FINAL REPORT

Evaluation of External Corrosion-Rate Using Polarization Resistance and Soil Properties

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Executive Summary

The research project evaluated the use of the Linear Polarization Resistance (LPR) and the Electric Resistance (ER) technologies in estimating the external corrosion growth rates of buried steel pipelines. This was achieved by performing laboratory and field tests to evaluate the technologies and correlating the results with other methods such as measurements of weight-loss of buried coupons.

The LPR method provides instantaneous estimates of corrosion potential. The results may be used to identify corrosion upsets due to the changes of soil conditions and, consequently, help initiating remedial action. However, the laboratory and field measurements of corrosion rates using the LPR device showed uncertainty about their validity in partially and totally dry soils, which makes it difficult to obtain a reliable estimate of the general corrosion rate. Additionally, the average long-term measurements of the LPR in the field did not correlate with the general corrosion rates from weight-loss measurements of buried coupons.

The electrical resistance (ER) method measures the metal loss of an alloy having a composition similar to the pipe material and the device is suited to estimate corrosion rates of unprotected pipes in environments having either poor or non-continuous electrolytes such as soil. Field measurements of corrosion rates were performed using the ER probes in eleven sites at four natural gas distribution companies. Additionally, five test sections were constructed at the GTI testing facility to evaluate the soil types which are not represented in the utility sites. The results of the measurements showed that the ER device provides consistent long-term measurements of corrosion rate.

Field applications of the ER method demonstrated that the technology is an efficient one to obtain the long-term corrosion growth rate of the pipe without the need for field excavation. Field monitoring of the ER devices continues at the utility sites to enhance the estimation of the corrosion rates of the pipeline sections at the monitored locations.

External pipe corrosion is affected by a significant number of soils and environmental parameters including soil resistivity, water content, pH, soluble salts, and oxygen concentration, which makes it difficult to determine an accurate estimate of corrosion rates. The report presents the effects of these parameters on the corrosion growth rates from the established relationships in the literature.

A procedure for estimating the corrosion rate based on soil properties was developed to improve the determination of the reassessment intervals of pipelines subjected to the integrity management requirements. The procedure builds on correlations with soil properties from the field measurements, historical data, and an earlier field study by the National Institute of Standards and Technology (NIST).

The procedure was incorporated in a web-based computer program to identify the soils with high corrosion potential and to provide a simplified approach for the estimation of corrosion growth rate from the measured soil parameters.

Introduction

External corrosion growth-rate is an essential parameter to establish the time interval between successive pipe integrity evaluations. The Code of Federal Regulations (CFR) Part 192- Subpart O for pipeline integrity management requires establishing a reliable estimation of corrosion growth-rate. When valid methods for the determination of corrosion growth-rate are not used by the pipeline industry, regulators require the use of a default corrosion rate of 16 mils per year (mpy) for determining the inspection intervals.

ANSI/NACE Standard RP0502 (1) for the direct assessment of pipe external corrosion recommends several methods for obtaining corrosion rates, including direct comparison with historical data, use of buried coupons, electrical resistance (ER) probes, and Linear Polarization Resistance (LPR) measurements.

The ER and LPR measurements can be efficient methods for real-time measurements of corrosion rates. However, they are rarely used by the gas industry. The primary reasons for this include the need for standard procedures for using these methods on underground pipelines and the lack of established correlations between instantaneous corrosion rate as measured by the LPR, the long-term corrosion rate from the ER probe, and other measurement methods.

Both the LPR and ER measurement techniques are investigated in this project. Chapters 1 and 2 of the report present the testing programs to investigate the applicability of the LPR and ER methods, respectively. Chapters 3 and 4 present the field monitoring studies of corrosion rates at the GTI test sections and utility sites, respectively.

A literature review of the established relationships on the effect of soil properties on the corrosion potential of metal pipes is presented in Chapter 5. Chapter 6 presents the procedure used to estimate corrosion rates from soil and pipe characteristic based on these relationships.

