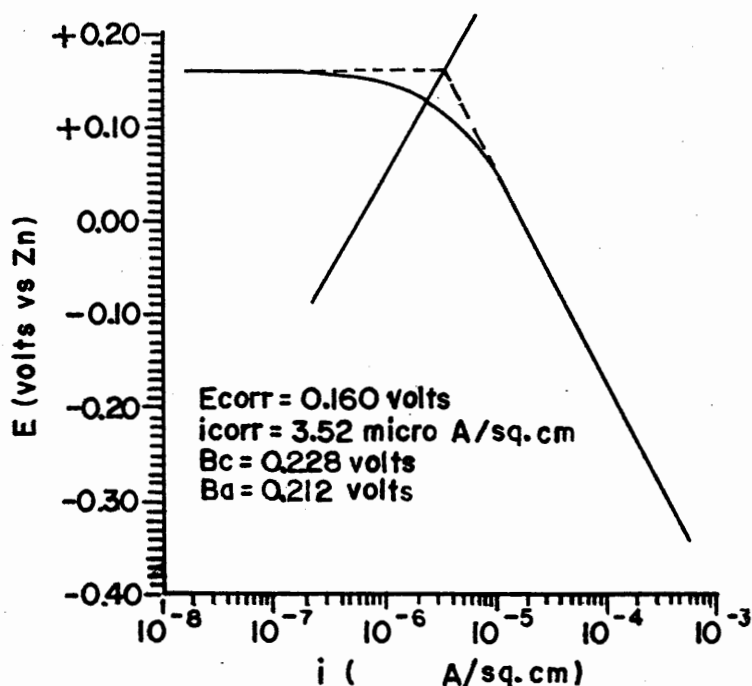


Figure 12: Typical Tafel plot for steel in contact with a sand. (Abraham et. al, 16)

11. LINEAR POLARIZATION

The disadvantages of the Tafel extrapolation technique can be largely overcome by using a linear polarization analysis in which the data from a polarization curve is plotted in a different manner. Within twenty millivolts of the equilibrium, potential it has been observed that the applied anodic or cathodic current is a linear function of the working electrode potential. This concept was illustrated in Figures 8 and 9 and is shown again in Figure 13.(23)

In Figure 13, the equilibrium potential was used as a reference point from which overvoltages were measured, and a plot of overvoltage versus applied anodic and cathodic current is shown on a linear scale. This plot represents the first twenty millivolts of the polarization curve shown in Figure 11 in the previous section. The Stearn-Geary equation,

$$R_p = \frac{\beta_a \beta_c}{2.3 \cdot i_{corr} (\beta_a \beta_c)} \dots \dots \dots 24$$

can be used in conjunction with a linear polarization plot and a semi-logarithmic plot to obtain the corrosion current and

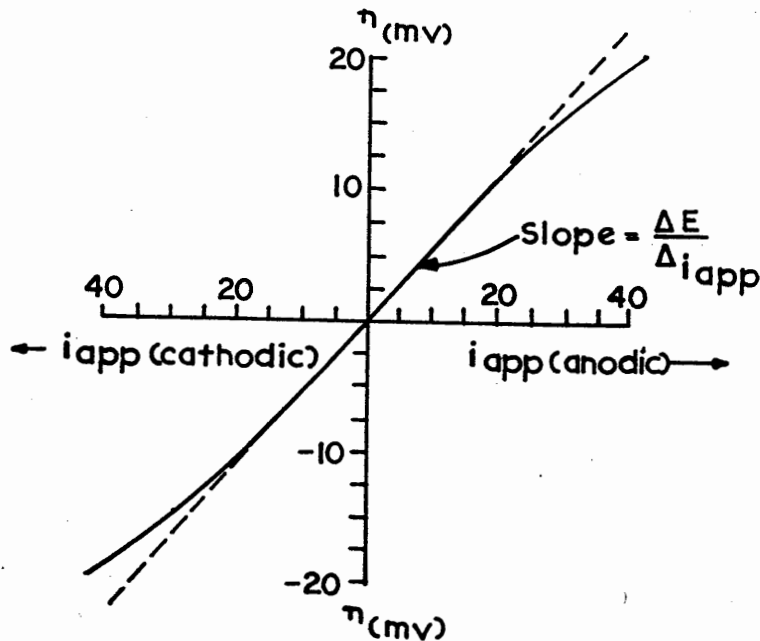


Figure 13: Applied current linear polarization curve
(From Fontana and Greene, 23)

consequently the corrosion rate. R_p (measured in millivolts/milliampere) is called the polarization resistance and is the slope of the linear polarization plot. β_a and β_c , introduced in the derivation by Stearn and Geary in section 2.3, are the slopes of the anodic and cathodic Tafel regions (measured in volts/decade) respectively on the semi-logarithmic plot (Figure 11) and are called "beta values." Fontana and Greene (23) also used a linear polarization analysis; a schematic of their results is presented in Figure 14.

The beta values used in the Stearn-Geary expression were those found in the Tafel extrapolation plot for the steel in contact with the sand (Figure 12).

It would seem, therefore, that the use of linear polarization is dependent on the determination of beta values which are determined from the anodic and cathodic Tafel regions. These regions, may be distorted, especially in real soils having unknown chemicals at various concentrations thus making the accurate determination of beta values very difficult. However, the calculation of the corrosion current using Linear polarization is not greatly affected by errors in

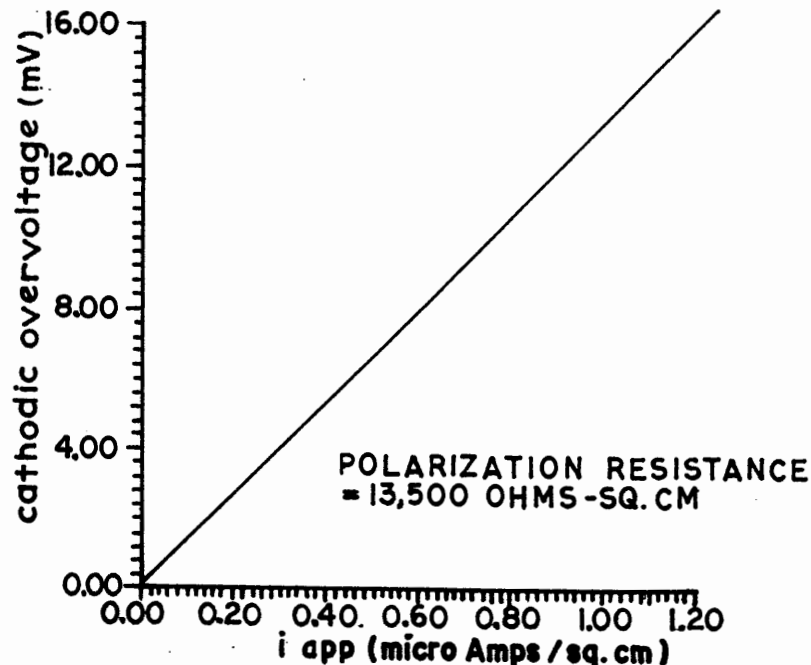


Figure 14: Typical linear polarization plot for steel in contact with a sand. (From Abraham et. al, 16)

the Tafel slope values, because the Stearn-Geary relationship involves the multiplication of the Tafel values divided by the sum of the Tafel values. In addition, the Tafel values are typically limited to a relatively small range. Using $\beta_a = \beta_c = 0.12$ volts results in corrosion current values that are good within a factor of 3, and which can then be used for comparative purposes. The value of 0.12 volts represents an average value for all corrosion systems.

Errors in polarization techniques must be minimized to obtain accurate and reproducible values of the corrosion current. The largest of these errors is termed the "IR Drop." Much time and effort has been spent by researchers in developing methods to minimize this error.

The IR drop error is introduced when a polarizing current is applied to the steel electrode (or pile) through the soil sample having resistance R. As seen in Figure 10, the potential between the steel working electrode and the soil is measured by placing a reference electrode in the soil. However, in soils this reference electrode is usually some type of a metal "rod" such as zinc which is placed at some distance, x, from the surface of the steel working electrode. The polarizing current, i, must travel the distance x between the reference electrode and the working electrode through the soil having resistance R. This flow of current through the soil results in a voltage drop equal to the current i multiplied by the soil resistance, R, which is included, incorrectly, in the measurement of the overvoltage. Various ways have been proposed to deal with this error, including placing the reference electrode as close as possible to the working electrode. In any event, this error must be dealt with for soils in some manner in the process of determining instantaneous corrosion rates.

12. TESTING PROGRAM/TEST PROCEDURES AND EQUIPMENT

A. Testing Program

Soils from Hartford, Windsor and Bridgeport, Connecticut were tested. The soils from Hartford were collected as result of the reconstruction at the I-84 to I-91 interchange. The soils from Windsor were collected due to the reconstruction of Route I-91. Both of these construction projects included the extraction of steel piles which were severely corroded.

Samples were also collected from the vicinity of the Bridge over the Yellow Mill Brook in Bridgeport. This bridge supports I-95 and construction drawings show miscellaneous fill materials over clay in this area. The ground water table was at the top of the clay according to the original borings.

These conditions were found in a previous study to support corrosion of steel piles. (1)

Figure 15 is a map showing the general locations of the sites in Hartford, Windsor, and Bridgeport from which soil samples were collected. In addition, a sample of slag backfill used in constructing a steel reinforced earth wall in Lockport, New York was tested and analyzed.

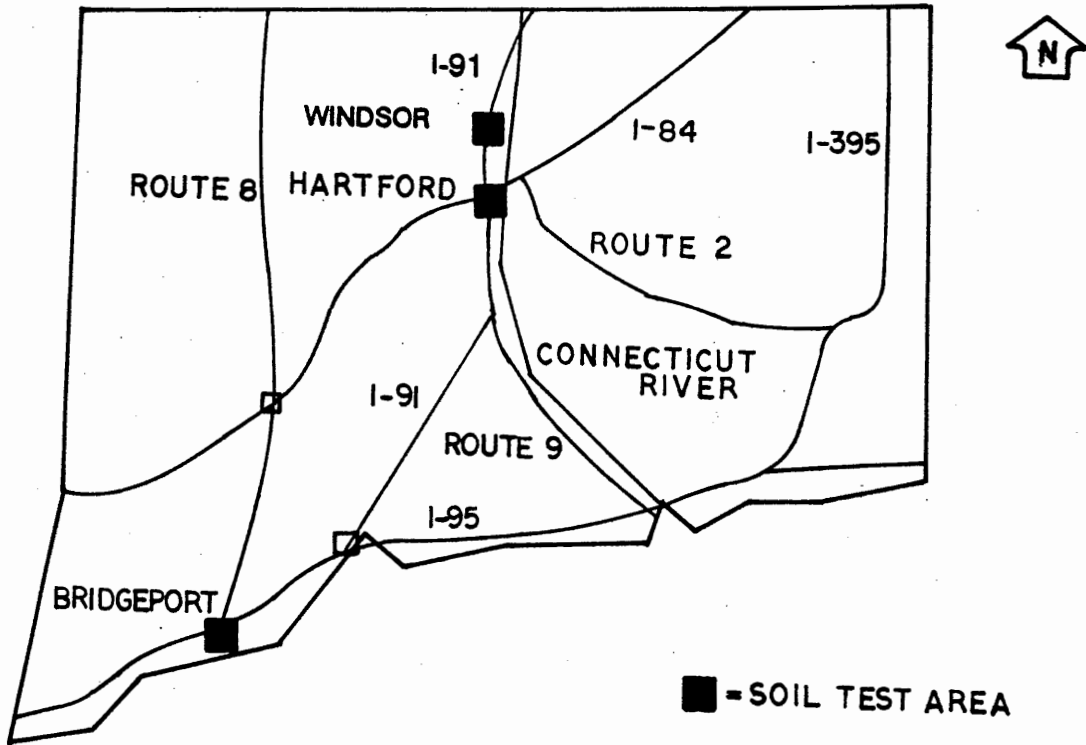


Figure 15: General location map of areas from which soils were collected.

The Connecticut soils are identified by project numbers or names and consist of soils from (1) Project 375-08 collected 10/2/89, (2) Project 358-08 collected 2/7/90, (3) Abutment 2 wingwall collected 7/9/90 and (4) Bridgeport Corrosion Study collected 3/20/91. Figures 16 and 17, 18, and 19 detail the sites of the borings from which soil samples were taken.