A web-based computer program was developed to estimate the localized external corrosion rates of buried steel pipes based on measured soil parameters and environmental conditions around the pipe. The program is presented in Chapter 7 and it ranks these parameters according to their effect on corrosion potential and assigns weighted values to quantify the contributions of these parameters. The program helps in identifying the soils with high corrosion potential and provides a simplified approach for the estimation of corrosion growth rate.

CHAPTER 1

The Linear Polarization Resistance (LPR) Probe

The Linear Polarization Resistance (LPR) technology is an effective electrochemical method to monitor corrosion rate. The device consists of an LPR probe and a readout box. The probe consists of two or three electrodes inserted into the soil or corroding system, with the electrodes being electrically isolated from each other. Figure 1 and Figure 2 show the 3-electrode LPR device used in the laboratory testing program.

The LPR device functions by applying a small potential in the range of 20 mV (which does not affect the natural corrosion process) between the device electrodes and the resulting current is measured. The polarization resistance of the material is defined as the ratio between the applied potential (ΔE) and the resulting current density (Δi). The measured resistance is inversely related to the corrosion rate (i.e., if the electrodes are corroding at a high rate with the metal ions passing easily into solution; thus causing a high current and, consequently, a low polarization resistance). The laboratory procedure for estimating corrosion rates from the LPR measurements is described in ASTM G59 (2).

The LPR method has been applied for decades in corrosion monitoring of above-ground pipeline systems in power, water, and wastewater plants. It is also used to estimate corrosion rates of rebar in reinforced concrete structures as shown in Figure 3. Its major advantage is its speed in allowing an operator to evaluate quantitative changes of the corrosion process. However, it is seldom used by gas utilities to monitor the external corrosion in their pipelines.

Figure 1 - 'Metal Samples' LPR probe used in the laboratory testing

Figure 2 - View of the 3-Electrode LPR probe

Figure 3 - Commercial LPR probe mounted above rebar

The use of the LPR method for external corrosion of gas pipelines is not challenge-free. Procedures for its use and analysis to determine pipe corrosion in soil are not well established. Furthermore, it requires the measurements to be made at a free-corroding surface of the metal and it is most effective in aqueous solutions.

As with other electro-chemical measurements, corrosion rates are dependent on the specific environment to which the pipeline is exposed. These conditions are difficult to predict and should be estimated with caution. Corrosion rate measurements are affected by various soil characteristics (e.g., soil type, void ratio, resistivity, and pH). Furthermore, the determination of corrosion-rate depends on an accurate estimation of corrosion starting time, as corrosion rates often drop over time due the formation of a corrosion film, which slows the rate. NACE RP0502 (1) provides a comprehensive list of factors that affect the estimation of corrosion rates in Appendix D.

The LPR probe applies a small potential in the range of 20 mV between the elements and the resulting current is measured. The polarization resistance of the material is defined as the ratio between the applied potential (ΔE) and the resulting current density (Δi). The measured resistance is inversely related to the corrosion rate.

The linear polarization process when a metal/electrode is immersed in an electrolytically-conducting fluid can be summarized as follows:

- Dissolution of the metal occurs at anode sites at the metal surface where it passes into the adjacent solution. The excess electrons will flow through the metallic circuit to nearby site where a cathodic reaction occurs with the corrosive liquid. A simple example, of iron dissolving in acidic solution, is illustrated in Figure 4.

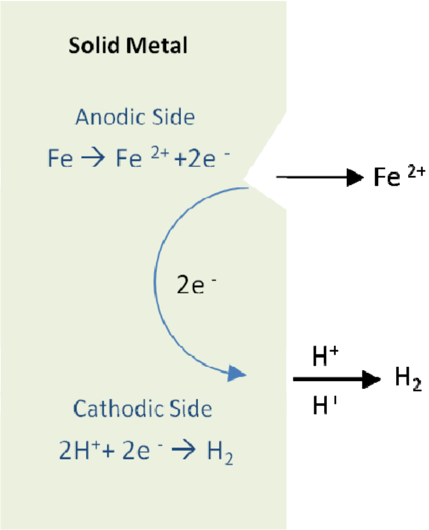


Figure 4 - An illustration of the corrosion process in iron sample (3)

- Since anodic and cathodic sites continually shift position within the conductive surface, making direct measurement of the corrosion current is not possible. To allow for this measurement, the linear polarization process imposes an external potential (ΔE) to produce measurable current flow at the corroding electrode. At small values of ΔE, the polarization resistance of the material is related to the corrosion current (i_{corr}) by the Stern-Geary equation (4):

$$R_p = \frac{\Delta E}{\Delta i} = \frac{b_a \, . \, b_c}{2.3 \, i_{corr} \, (b_a + b_c)}$$

Where, b_a *and* b_c are the the anodic and cathodic Tafel slopes. Tafel slopes can be evaluated experimentally using polarization plots. Commercial instruments generally have the slope ratios implemented in empirical constants to provide direct corrosion-rate measurements.

- The corrosion currents estimated from the above equation is used to calculate the penetration rate using Faraday's law in the following equation:

  $$CR = \frac{i_{corr} \, . W}{A \, . D} \; x \; 128.67$$

  Where, *CR* is the Corrosion rate in mils per year (mpy), *W* is the weight of the corroding metal (g), *A* is the area of the corroding electrode (cm^2), and *D* is the density of the corroding metal (g/cm^3).

From the above discussion, the function of the LPR probes requires a conductive environment such as aqueous solutions or other electrolytes. Accordingly, they have been used successfully when placed inside pipes or systems where instantaneous on-line corrosion rate readings are required. Some of the common applications of LPR are in water treating industry, cooling water systems, and waste water treatment systems.

The LPR monitoring can provide a qualitative pitting tendency measurement and can identify corrosion upsets and initiate remedial action. The major advantage to LPR monitoring is its speed in which it can provide a measurement of the corrosion rate. Changes in the corrosion rate can typically be detected in minutes, providing an almost instantaneous measuring system. The measurement time varies according to the specific characteristics of the metal and the environment system. Most practical measurements can be concluded within 20 minute duration.

However, LPR is seldom used by the gas industry to monitor external corrosion of pipeline in soil. This is mainly due to the uncertainties related to the reliability of the LPR measurements in varying dry and wet soil conditions. Furthermore, the procedures for its use and analysis to determine the corrosion potential in soil are not yet established.

Laboratory Evaluation of LPR Measurements in Soil

A testing program was performed to evaluate the LPR measurements in soil samples in the lab. The tests were performed using a 3-Electrode LPR probe model 'Metal Samples' (shown in Figure 1) with alloy type G10100 which is equivalent to steel pipe material with 0.1% carbon steel. The readout system was model Metal Samples MS1500L.

The first soil sample was obtained from the GTI test site and it is cohesive soil with about 85% of silt and clay content (i.e., content of soil particles passing sieve No. 200 as per ASTM D6913

(5)). The second type of soil was a silty-sand soil typically used as a backfill material. Table 1 shows the physical and chemical properties of the two soils.

The two soils samples were dried in the oven and distilled water was added to reach a wet soil condition with water content level of about 20%. Measurements using the LPR device were taken periodically in the two samples until constant corrosion-rates were obtained.

Table 1 - Properties of the soils used in LPR measurements

Soil	% Passing sieve #10	% passing sieve#200	Resistivity (Ohm-cm)	Chloride Content (µg/g)	Nitrate Content (µg/g)	Sulfate Content (µg/g)	pH
Soil No. 1	85	70	1500	13.8	<1.0	70	7
Soil No. 2	72	15	2300	45	50	10	6.4

Note: Soil resistivity measured in saturated soil

Additionally, LPR measurements were performed on various types of soils obtained from utility sites during the External Corrosion Direct Assessment (ECDA) of gas transmission pipelines. The soil properties (i.e., soil type, resistivity, and pH) were determined in the lab and corrosion rate measurements were performed using the LPR. The measurements were performed using the 2-probe and 3-probes devices and were taken at various durations for 24 hours. The measurements of these tests are shown in Appendix-A.