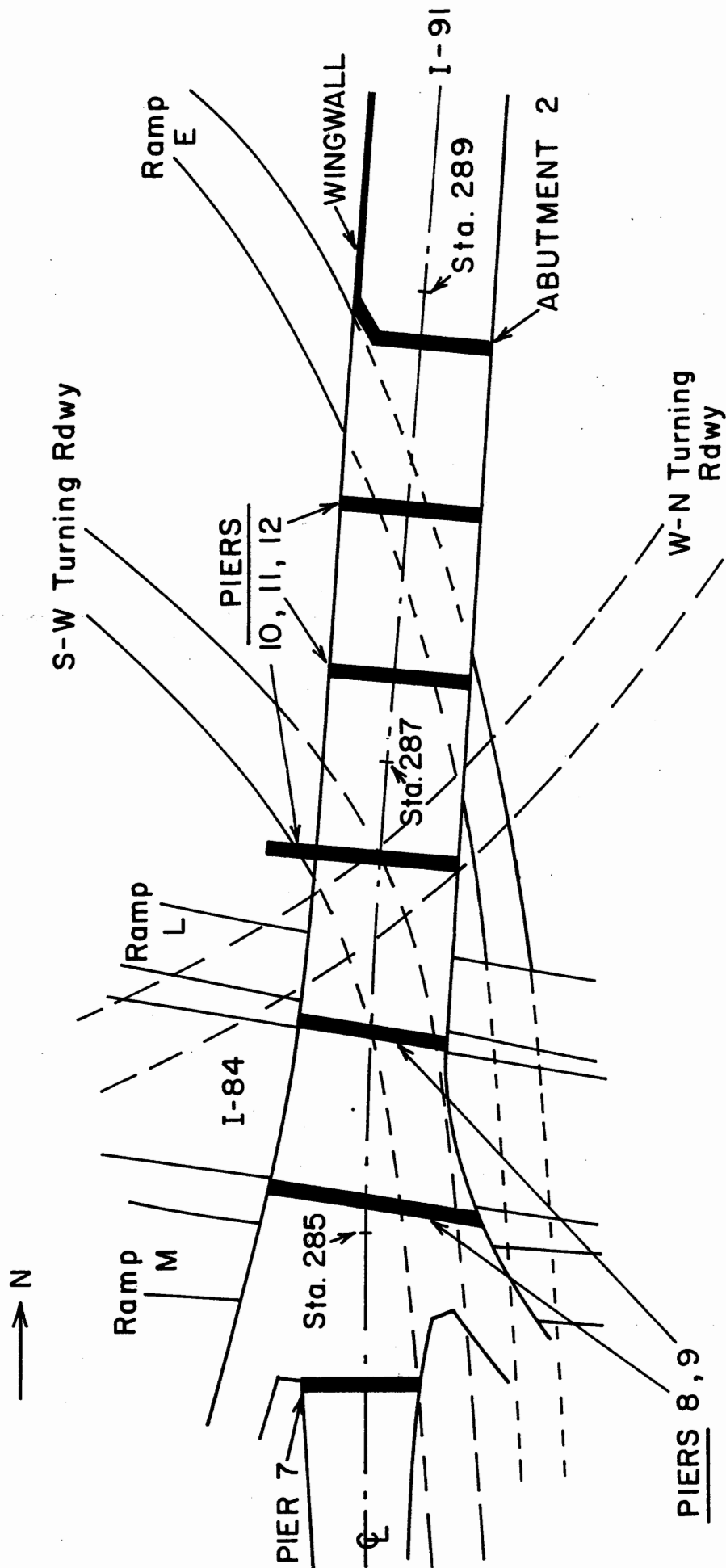


Figure 16: Boring locations for Project 63-375-08 and Abutment 2, Hartford, CT.

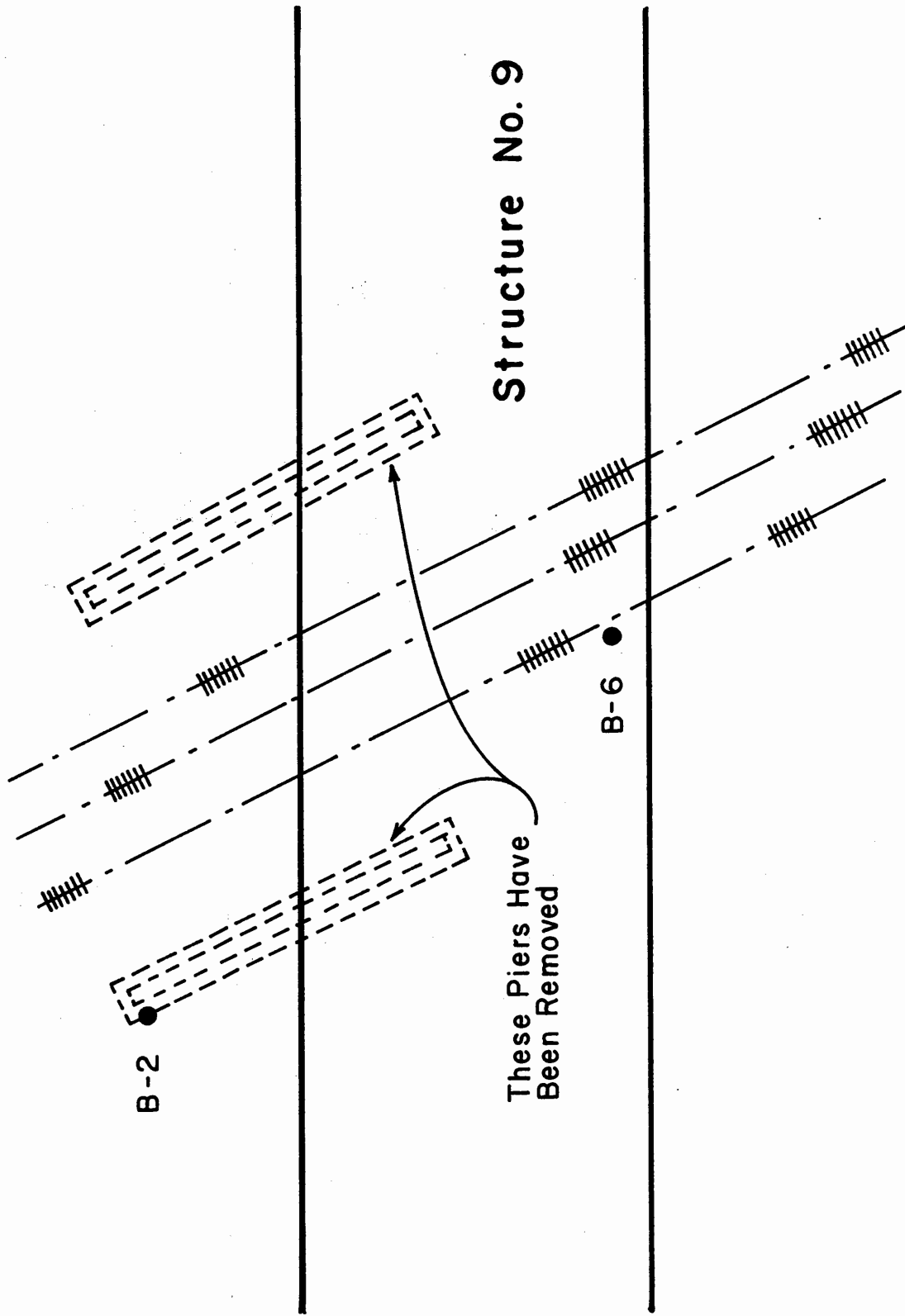


Figure 17: Boring locations for Project 63-358-08 in Windsor, CT.

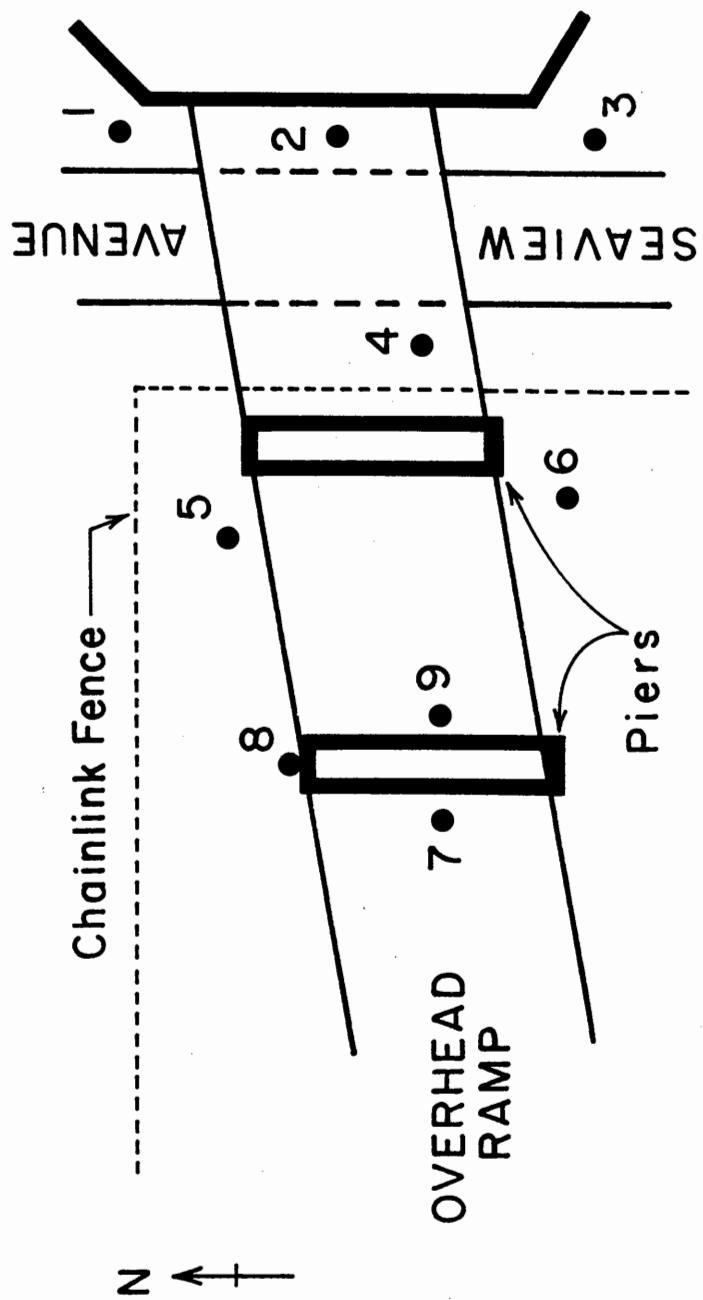


Figure 18: Boring locations for soils from Bridgeport, CT.

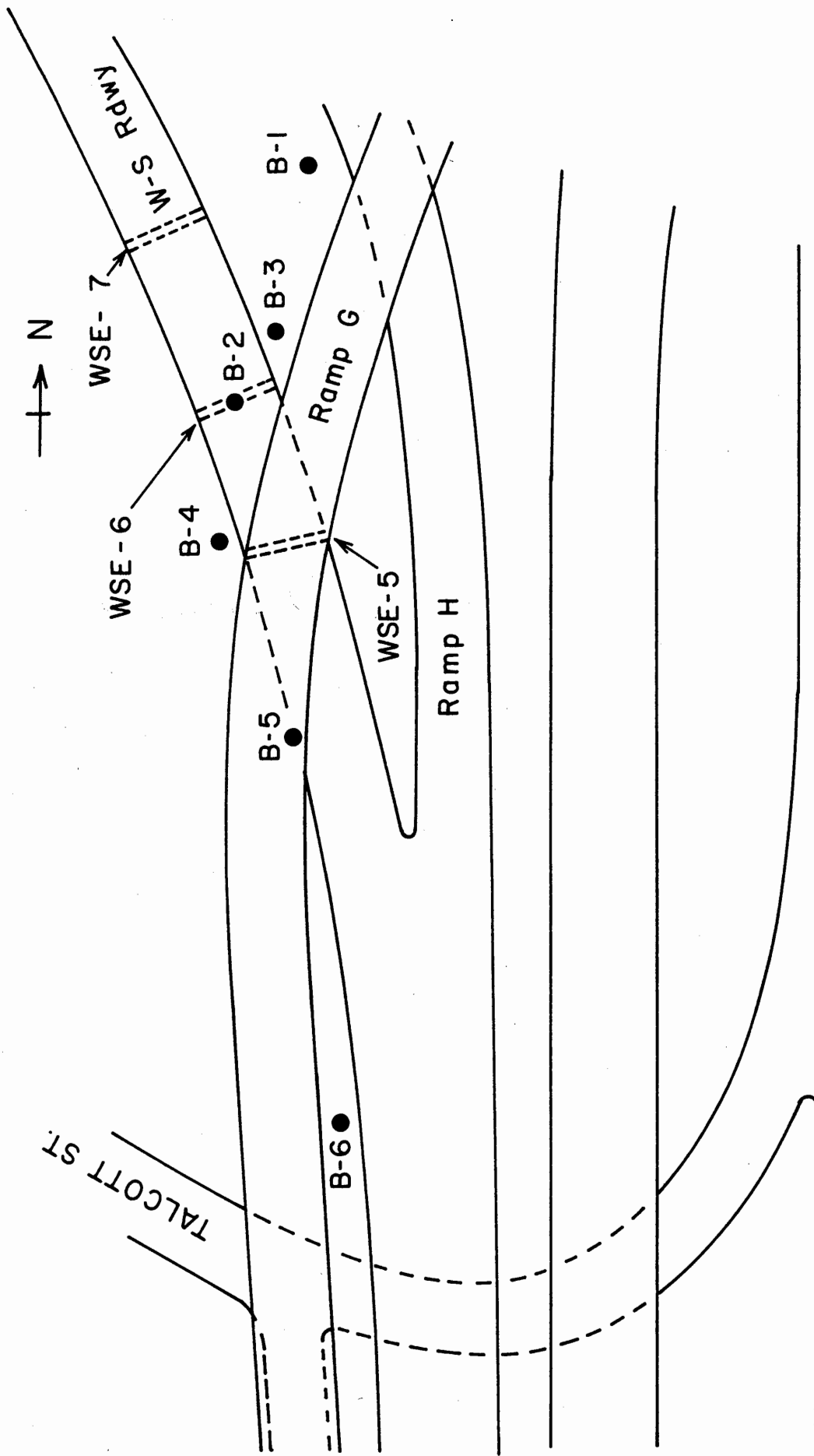


Figure 19: Additional Sample Locations
from Project 63-375-08

Approximately 30 samples were collected from Project 63-375-08, 35 samples from Project 63-358-08 and 40 samples from Bridgeport. Not all samples were tested. The samples were first inspected visually and soil type such as clean sands that showed no aggressive corrosion behavior were not tested. The samples tested are shown in Table 1, listed by: assigned sample number, project number, boring number, depth of sample, and sample type.

Soil samples clinging to extracted piles were collected directly from piles numbered 12 to 15 from the wingwall of Abutment 2, in Hartford. These soil samples adhered to the piles in the vicinity of the corrosion. The letters T, M, and B following the pile numbers stand for the "top," "Middle," and "bottom" of the corroded pile sections studied.

Pile corrosion measurements consisted of the measurement of the loss of cross sectional area. These measurements were made using special calipers to measure the remaining thickness of flanges and webs on piles from all of the project locations except for Bridgeport, where piles have not been exposed. Pile weight loss data is presented in a subsequent section.

The basic concept of the testing program reported here is to investigate two contributions to the corrosiveness of soils. The first series of tests is used to investigate contiguous soils which, when placed in contact with steel, generate contact-potentials and thus form macro cells. The second involves testing the properties of soils known to support corrosion of buried metals. These tests are performed to investigate the hypothesis that macro cells may render pile sections near these cells susceptible to corrosion attack as if these pile sections were buried in disturbed soils. These tests, conducted on soils acting alone, consist of resistivity, pH, and corrosion currents. The results from both types of tests are presented in the following chapter.

B. Resistivity and contact-potential

Previous research (1) dealing with the corrosion of soils near the interchange of I-84 and I-91 in Hartford indicated that miscellaneous fills can contain macro cells that override the global protection system described by Romanoff (4). The situation leading to the macro cell corrosion appears to be as follows:

- (1) Contiguous soil layers that have a contact-potentials of approximately .10 volts can develop a macro cell. The contact-potential is the potential of the macro cell of the type

STEEL/SOIL1/SOIL2/STEEL. In the field, the pile represents the steel in this type of cell; in the laboratory steel electrodes are used.

- (2) One of the contiguous soil layers is usually some type of miscellaneous fill, such as cinders. The other is a natural fine grained soil, often a clay.
- (3) The saturated resistivities of each of the contiguous soils, determined in the laboratory, are each less than 1000 ohm-cm.

Based on the conditions listed above it was decided to conduct resistivity measurements, as received and saturated on all of the soil samples from Hartford and Windsor. Soil samples from Bridgeport containing miscellaneous fill material were tested in the saturated condition only. After completing these tests, contact potential measurements on contiguous soil layers were made but only on the soil layers having resistivities less than 1000 ohm-cm.

These samples were identified visually. Table 1 lists the soils tested in this research. Each sample is numbered for reference and is identified by soil type, depth of recovery, Boring number, and project. In the soil description column of Table 1, the letter "F" stands for "fine," "C" stands for "coarse," "S" stands for "some," "L" stands for "little," and "T" stands for "trace." In addition, the abbreviations "CIND.," "ORG," and "MISC." stand for cinders, organics, and miscellaneous fill materials, respectively.

C. Standard tests for predicting corrosion for soils in contact with buried metals.

Piles pulled from the foundation of the wingwall of Abutment 2 in Hartford were more severely corroded than piles in the vicinity of soils from projects 358-08 and 375-08. It was hypothesized that the regions of the piles from Abutment 2 that were severely corroded were rendered susceptible to corrosive attack similar to buried metals. Consequently, the loss of metal near the macro cell measured on these piles was believed to be due to corrosive agents acting in this region, as well as to the current generated by the macro cell. It became necessary to conduct tests typically performed on soils in contact with buried metals to help distinguish which types of soil strata will severely corrode piles, not only by galvanic action, but also by corrosive agents acting on buried metals. These tests consisted of:

Table 1: Critical soil samples

SAMPLE #	PROJECT	BORING	DEPTH (FT)	SOIL TYPE
1	63-375-08 "LOW" CORROSION	#1	19-21	F. SAND/ S. SILT/ T. ORG.
2		#1	25-27	F. SAND/ S. SILT
3		#2	5-6.5	F. SAND/ S. SILT/ T. GRAV.
4		#3	11-13	F-C SAND/ S. SILT
5		#4	9.5-11	F. SAND/ S. SILT/ T. CIND.
6		#6	14-16	F. SAND/ L. SILT
7		B7	15.5-17	F. SAND/ S. SILT/ T. CLAY
8		B7	17-18.5	F. SAND/ S. SILT/ S. CLAY
9	63-358-08 "HIGH"	B2	8-8.5	CINDERS
10		B2	12.5-14	F. SAND/ S. SILT/ T. CIND
11		B3	9-10.5	CLAYEY SILT/ T. CIND
12		B3	13.5-15	CLAYEY SILT/ T. ORG.
13		B4	7.5-9	CLAYEY SILT/ T. CIND.
14		B6	9.5-11	CLAY/ S. C. SAND/ T. CIND.

SAMPLE	PROJECT	BORING	DEPTH (FT)	SOIL TYPE
15		B6	14-15.5	F. SAND/ T. SILT/ T. CLAY
16	ABUT. 2 "SEVERE"	#12T	-	CINDERS
17		#12M	-	SILTY CLAY
18		#12M	-	ASH
19		#13T	-	CLAY
20		#13M	-	CINDERS
21		#13B	-	ASH
22		#15T	-	SLAG
23		#15M	-	ASH
24		#15B	-	CLAY
25		CINDERS	-	-
26	BRIDGEPORT	#1	3-4	ASH/SLAG/ MISC.
27		#2	4.5-6.5	CIND./ASH/ MISC.
28		#6	7-8	CIND./ASH/ MISC.
29		#6	10.5-12.5	CLAY
30		#8	10.5-12.5	CIND./ASH/ MISC.
31		#9	7.5-8.5	CIND./ASH/ MISC.
32		#9	9.5-10.5	CIND./ASH/ MISC.
33	OTHER	COAL	-	-
34		LOCKPORT SLAG	-	-
35		LAB CLAY	-	-

- (1) Chemical analysis for the soils from Abutment 2- Wingwall, Hartford. These tests included the determination of chloride and sulfate contents which can be indicative of the corrosivity of disturbed soils.
- (2) pH measurements which are normally conducted on disturbed soils.
- (3) Corrosion currents which are also conducted routinely on disturbed soils.

A previous report presented a model that demonstrated metal loss from current generated by a macro cell. However, the current was back-calculated from Ohm's law using the contact-potential between the soils comprising the galvanic cell and an average resistivity of both materials. Only one self-generated current measurement was made using cinders and clay to show that the phenomenon could occur but the measurement was not well controlled.

Consequently, it was decided to conduct the following tests:

- (4) Self generated potential and current between contiguous soil layers, each having resistivities less than 1000 ohm-cm., were monitored at short intervals of time that ranged from one day to one week depending on the stability of the readings.
- (5) Long-term contact potential and current measurements for contiguous soil layers showing an appreciable self-potential between steel electrodes to correlate anodic and cathodic weight loss.

D. Corrosion Currents

Corrosion current data will be presented for the soils from each site that have been previously determined to be the most corrosive. This determination was based on resistivity for soils from projects 358-08, 375-08, and Bridgeport. Chemical analysis as well as resistivity were considered in choosing the soils to be tested for corrosion rates from the wingwall of Abutment 2.

The testing program for corrosion current was aimed at using corrosion currents as an indicator of metal loss in cases where a macro cell overrides global cathodic protection. Comparative values of corrosion currents are obtained by using

beta value of 0.12 volts each, as recommended by Fontana and Green (23). In order to make these comparisons meaningful, it must be remembered that polarization resistance from which corrosion currents are computed, vary with exposure time of the steel to the soil, and the water content of the soil. It was decided then to (1) allow all soils to be exposed to the steel electrode for approximately the same amount of time, and (2) tests all (critical) soils in the saturated condition. A zinc reference electrode was used to measure overvoltage of the steel working electrode because it worked well in other studies on soils (14). Other reference electrodes including steel, copper, and the saturated calomel electrode were investigated. The most consistent data was obtained using zinc.

Finally, corrosion current data will be presented for long term two soil macro cells consisting of miscellaneous fills in contact with clays. These tests were performed to compare calculated to measured steel weight loss and to document the self-generated current over time from selected two soil cells.

E. Equipment and Procedures

1. Resistivity

The measurement of the electrical resistivity of the soils was based on a definition of electrical resistance similar to a wire: $\rho = RA/L$ where ρ is the resistivity of the wire, R is the electrical resistance of the wire, A is the cross sectional area of the wire and L is the length of the wire.

In order to apply the equation for resistivity to soils, the soils were tested in a soil box, shown in Figure 20, having a length L and a cross sectional area A which is part of an electrical circuit.

The electrical resistance of the soil was calculated using Ohm's Law; $R = V/I$. A power source drove an alternating current through the soil in the box and a 10 ohm resistor which was connected in series with the power source and the soil box and completed the circuit. The current flowing through the circuit was calculated by measuring the voltage drop across the 10 ohm resistor and applying Ohm's Law. The voltage drop across the soil was measured across the steel pin electrodes, shown in Figure 20. This voltage drop, divided by the current flowing through the circuit, equals the resistance, R , of the soil. This value of resistance was used to calculate the resistivity of the soil. Saturated soil resistivities are determined by adding as much water as possible to the soil while mixing the soil well.

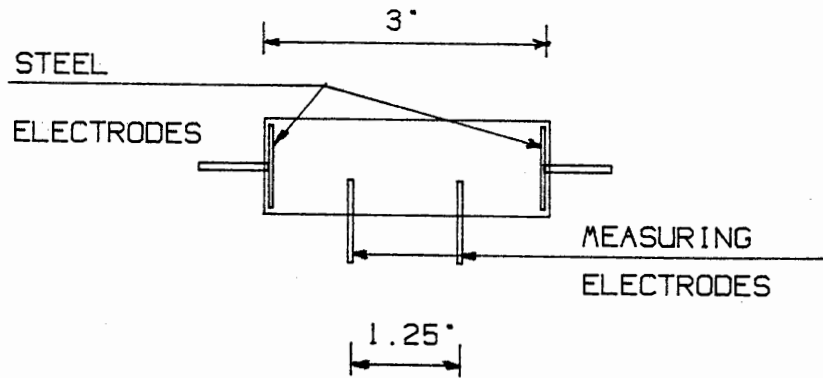


Figure 20: Resistivity testing box

2. Contact-potential/Current

Contact-potential and self generated current are terms referring to the electrical potential available and the current generated from the macro cell of the type STEEL/SOIL1/SOIL2/STEEL.

In order to measure the value of contact-potential, two different soils types, for example, cinders and clay, are placed in contact in a soil box having steel plate electrodes at the ends. As can be seen in Figure 20 holes exist in the soil box through which steel pin electrodes can also be inserted. The contact-potential is measured by simply reading the value of voltage on a high resistance voltmeter which is connected across the pin electrodes.

The self-generated current is measured using the same circuit as the resistivity of the soil, but without the power source. The circuit consists of a 10 ohm resistor in series with the soil box. The voltage drop is measured across the ten ohm resistor. The self-generated current is then calculated using Ohm's Law; $I = V/10$ ohms. Both short term and long term self-potential/current measurements were conducted in this manner.

3. pH

The measurement of soil pH was made, in the laboratory, according to the New York Department of Transportation Standards.(22) Thirty grams of soil particles passing through a quarter inch sieve were mixed with thirty milliliters of distilled water for each soil sample to be tested. The samples were then mixed every fifteen minutes for a one hour period. After the one hour period, the soil slurry was tested for pH using a portable mini-pH meter.