A) Measurements Using 2-Probe and 3-Probe LPR Methods

The applied potential in the LPR probe is required to overcome the solution resistance during the measurement. The solution resistance introduces error which makes the 2-electrode measurement valid only in metal and environment systems with low corrosion rate and low solution resistance (3).

The use of the 3-electrode measurement addresses this limitation since a separate circuit is used for the ΔE measurement, which is made at high input impedance and consequently, the solution resistance has negligible effect.

Figure 5 shows the results of corrosion rate measurmeents of soil samples using the 2-electrode and 3-electrode LPR propes. The measurements were taken after 24 hours of inserting the probes in the wet soil samples. The results show significantly higher corrosion rates when the 2-electrode probe was used. The difference in the measurements is also shown in Figure 6. The figure shows that the difference between the 2-probe and 3-probe measurements is more significant at high soil resistivity.

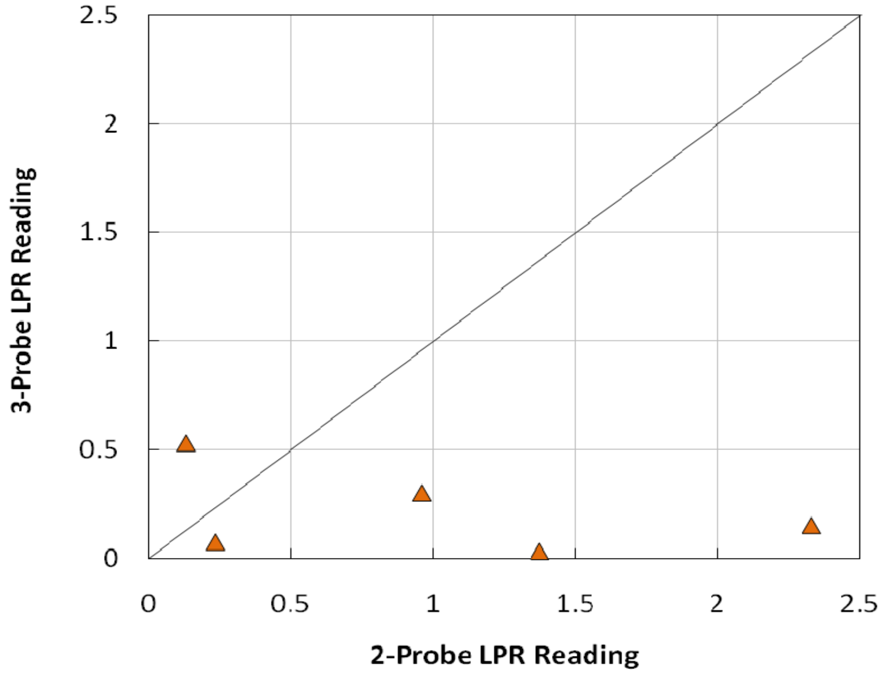


Figure 5 - Corrosion rate measurements using 2-electrode and 3-electrode LPR probes