4. Corrosion Currents

interrupted, whereas overvoltage requires a finite time to decay. This idea can be used when selecting the proper value of X to balance the bridge. Suppose the polarizing current in Figure 21 is momentarily interrupted. IX and IR immediately disappear, and for a brief instant the measured potential assumes a value which does not include $IX - IR$ (Equation 29). Thereafter, activation overvoltage decays more slowly. If X has the proper value ($X = R$), IX balances IR exactly, and no brief initial change can be observed.

Figure 22 is a schematic of Jones' (14) recorder tracings taken from a null detector to illustrate the procedure. A cathodic polarizing current was intermittently interrupted, as indicated by the rapid return of potential to more noble values

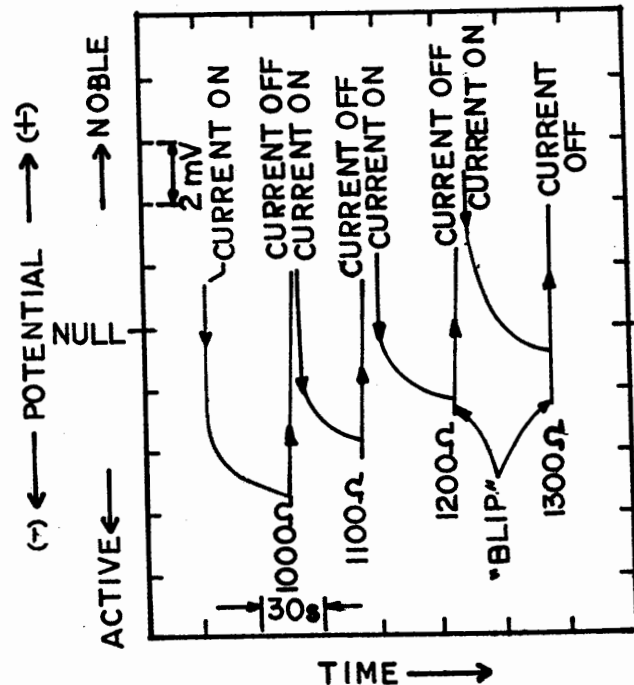


Figure 22: Balancing the Bridge
(From Jones, 14)

and the rapid approach to a steady-state cathodic overvoltage on resumption of the cathodic current. Increasing X results in an increased (more noble) steady-state potential. When $X \neq R$, the measured potential instantaneously shifts to a value which is free of $IX - IR$, and thereafter decays in a noble

direction; this is quite pronounced when $X > R$. There is a momentary decrease in potential followed by a rapid increase in the noble direction and the resulting "blip" on the recorder tracing disappears as $X \rightarrow R$.

When $X < R$, there is a momentary increase in potential, but this is masked by the rapid decay of cathodic activation overvoltage in the same (noble) direction. The chart speed is not fast enough to resolve the difference between the instantaneous disappearance of IR and the rapid decay of activation overvoltage. Therefore, one must approach the proper value of X from the high side, and X is taken as the value at which the blip disappears: the bridge is balanced.

Figure 23 is a copy of the chart recorder tracings taken from the null detector used in this study. The tracings in the figure were from the bridge balancing when a silty clay from project 63-358-08 was being tested. As indicated in the figure, the bridge was balanced when the blip disappeared. This occurred when the variable resistor was set at 290 ohms.

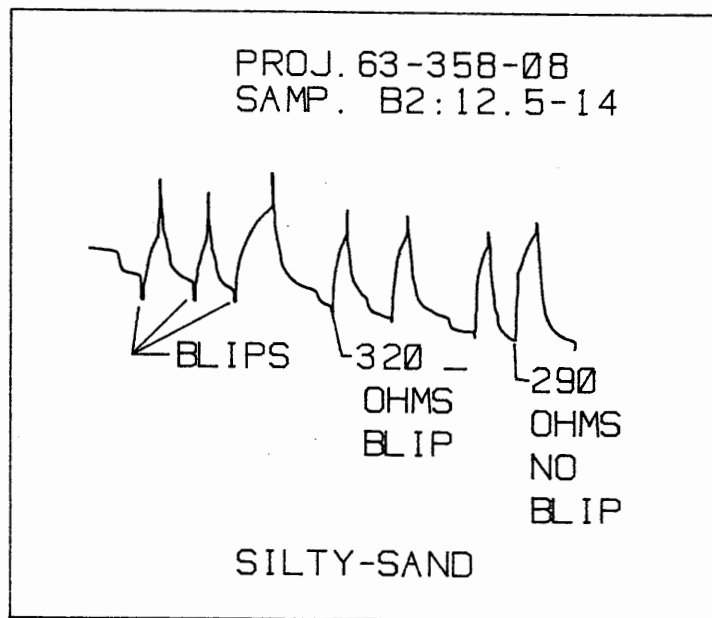


Figure 23: Null detector tracings for sample #10

After the bridge circuit was balanced the linear polarization curve was determined. This plot of applied anodic or cathodic current versus overvoltage results in the polarization resistance from which the corrosion current is computed. Anodic polarization was used consistently in this study since it was desirable to polarize the steel as the anode. Jones (14) outlined the galvanostatic procedure which

was used in this project and is summarized here.

The first step in obtaining the polarization plot (applied current versus overvoltage) is to determine the corrosion potential, E_c . The corrosion potential is simply the potential between the zinc reference electrode and the steel working electrode which drifts over time due to self-polarization because the dissimilar metals result in a small amount of current flowing between them.

The corrosion potential serves as a reference value above which overvoltages are produced by the application of polarizing current steps. Figure 24 is a schematic presented by Jones (14) of a potential-time recorder trace during a galvanostatic polarization resistance measurement.

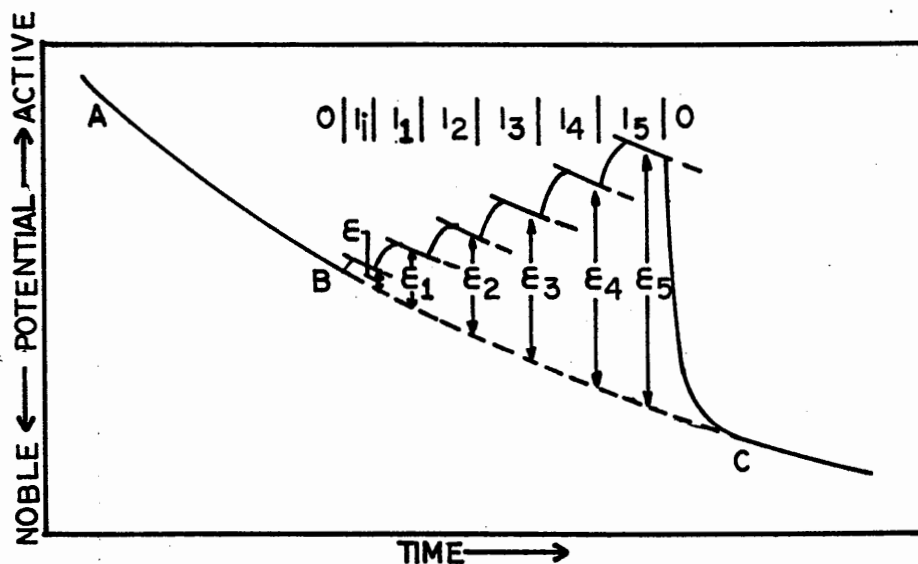


Figure 24: Potential-time recorder trace
(From Jones, 15)

Line A-B represents the drift of the corrosion potential over time. In this study, the soil samples were monitored, over time, for drift in corrosion potential. Line A-B was determined when the drift in corrosion potential was sufficiently minimized.

After Line A-B, representing the uniform drift of corrosion potential, was determined, the polarizing current

steps were applied. These polarizing current steps are represented by currents I_1 through I_5 , shown in Figure 24. I_1 is an initial current which is used to see how much overvoltage is produced by this value of current, and is chosen in a trial and error fashion. I_1 should produce an overvoltage of about 2 millivolts. The following current steps are applied and held constant over a chosen time interval so that the resulting overvoltages remained steady-state. The last of which should result in an overvoltage of no more than 20 millivolts. In this study, current steps applied for 30 seconds each routinely resulted in steady-state overvoltages.

After application of a current step that causes a total steady state overvoltage of about 20 millivolts, the power supply is shut off. This point is analogous to the second "0" in Figure 24. The potential now returns to a point analogous to point C in the figure.

Reducing the data involves first interpolating the line analogous to the dotted line B-C in Figure 24. The interpolation of this line can be subjective, depending on the regularity of the drift in the corrosion potential. Any error was minimized by allowing the corrosion potential to stabilize as much as possible before proceeding with the polarization procedure. The interpolated line represents the drift in corrosion potential if the polarizing current steps had not been applied. This line serves as the reference value of corrosion potential above which the overvoltages, ϵ_1 through ϵ_5 , in the figure, are measured from the strip chart recorder. The strip chart recorder, connected to the electrometer as null detector, is calibrated so that the overvoltages are measured in millivolts per centimeter. It must be remembered that the overvoltages measured must be multiplied by 2 as shown in Equation 29. Figure 25 is a copy of the potential-time recorder tracing when the same silty sand, Sample #10, from Project 63-358-08 was tested.

Figure 26 is a schematic linear galvanostatic polarization plot (from Jones (15)) of the data obtained in Figure 24; Figure 27 is the plot for the silty clay from this study.

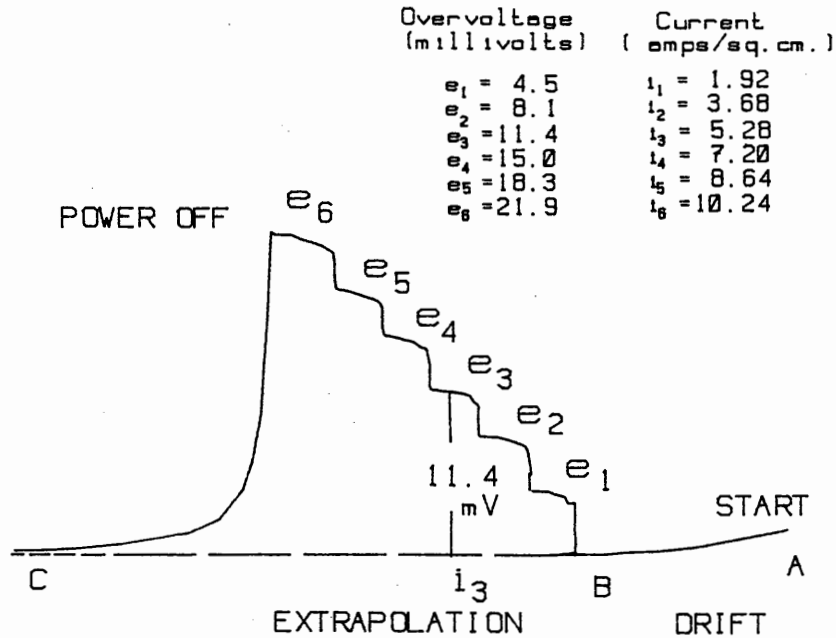


Figure 25: Potential-time recorder trace for silty sand from 63-358-08 (#10)

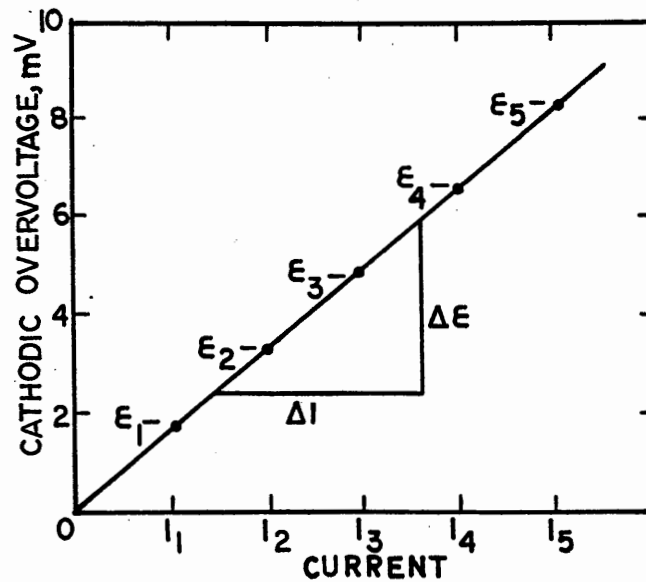


Figure 26: Linear polarization plot for data obtained from Figure 23 (From Jones, 15)

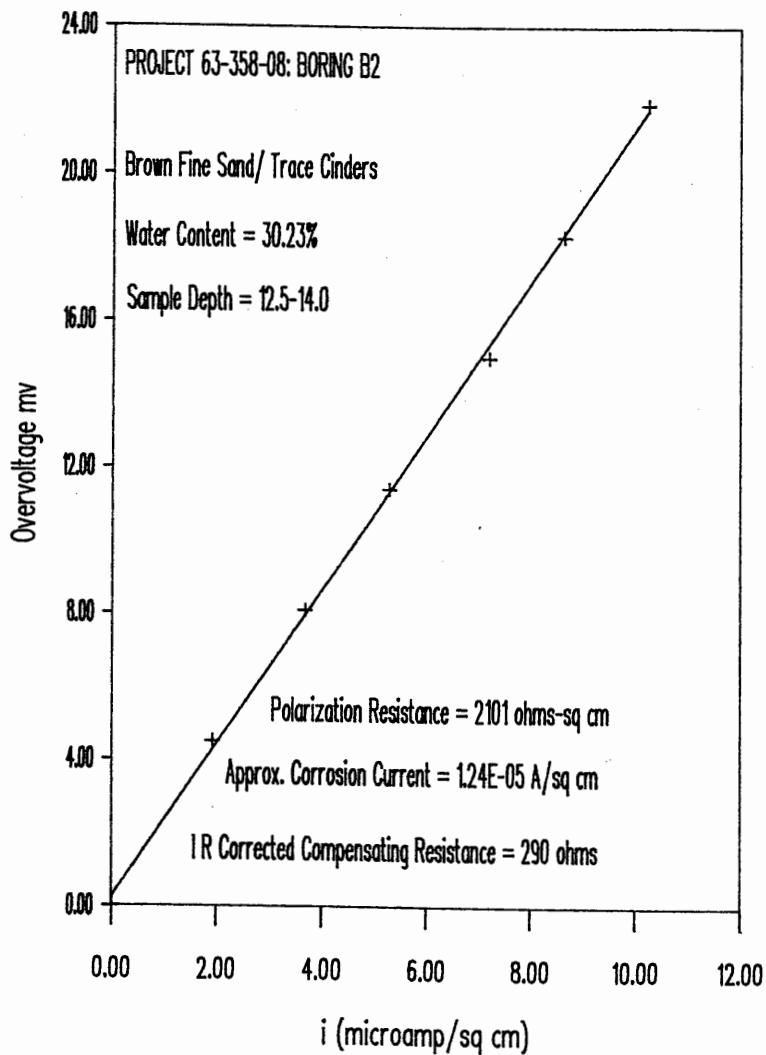


Figure 27: Linear polarization plot for the silty-sand (sample #10).

The slope of each of these plots is the respective value of R_p , the polarization resistance, which can then be used in Equation 24 to obtain the corrosion current.

13. DATA AND ANALYSIS

A. General

The data presented in this chapter follows directly from the outlined Testing Program. Pile corrosion data is presented in terms of the cross sectional area lost (corroded) on a six to eight inch long section of pile. Stress concentrations develop in the metal between the losses making the total loss along this length an effective cross section reduction. This idea was presented in a previous report and is shown in Figure 28.

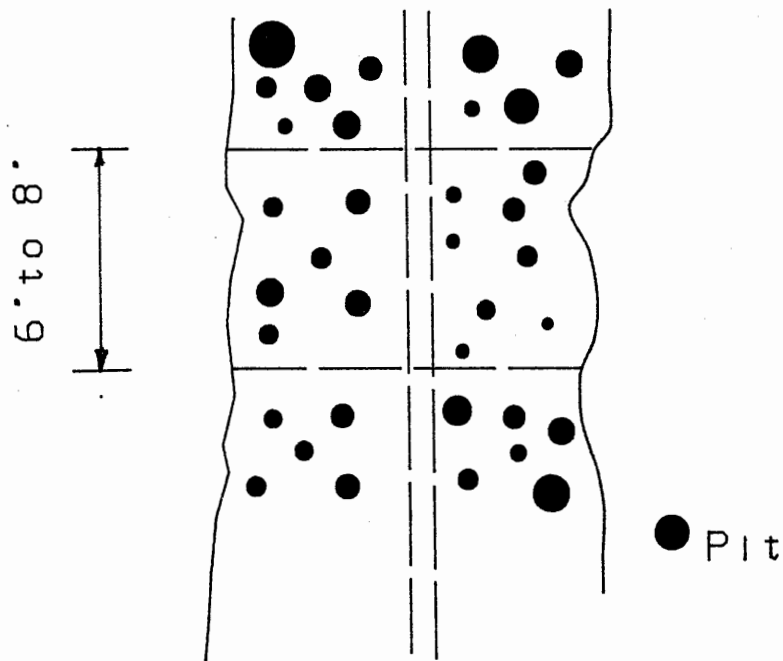


Figure 28: Schematic layout for measuring metal loss.

The cross-sectional area lost was determined using specially made calipers shown in Figure 29.

These calipers were used in the field on pile samples underneath pier SWE7 in Hartford. In addition, the calipers were used, in the laboratory, on pile samples taken from beneath Abutment 2 wingwall in Hartford and Structure 9, Windsor. A typical sheet used for the measurement and calculation of cross sectional area lost is shown in Figure 30.

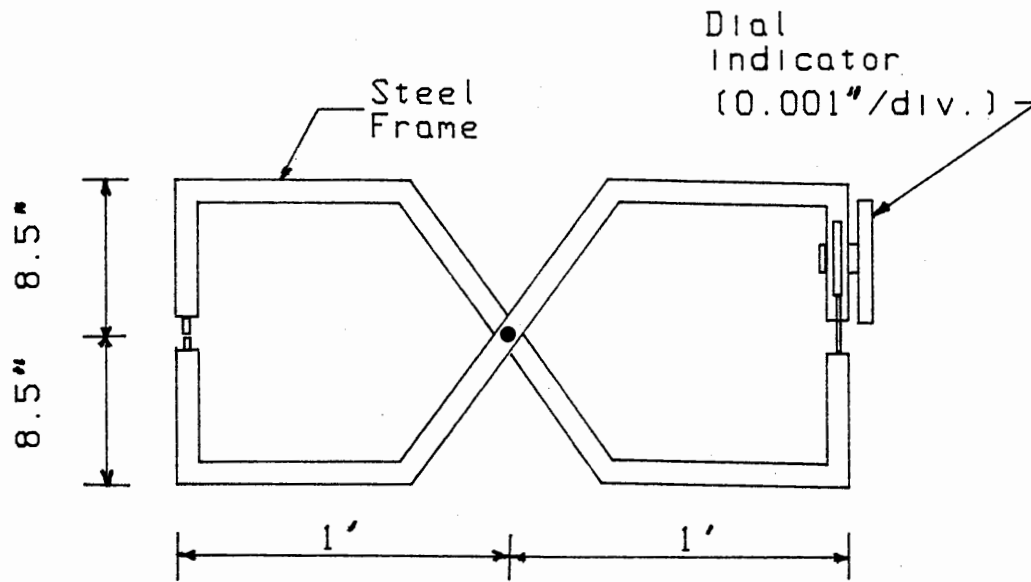


Figure 29: Calipers to measure pile thickness

Date Proj.	Corrosion Loss		Best Area Flg. Web
	Section Size Flg. Thk	Depth Web. Thk	

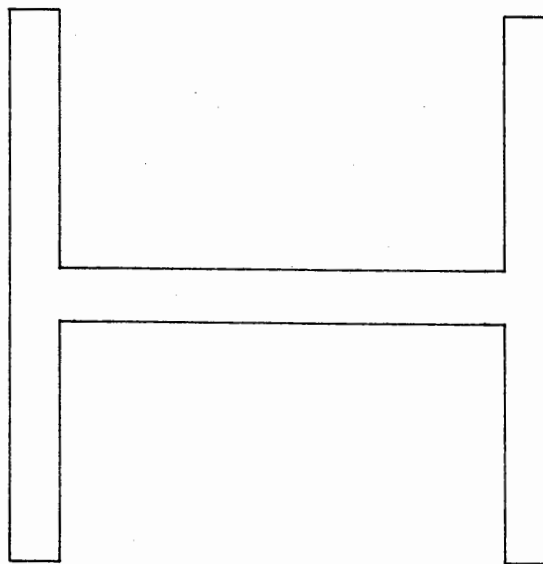


Figure 30: Sheet used for the calculation of pile cross sectional area lost.

Piles from Project 375-08 beneath pier SWE7 had an average cross sectional area loss of 6%, the highest loss being a loss of 10%. Corrosion of piles at this site is described as "low."

Piles from project 358-08 beneath Structure 9 in Windsor, CT. had an average loss of cross-sectional area of 45%. The highest measured cross-sectional loss was 70%. Corrosion of piles at this site was considered high. The electrical potentials between points on the surface of the ground were made using a high resistance voltmeter and CU/CU SO₄ electrodes. These measurements showed that the greatest potentials occurred near the railroad tracks, and the measured potentials decreased with distance from the tracks. The greatest corrosion occurred on piles that were on the side of the group away from the railroad tracks. It was concluded that these losses were due to stray currents because the losses coincided with the direction in which current flow in the ground would proceed i.e. from higher to lower potential.

Finally, piles numbered 12 through 15 extracted from beneath the wingwall of Abutment 2 in Hartford had an average cross sectional area loss of 45%, the highest being 55%. In addition, some of the pile sections at this site were so severely corroded that the pile sections broke in two while they were being pulled from the ground. Consequently, corrosion of piles at this site is described as "severe."

All of the soil samples from each site were tested for resistivity in the saturated condition, however, only those samples having saturated resistivities less than (or near) 1000 ohm-cm were further analyzed. These samples were listed in Tables 2 and 3.

B. Analysis of Corrosion Indicators

Corrosion indicators are presented in Tables 2 through 4 as well as Figure 31. The corrosion indicators examined in this study are: resistivity, contact potential, self current, pH, corrosion current and chloride and sulfate content. Following the analysis of the corrosion indicators taken separately, a collective analysis will be presented. Soils were tested for resistivity and polarization resistance in the saturated condition.

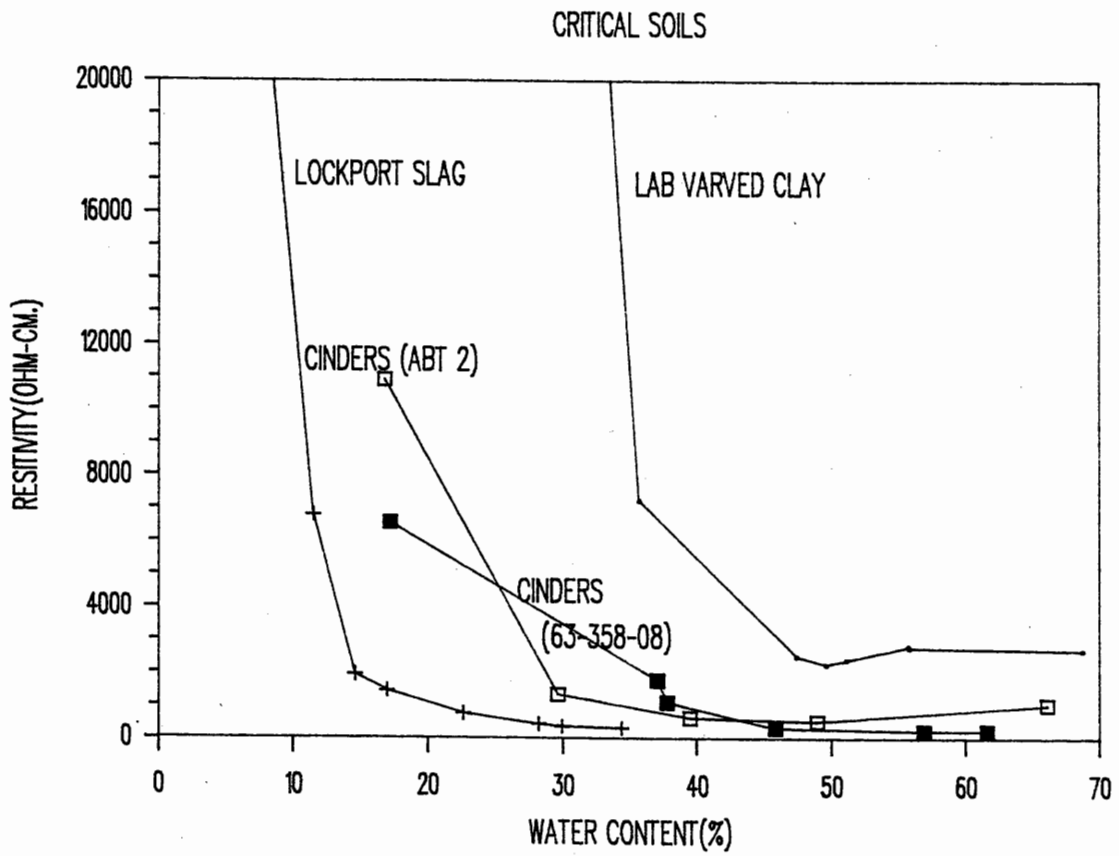


Figure 31: Resistivity vs. water content for selected soils

Table 2: Resistivity, pH, and corrosion current

(1)	(2)	(3)	(4)	(5)
PROJECT	SAMPLE #	RESISTIVITY (OHM-CM.)	Ph	CORROSION CURRENT amps/cm x 10 ⁻⁶
63-375-08	1	428	6.5	71
	2	1152	6.7	38
	3	1179	7.1	30
	4	985	7.1	29
	5	1204	4.6	46
	6	998	5.7	24
	7	1204	6.2	42
	8	760	6.0	24
63-358-08	9	1028	6.5	490
	10	1980	5.6	12
	11	1376	9.4	-
	12	1207	4.4	90
	13	2874	6.4	19
	14	950	7.9	29
	15	869	7.6	20

TABLE 3: Resistivity, pH, Corrosion Current

(1) PROJECT	(2) SAMPLE #	(3) RESISTIVITY (OHM-CM)	(4) pH	(5) CORROSION CURRENT i_{corr}	(6) CHLORIDES (mg/l)	(7) SULFATES (mg/l)
ABUT. 2	16	1489	4.2	-	323.9	184.6
	17	903	4.2	-	395.6	48.3
	18	408	4.6	-	256.6	32.4
	19	301	4.4	29	407.2	1648.2
	20	504	4.8	23	129.7	1624.9
	21	247	7.1	470	589.1	1373.5
	22	808	5.5	-	434	82
	23	425	3.2	-	475.7	15.3
	24	2707	5.5	-	88.3	33
	25	454	6.8	160	90.6	137.9
BRIDGEPORT	26	401	5.8	68		
	27	1139	5.2	39		
	28	493	6.3	36		
	29	185	4.2	27		
	30	508	6.4	56		
	31	339	4.2	48		
	32	109	4.8	96		
	33	61	6.4	20		
	34	300	7.3	-		
	35	2600	4.6	29	24	40

Tables 2 and 3 include approximate minimum resistivity data for the critical soils from all of the sites. As can be seen in Figure 31 resistivity varies with water content. Specifically, minimum values of resistivity are reached when soils are close to saturation. Minimum values of resistivity are of interest because they indicate the worst case conditions in terms of corrosion. In addition, saturated resistivities provide a standard for comparison of field samples.