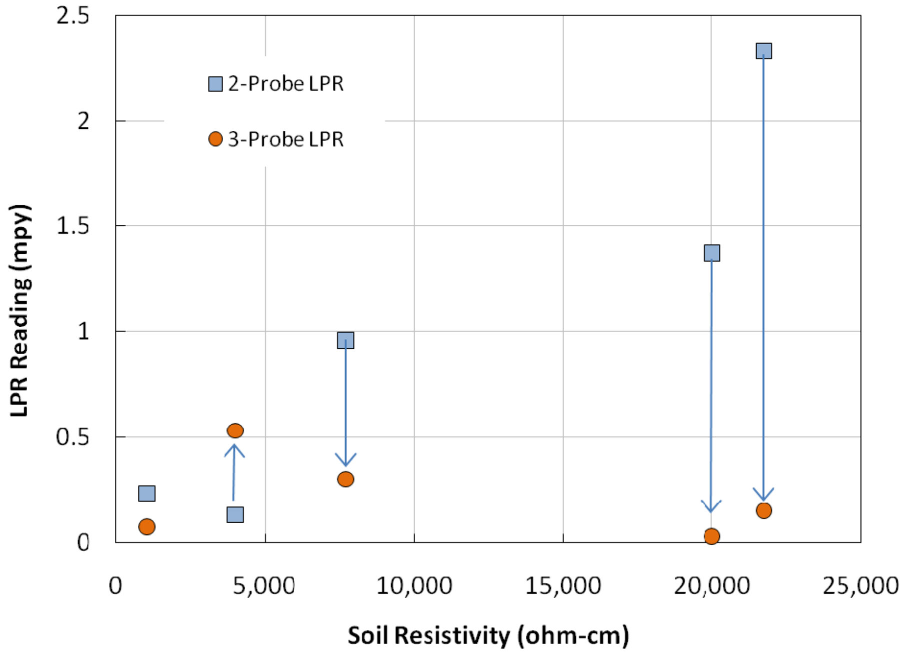


Figure 6 - The 2-electrode and 3-electrode measurements with soil resistivity

B) Measurements with Various LPR Monitoring Durations

A sufficient time is required for the LPR measurement to reach equilibrium and establish a stable corrosion current (Figure 7). The duration needed to reach equilibrium depends on the following two periods:

(a) A period of time during which capacitive discharge takes place at the electrode prior to the establishment of an equilibrium polarizing current (3). The capacitive current discharges after a finite time leaving only the residual polarizing current that is the true measured value. This time lag depends on the specific characteristics of the metal and the environment system and it varies from 30 seconds to few hours. Commercially available instruments commonly account for this period.

(b) The time required for the electrolyte solution in the soil to reach a steady state condition. This time varies depending on soil moisture content, its permeability, and the electro-chemical characteristics of the solution during the monitoring period.

An insufficient time for the establishment of the equilibrium current may result in a corrosion rate measurement that is falsely high. As the testing duration will vary according to the measuring device and soil environment, a preliminary investigation was performed in the lab to determine the duration required to establish a stable reading.

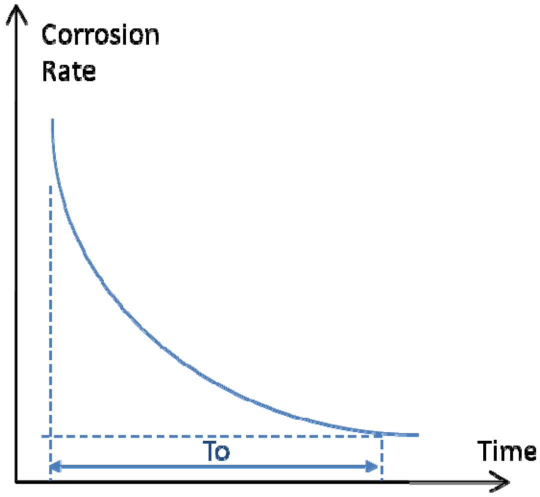


Figure 7 - Equilibrium time for the LPR measurement

The results in Figure 8 show that the LPR readings in the two GTI soils (shown in Table 1) asymptotically reached equilibrium after 6 to 10 hours of installing the probe in the sample with a shorter time to equilibrium was reached in the silty-sand soil sample. The time required for the LPR measurement to stabilize was also investigated in the soil samples from the utility sites.

The results show that duration of 24 hours is usually required for the LPR reading to stabilize. Figure 9 shows the variations between the 1-Hour and 24-Hour readings using the 3-electrode LPR probe. The results in Figure 10 show the variation in the LPR measurements with time in soils with various resistivities. The difference between the 1-Hour and 24-Hour measurements is more significant at high-resistivity soil.