Each of the projects have a number of soils with minimum resistivities less than or near 1000 ohm-cm. so it is difficult to correlate pile corrosion to resistivity without some supporting data. However, it is interesting to note that samples from Bridgeport, CT have the lowest resistivities of the critical samples from all of the project sites. In addition, miscellaneous fill materials from all of the sites have lower saturated resistivities than natural soils.

The Column (4) in Tables 2 and 3 lists the pH values for the critical soils. Elias (20) summarized the pH criteria for the determination of the corrosiveness of soils in contact with metallic buried reinforcements. This criteria is expressed in terms of limits on the pH value for soils to be used as backfill in contact with steel. In the United States, these fill materials must have a pH value greater than 5 but less than 10, indicating that soils with pH values outside this range tend to be corrosive when in contact with steel. Soil pH values may be meaningful for piles in contact with macro cells if indeed these pile sections are rendered susceptible to corrosion attack similar to buried metals. Consequently, soil pH values should be analyzed collectively with contact-potentials.

The Column (5) in Tables 2 and 3 shows the corrosion current density for the critical soils. As stated earlier, the testing program was designed so that the corrosion current for the critical soils could be compared for soils setting up macro cells. Consequently, corrosion current data should be interpreted along with contact potential data. The basic premise is that soils with high corrosion currents in contact with steel are more corrosive than soils with lower corrosion currents; the comparisons are relative. Corrosion current conversions to corrosion rates were made for two reasons: to obtain relative values for comparative purposes and to determine if the losses as observed at abutment 2 correlated with loss from macro cells and corrosion current. Stearn's equation, relating the polarization resistance to the corrosion current, was used. Beta values of 0.12 volts were used, to obtain the comparative values of corrosion current (23).

As seen in Tables 2 and 3, several samples have corrosion current values significantly greater than average of these soils. This can be seen more clearly in Figure 30 which is a plot of corrosion current versus resistivity.

As can be seen in Figure 32, the soils with the relatively high corrosion currents are mostly miscellaneous fill materials. Project 63-375-08 does not include any of these samples, Project 63-358-08 has two of these samples (sample #9 and 12), Abutment 2 includes 2 of these samples (#21 and #24), and Bridgeport includes one of these samples (#32).

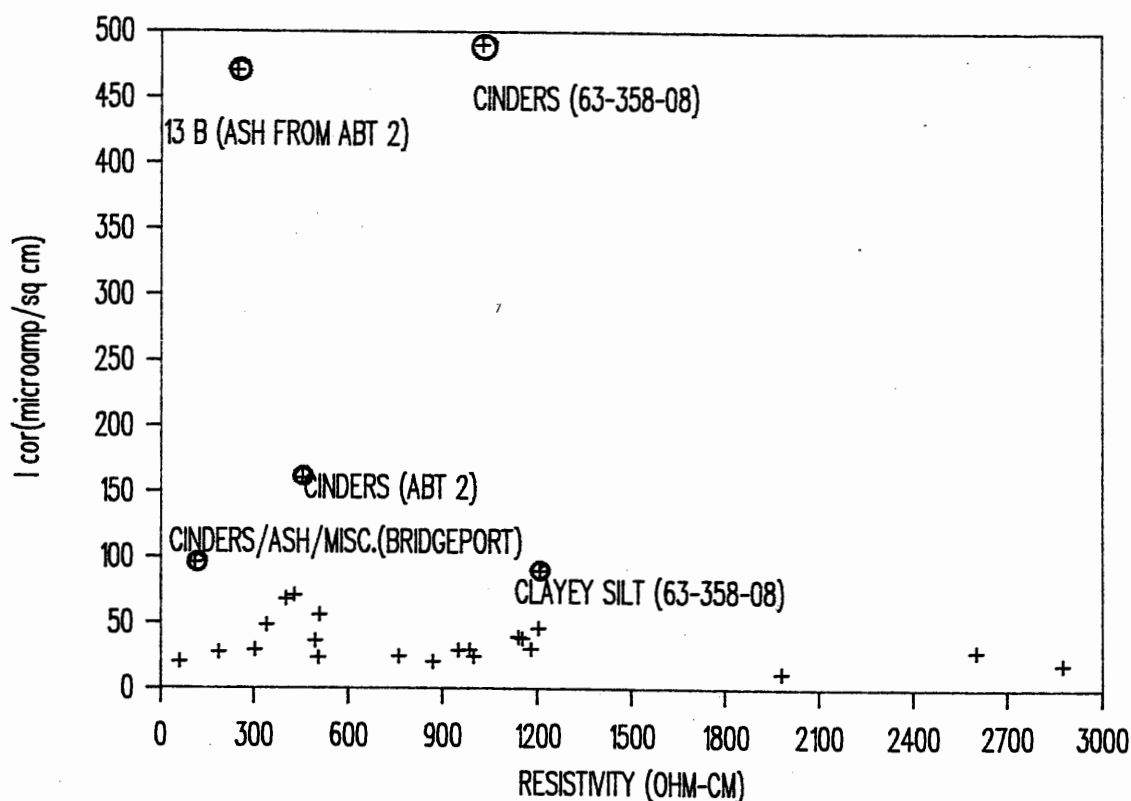


Figure 32: Corrosion current versus resistivity

Corrosion currents were determined for those soils having low resistivities and high sulfates or chlorides for soils from Abutment 2 in Hartford. As can be seen in Table 3 samples 19, 20, and 21 have the highest values of chlorides; consequently samples 19 through 21, as well as sample 25

(cinders) were tested for corrosion currents. Of these four samples tested, two samples (#21 and #25) had high relative corrosion currents, a result which may be used in an analysis along with contact-potentials to explain the severe corrosion measured at Abutment 2.

It is interesting to note that cinders were found in two instances to have relatively high values of corrosion current in comparison to natural soils. This fact again points to the corrosive nature of certain layers of miscellaneous fill. Crushed coal, on the other hand, had a relatively low value of corrosion current (in the same range as the natural soils tested) indicating that coal particles are not as corrosive, acting alone, as cinders.

Table 4 lists the maximum values of contact-potential for contiguous soil layers each having resistivities less than or near 1000 ohm-cm. Maximum values were used because self-potential values vary over time and a standard value was needed to make consistent comparisons. The use of maximum values is conservative. Some samples were checked periodically for self-potential over the course of one day; other samples that varied greatly were monitored over the course of one week. It is interesting to note that the most stable values of self-potential were generated from soils taken from the wing-wall of Abutment 2 in Hartford, where the greatest corrosion of piles occurred.

The previous report on corrosion of steel piles indicated that contact-potential values greater than 0.10 volts could be indicative of corrosive galvanic action, if the soil resistivity was less than 1000 ohm-cm. (1)

Project 63-375-08 (samples 1 through 8) includes only two situations in which contiguous soil strata have low resistivities. Furthermore, the maximum self-potential values are less than 0.10 volts, indicating that galvanic action is not pronounced at these sample locations. These low values of contact-potential correlate well with the minimal corrosion found on piles in this area.

Project 63-358-08 (samples 9 through 15) includes only one situation in which contiguous soil strata each having low resistivities are present. In addition the contact-potential between these two layers (samples 14 and 15) is only .026 volts maximum. However, high corrosion was measured on piles which were driven through these soils. This corrosion could be explained by stray currents present due to a greater potential in the ground near the railroad tracks in this area.

Soil samples removed from piles exposed from the wingwall of Abutment 2 in Hartford were tested for contact-potential as

Table 4: Contact-Potential between Contiguous Soil Layers (resistivity <1000 ohm-cm. each)

PROJECT	CONTIGUOUS SAMPLES	CONTACT-POTENTIAL (VOLTS)	SELF-CURRENT (milliamps)
63-375-08	#1/#2	.04	-
	#7/#8	.08	-
63-358-08	#14/#15	.026	-
ABUT. 2	#16/#17	.08	.15
	#17/#18	.40	.12
	#19/#20	.42	.12
	#20/#21	.45	.19
	#22/#23	.60	.20
	#23/#24	.68	.06
	#25/#35	1.0	.56
	BRIDGEPORT	#26/#29	.18
	#27/#29	.05	.03
	#28/#29	.05	.05
	#30/#29	.065	.06
	#31/#29	.05	.05
	#32/#29	.17	.035
OTHER	#33/#35	1.0	.65
	#34/#35	.60	.1

well as self generated current. As one can see in Table 4, samples corresponding to pile sections 12, 13, and 15 had appreciable contact-potentials; almost all values were much greater than the .10 volt minimum. Maximum self-generated current values (which also vary over time) ranged from 0.06 mA to 0.20mA. It is important to note that sample #24, corresponding to soil 15B, had a saturated resistivity of 2707 ohm-cm., which could explain why the junction of soils 15M (#23) and 15B (#24) passed only 0.06mA. All of the other samples tested for contact-potential from Abutment 2 had

resistivities less than 1000 ohm cm. (see Table 3) and thus passed greater amounts of current.

Cinders taken from a layer near Abutment 2 (sample 25) were tested contiguous to a clay sample from the University of Connecticut Soils Laboratory. These two soils contiguous to one another generated a maximum contact-potential of 1.0 volts and passed a maximum of 0.56 milliamps of current. These extremely high values point to the potential for the cinders in this area to set up corrosive galvanic cells when in contact with the clay in the area.

In general, the high values of self-potential for contiguous, low resistivity soils from Abutment 2 correlate well with the measured severe corrosion.

Samples from the site in Bridgeport, CT. that contained miscellaneous fill material were checked for contact-potential/current versus a clay sample from Bridgeport. Two of these contact-potential measurements (samples 26 and 32) resulted in maximum values greater than 0.10 volts; however self generated current values were, in general, lower than those values of current generated from soils from Abutment 2. These relatively lower values of self-generated current could indicate that the piles near these soils are not as severely corroded as those taken from beneath Abutment 2. However, the high values of contact-potential should cause concern.

Contact-potential/current measurements were also made on crushed coal and Lockport slag; both samples were tested contiguous to a remolded varied clay sample from the University of Connecticut Soils Laboratory. Coal particles are present in coal-ash, a common type of miscellaneous fill material. It is interesting to note that both the coal and the slag, in contact with the lab clay, produced high values of contact-potential, current indicating corrosive activity. As seen in Table 4, the values are in the same range as those from Abutment 2 in Hartford. The high value of contact-potential/current resulting from the Lockport slag/lab clay cell correlates well to severe corrosion found on reinforcing steel strips used in the slag backfill in Lockport, New York (8). A clay layer actually exists beneath the Lockport slag which could set up a galvanic cell producing the contact-potential/current analogous to the cell set up in our laboratory.

Now that the corrosion indicators have been discussed individually, it is easy to see what types of values for all of the indicators together would signal a very corrosive situation. Specifically, one would search for contiguous soils generating a contact-potential of about 0.1 volts and a self-generated current of about .1mA when using a soil box

having an A/L ratio of 0.9. Each of the soils should have resistivities less than or near 1000 ohm-cm. If indeed the pile sections in the area of the macro cells become analogous to buried steel, then corrosion currents, chemical composition, and pH values for the soils could cause weight loss in addition to that from the macro cell. Specifically, one would be concerned by relatively high corrosion currents and chloride and sulfide contents which are also relatively high. In addition, pH values less than 5 or greater than 10 could also point to added corrosion in the region of a pile subjected to a macro cell.