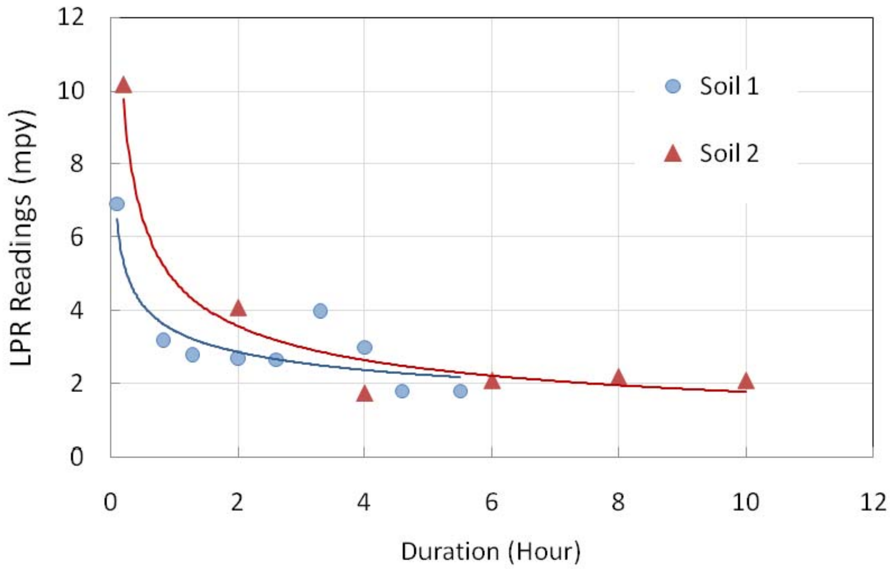


Figure 8 - LPR readings at various durations in the GTI soil samples

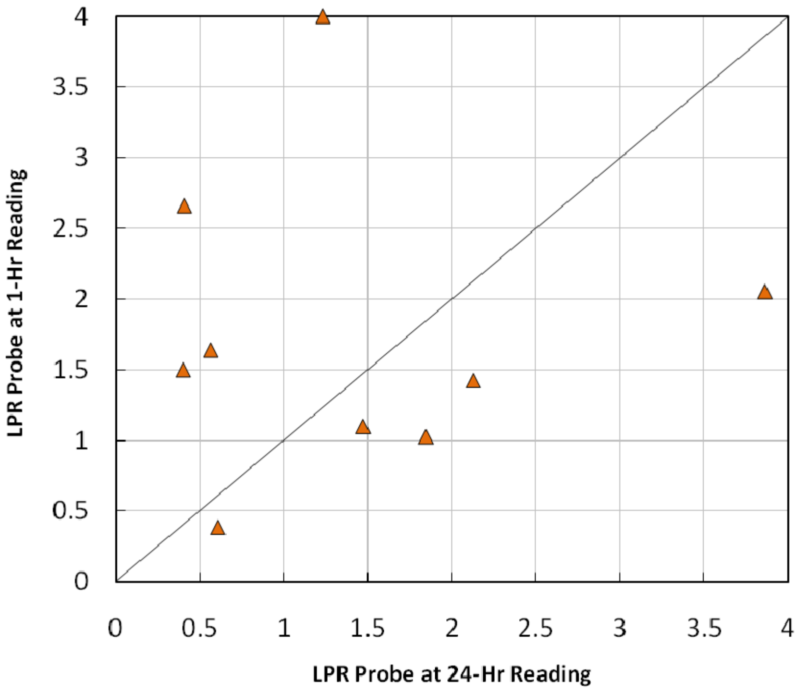


Figure 9 - Short and long-term LPR measurements of utility soil samples

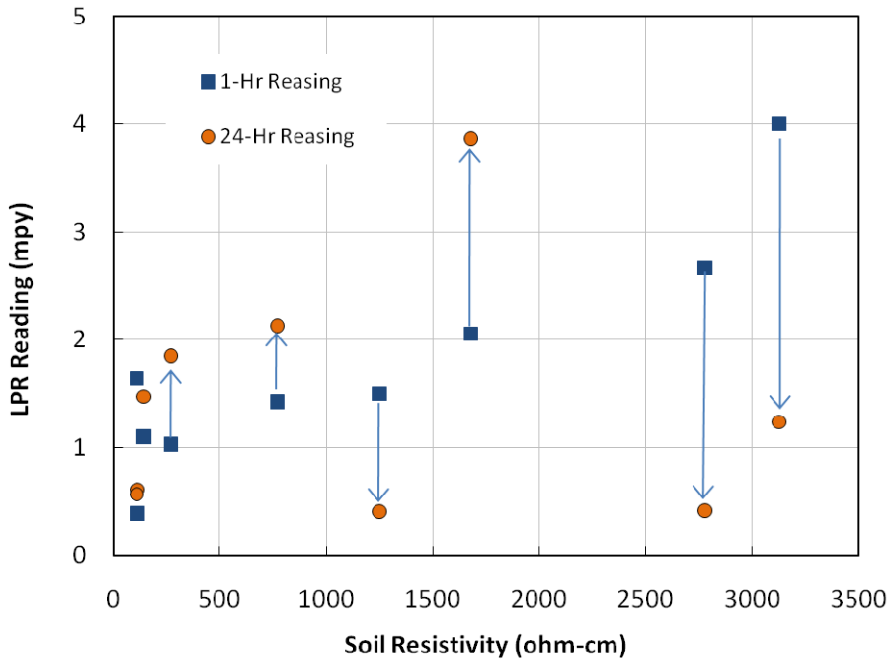


Figure 10 - 1-Hr and 24-Hr LPR measurements in various soil resistivities

C) Effect of Soil Moisture on the LPR Measurements