Obviously, it would be rare that all of the above criteria would be satisfied by contiguous soils, so it is necessary to evaluate which, or which combination, of these criteria is the most important. One would speculate that any combination of the critical parameters would point to a potentially corrosive situation. However, the fact that contact-potential values for soils from Abutment 2, where severe corrosion occurred, are much greater and more stable than contact-potential values for soils from the other sites, where less galvanic corrosion occurred, highlights the importance of contact-potential values in general. High relative values of corrosion current for the contiguous soils are indeed additive to the effect of the macro cell. However, the effect of a macro cell can, by itself, lead to a significant loss of metal (1). The same idea holds true for the pH values; corrosive (<5 or >10) pH values for soils which are not part of a contiguous current generating system, with contact-potentials of at least 0.10 volts, do not indicate a corrosive situation for driven steel piles. An example of this premise would be sample #5 from Project 63-375-08 which has a corrosive pH value but is not part of a two soil galvanic cell comprised of low resistivity soils with an appreciable contact-potential.

The soils corresponding to pile sections 12 through 15 from beneath the wingwall of Abutment 2 in Hartford comprise situations conducive to corrosion of steel piles. Specifically, the worst of these situations includes samples #20 and #21, corresponding to pile section 13, which set up a system with a high contact-potential/current. In addition, both of the samples have low resistivities and relatively high values of chlorides as compared to the other soil samples that were remaining on the extracted piles. Furthermore, one of the samples has a low value of pH (#20) while the other has a high value of corrosion current (#21). Soil samples corresponding to pile sections 12 and 15 also set up macro cells with high contact-potentials. Some of these samples have corrosive pH values as well, adding to the severe corrosion measured on these pile sections.

Although Projects 63-375-08 and 63-358-08 include many soils with low resistivities, no situations exist in which contiguous low resistivity soils set up an appreciable

Although Projects 63-375-08 and 63-358-08 include many soils with low resistivities, no situations exist in which contiguous low resistivity soils set up an appreciable contact-potential. This is why minimal galvanic corrosion occurred at these sites. It must be remembered that the low resistivity samples easily could have enhanced the stray-current corrosion of piles beneath Structure 9 (63-358-08).

Bridgeport, on the other hand, has a situation that might include a local galvanic cell. The contiguous soil layers in question are samples #32 and #29. As can be seen in Tables 3 and 4 the maximum contact-potential of these extremely low resistivity soils is high (0.17 volts). Although this data in itself is enough to cause concern, it should be noted that both of the soils have corrosive pH values and one of the soils (#32) has a relatively high corrosion current. All of these factors analyzed collectively point to a situation leading to corrosive action. The corrosion at this site in Bridgeport has no danger of causing failure because the steel is in a cylinder that surrounds a cast-in-place concrete pile. Exposing the piles will be a check on the hypothesis presented here.

C. Long Term Studies on the Galvanic Cells of Miscellaneous Fills

The purpose of the following two sections is to provide further analysis of contact-potential and self generated current between contiguous soil layers. In essence, we are investigating the galvanic cell of the type STEEL/SOIL1/SOIL2/STEEL mentioned by Evans (10). Of course, the steel in this cell is represented by the driven pile in the field.

Contact-potential and self generated current vary over time, depending on the two soils in contact. It was decided that tracking the self-generated current over time is of great significance, since it is the current which leads to the corrosion of steel at the anode. In addition, the effect of miscellaneous fills in contact with clay sample was chosen for long term study because of the relatively high values of contact-potential generated between these types of soils.

Figures 33 through 35 show the variation of current with time for two soil cells consisting of coal/clay, Lockport slag/clay, and cinders from Abutment 2/clay.

CRUSHED COAL/LAB CLAY

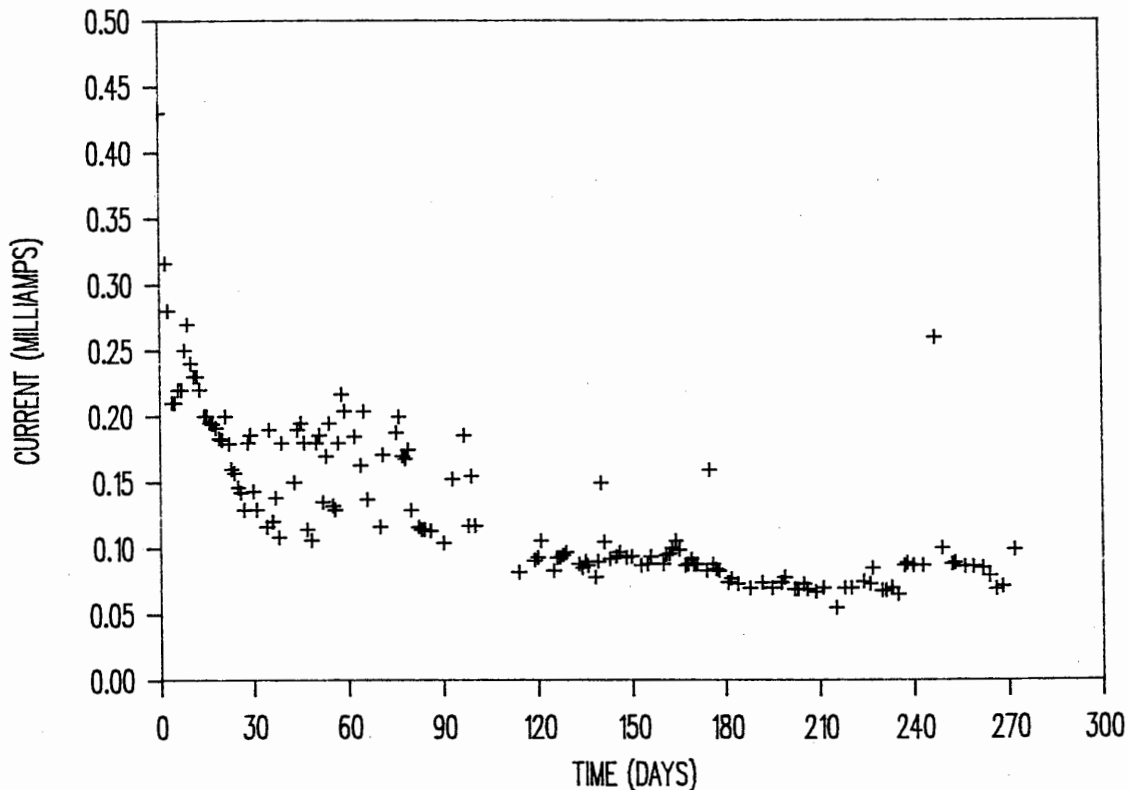


Figure 33: Current versus time for coal/clay cell

An attempt was made to keep the water content of the soils constant over time by covering the samples and storing them in a high humidity environment. However, the samples lost moisture and distilled water was added to the surface of the soils approximately every 2 months. It is important to note that the steel electrode in contact with the clay became the anode in all three cases.

As can be seen in Figures 33 through 35, all of the 2-soil cells passed appreciable amounts of self generated current over a nine month period, even though the samples were slowly drying out. In addition the contact-potential of these 2-soil cell was fairly constant over this nine month period; all of the 2-soils cells had contact-potential values greater than 0.10 volts.

In some cases, the self-generated current increased sharply when water was added to the 2-soil cell. An example of this is at a time of approximately 140 days for the cinders/clay cell. This phenomenon points to the possibility that self-generated current could increase or decrease depending on rainfall. In any event, this simple laboratory

model indeed confirms that current is passed by 2-soil cells over time. Weight loss data resulting from this self

CINDERS FROM ABUTMENT #2/LAB CLAY

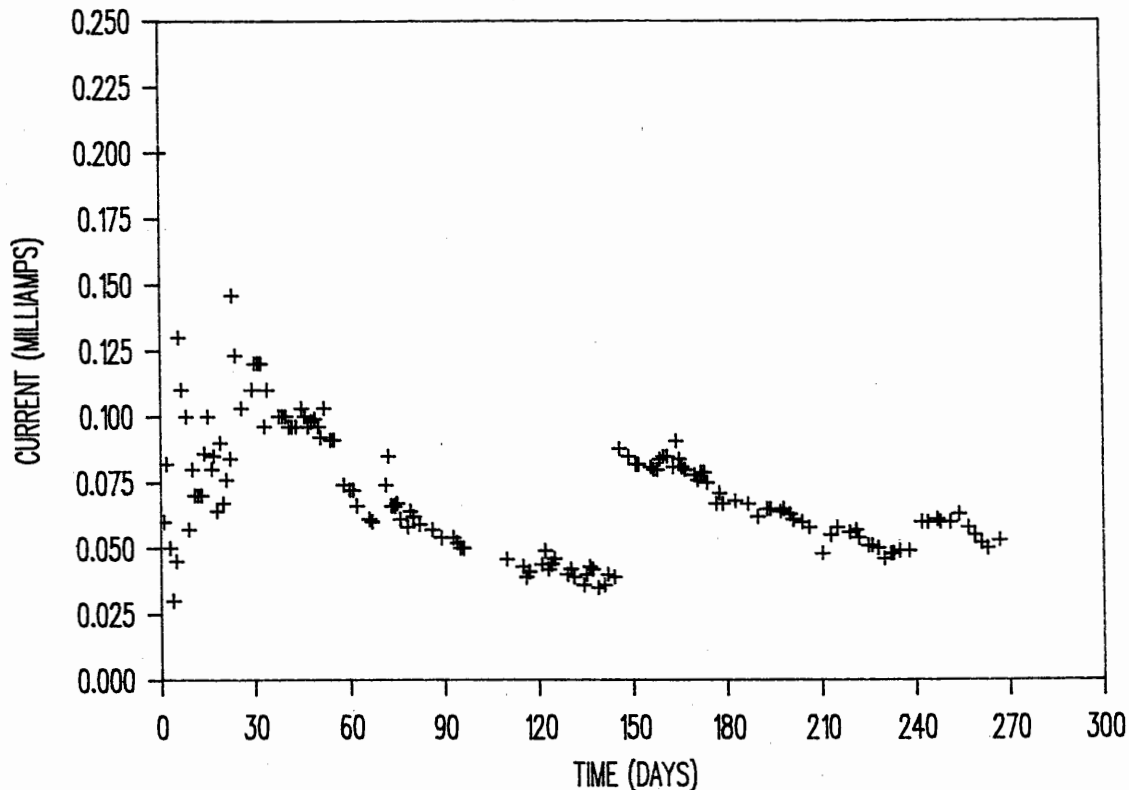


Figure 34: Current versus time for cinders/clay

generated current is presented and analyzed in the following section.

D. Analysis of Weight Loss Resulting From Long Term 2-Soil Galvanic Cells.

the corrosion current, which is just the exchange current at equilibrium resulting from the two soils in contact with the steel, from the miscellaneous fill/lab clay should be added to the weight loss from the self-generated current. In essence, we have an additive effect since the miscellaneous fill/lab

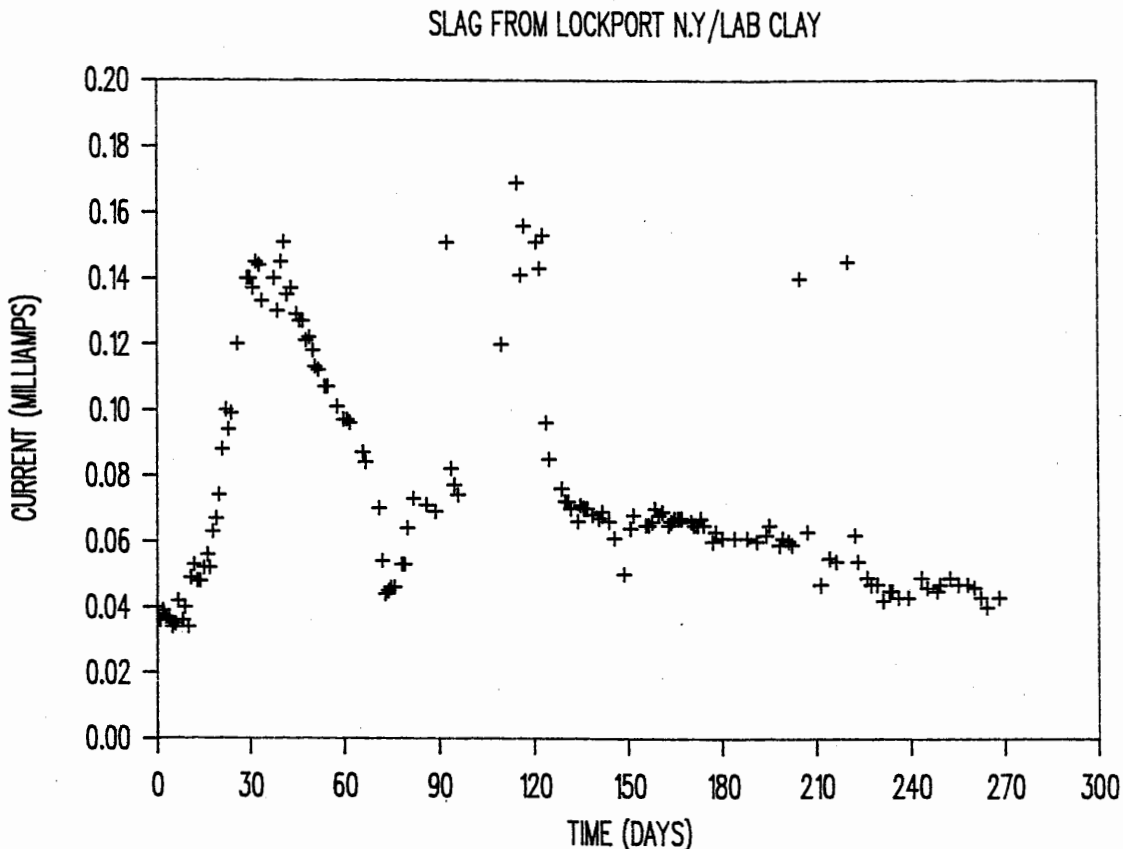


Figure 35: Current versus time for slag/clay cell

clay itself would cause corrosion even if it did not set up a galvanic cell.

The situation at the cathodes is different. The self generated current should not result in any weight loss at the cathodes. However, weight loss may occur at the cathode resulting from the corrosion current developed from contact between the soil and the steel electrodes.

It is evident that we need values for corrosion current for the 2-soil cells. Table 5 shows the values of corrosion current for the 2-soil cells at the end of the 9 month period. The zinc reference electrode was placed in the clay for all three determinations while the working electrode was the

anode.

Examining figures 33 through 35 and Table 5 reveals that after a nine month period the corrosion currents resulting from the 2-soil cells are of the same magnitude as the self generated currents. We can assume that this held true throughout the testing period in order to make a first approximation of weight loss. To further simplify the analysis we can assume that at any given time the self-generated current is equal to the corrosion current (from the 2-soil cells). This assumption allows us to calculate the

Table 5: Corrosion Currents for 2-soil cells

CELL	I_{corr} ($\mu\text{A}/\text{sq.cm.}$)
(1) slag/clay	31
(2) cinders/clay	30
(3) coal/clay	48

weight loss due to the self generated current and to double this value to obtain the total calculated weight loss at the anode.

The weight loss at the cathodes should be calculated only from the corrosion current which would result in one half of the total weight loss at the anodes. Table 6 shows the results of the calculated and measured weight losses.

Table 6: Weight loss data for 2-soil cells

CELL	ELECTRODE	MEASURED LOSS (grams)	CALCULATED LOSS (grams)
(1)	anode	.86	1.08
(1)	cathode	.48	.54
(2)	anode	.83	.84
(2)	cathode	.40	.42
(3)	anode	.73	2.1
(3)	cathode	.27	1.05

Our assumptions allow the calculation of an approximate weight loss. Calculated and measured weight loss for cells

(1) and (2) compare. However, the measured losses were lower than the calculated losses for cell (3), the coal/clay cell. The overall agreement between measured and calculated weight loss for all three cells is good considering the substantial scatter in the data points comprising the current versus time curves for the two-soil cells.

In any event, the measured weight loss can be converted to a penetration rate. For example, cell (2) had a weight loss of 0.83 grams at the anode over a nine month period. Using the density of steel, and the area of the anodic plate (1 sq. inch), one computes a penetration rate of 8.6 mils per year (1 mil = 1/1000 of an inch) in thickness. Over a thirty year period (the amount of time that the piles in Hartford were in place) the flange of a pile would lose 0.26 inches in thickness. The loss could also take place from both sides of the flange, causing that part of the flange, which had a thickness of 0.436 inches when driven, to disappear. The actual corrosion may slow somewhat with time, but this demonstration shows that the observed weight loss at Abutment 2 can be predicted with reasonable accuracy if all of the contributions to corrosion are taken into account.

14. SUMMARY AND CONCLUSIONS

A. Summary

This investigation has included an examination of the subsurface conditions conducive to the corrosion of driven steel piles. Two situations were investigated. The first situation involved testing soils for their corrosive properties acting alone. Tests on soils were performed which resulted in parameters normally used as corrosion indicators for buried metals. These tests consisted of resistivity, pH, and corrosion currents and were used to investigate the possibility that local galvanic cells override global protection, rendering pile sections in the region of the local cells susceptible to corrosion attack, as if these sections were buried metals.

The second situation involved the investigation of contiguous soil layers that set up macro cells of the type found in the literature. A method for measuring the contact-potential and self generated current from contiguous soil layers was developed. These two parameters were found to be highly indicative of subsurface conditions resulting in corrosion of steel piles.

A collective analysis of the results from the soil tests listed above was used to explain the corrosion measured. It was shown that an appreciable self-potential is necessary to cause galvanic corrosion; without this potential, current can

not be driven to corrode the pile.

Finally, long term weight loss tests were conducted on two soil cells which generated relatively large contact-potentials. These cells consisted of miscellaneous fills in contact with clay samples. Measured weight loss compared reasonably well to calculated weight loss.

B. Conclusions

1. Driven steel piles may experience substantial corrosion when surrounded by contiguous layers having contact-potential values of 0.1 volts and resistivities less than 1000 ohm-cm.

A) This situation is often found in miscellaneous fills in contact with clays, above or at the ground water table.

B) These contiguous soils, in the saturated condition, may initially pass approximately 0.1 milliamp (minimum) of self generated current when placed in a soil box having an A/L ratio of approximately 0.90.

C) Values of soil pH in the corrosive ranges and corrosion currents may increase the metal loss above that due to corrosion by the macro cell.

2. Values of contact-potential and self-generated current high enough to cause the corrosion studied here were among the highest observed, and were relatively stable with time.

3. Miscellaneous fill materials tested in this study have very low resistivities and relatively high corrosion currents, conditions found to be corrosive against buried steel.

4. Cell composed of STEEL/SOIL1/SOIL2/STEEL develop anodic potentials in one steel electrode and cathodic potentials in the other. Both electrodes experience weight loss during long term tests. In this study, weight loss at the anode was approximately 2 to 3 times the weight loss at the cathode.

5. Corrosion currents are difficult to determine

for some types of particulate materials due to large, irregular drifts in corrosion potential.

15. RECOMMENDATIONS FOR THE INSITU DETECTION OF PILE CORROSION

The research to date has provided a working hypothesis and techniques for the detection of pile corrosion. These must be field verified. It is important to check all locations that appear capable of supporting substantial corrosion as well as some sites that are marginal to refine this hypothesis. The most severe losses found to date occurred above or at the ground water table.

As a result of this research the following steps are recommended to detect subsurface conditions that may support corrosion of steel piles:

1. Review drawings and boring logs of bridge foundations founded on steel piles. Select for further study those whose boring logs indicate are surrounded by layered particulate material such as that occurring in miscellaneous fills.
2. At the sites selected for field study, make machine borings taking continuous samples in such a way that contiguous samples can be identified and preserved for laboratory testing.
3. At the field site make a measurement of the corrosion potential of the individual piles in the group. The instrument to do this has been developed recently by the Federal Highway Administration. It has been used by N.Y. State. As of this writing there is no report available, but this technique should be investigated further.
4. In the laboratory measure minimum resistivity and contact potential of all the contiguous soil layers. With experience it will be possible to eliminate certain types of layers such as sand.
5. Select the contiguous layers having a contact potential of 0.1 v or more and a resistivity of about 1000 ohm-cm or less for further study including: pH, concentration of chlorides and sulfates, and polarization resistance.
6. Based on the test results make an estimate of the corrosion losses in the field.
7. Develop a tentative plan for strengthening the bridge foundation weakened by corrosion.

8. Excavate the pile group, inspect and correct as needed.

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APPENDIX A

Procedures for Measuring Polarization Resistance

1. Electrometer must be warmed up for about 30 minutes before beginning these procedures.
 - a. Move switch from power off to center zero.
 - b. Bottom dial (metal colored) should be set on volts.
 - c. Zero check should be locked.
 - d. Feedback set to normal.
2. Calibration of the working cell against the standard cell for the potentiometer. (Electrometer must be in the warmed up and zeroed in "lock" position.)
 - a. Power box switch to the off position.
 - b. S2 switch toward the Battery pot.
 - c. Set potentiometer to 1.0186 v.
3. Zero Electrometer and calibration of working cell
 - a. Keep in locked position.
 - b. Start with "3" scale; zero with medium and fine dial.
 - c. Unlock and adjust the working cell against the standard cell.
 - d. Proceed to next lower scale and return to b. zero in locked position then unlock and adjust the working cell toward the std. cell.
4. Set up cell with electrode.
5. Set the resistance on the bridge based on the resistivity of the soil. Make sure that the resistance is greater than actually expected. Pass between one and two milliamps through the cell and check for blip. Decrease resistance until blip disappears. Check the resistance at which the blip disappears. Record the value to be used in computing the IR drop.
6. Let the potential bleed off. Write down the time and potentiometer reading.
7. Calibrate the chart recorder.
 - a. Set chart recorder at the one mv position.
 - b. Set pen in the middle of the paper (approximately 60 on the paper) using zero knob.
 - c. Set electrometer to zero by adjusting the potentiometer.
 - d. Move the potentiometer so that the electrometer is at one extreme of the scale. Attenuate chart to one end of paper.
 - e. Move potentiometer so that the electrometer is at the other end of its scale. Attenuate chart.
 - f. check calibration several times.

8. Check for drift of Reference voltage - set chart speed 1 cm/min.
 - a. Move electrometer to 10 scale
 - b. Unlock
 - c. Go to lower scale. At each scale check to see the sensitivity. Try to reach the 0.03 scale which represents a full scale deflection of 30 mV.

9. Apply current; measure voltage (overvoltage trace on chart recorder-limit $dv < 10$ mv).
 - a. Time of each step-approximately 30 sec. - If overvoltage is not steady try different intervals.
 - b. First current step should result in no more than 2 mv so that the chart space is not exceeded.
 - c. Each additional current step should be about 2 to 3mv.
 - d. After the 5th current step shut off power source, let potential bleed off and let chart continue until you can interpolate the line correctly.

Check to insure that voltage in each increment is steady.
Change interval.

APPENDIX B

As a trial run for finding the information needed to do a field investigation of sites corrosive to steel piles, the construction drawings for I-95 the Connecticut Turnpike were reviewed. The review included the following projects by city:

<u>Town</u>	<u>I-95-Project No.</u>
Greenwich	302-01,-02,303-01,304-01
Stamford	304-02,305-01,306-01,-03
Darien	include w/Stamford and Norwalk
Norwalk	306A-01,02
Westport	307-01,02,308-01
Fairfield	309-01,-02
Bridgeport	310-01,02,311-02,-02,-03,312-01,-02
Stratford	313-03
Milford	314-01,-02
West Haven	315-02,316A-01,316B-01,316-02
New Haven	317-01,-02,-03,-04,-05
East Haven	319-01
Branford	320-01
Guilford	320-01,321-01
Madison	321-01,75-56,75-58,75-60
Clinton	321-01
Westbrook	321-01,322-01
Old Saybrook	322-01
Old Lyme	324-01
East Lyme	324-01,44-74
Waterford	324-01,325-01,-06
Montville	325-01,-06,326-01

<u>Town</u>	<u>I-95-Project No.</u>
Norwich	326-01
Lisbon	327-01
Griswold	328-01
Plainfield	329-01, 330-01
Killingly	68-91
Danielson	108-69

These plans are on microfilm. Copies of drawings showing the structure, foundation, and boring logs of all projects having steel in the pile foundations and miscellaneous fill of cinders in the boring logs were made. The drawings were then studied to see if the suspicious items on the boring logs were in a position to cause damage to the piles. In addition to the bridge over the Yellow Mill Brook in Bridgeport which was discussed in the report, the following are candidates for further study:

<u>Project Name</u>	<u>Project Number</u>
Norwalk River	306A-01
NY NH & HRR Danbury Branch	306-01-0131
Ferris Drives	304-01
NY NH & HRR Cos Cob Station	N/A
Broad Street Bridgeport	320-01
Cherry Street and Boswick Ave. Bridgeport	320-01
South Ave. Bridgeport	320-01

<u>Project Name</u>	<u>Project Number</u>
State Street Extension Bridgeport	319-01
Over Quinnipiac River	317-04
Relocation Route 7 I-95 Ramp E	102-114-03B
Ramp E - Nichols Bridgeport	311-03

The foundations of all the bridges in Bridgeport were reviewed. Only the ones included in the above list need further study.