The change of the LPR corrosion rate with the change of soil moisture content in the GTI soil samples is shown in Figure 11. Since the LPR measurements are most effective in aqueous solutions, the measurements are sensitive to the water content in the soil and are usually unreliable in dry soils.

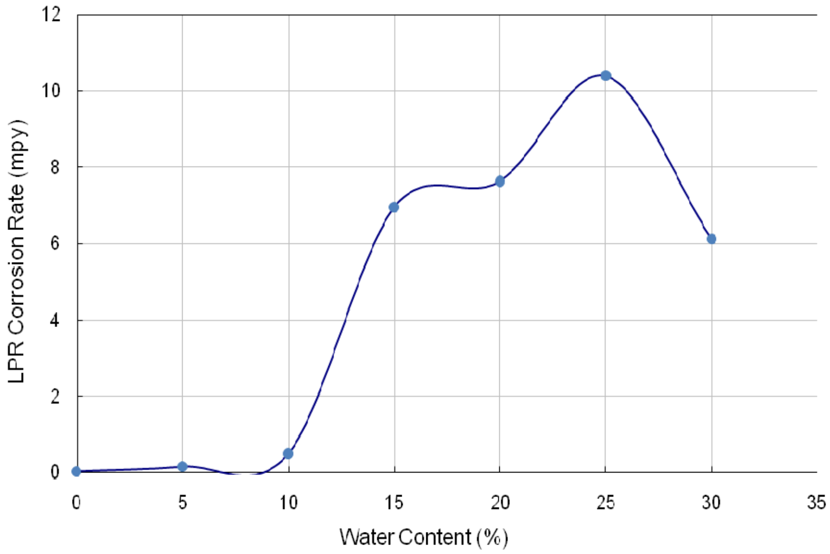


Figure 11 - Variation of the LPR corrosion rate with soil moisture

D) LPR Measurements with Soil Resistivity

Soil resistivity indicates the ability of the soil to carry corrosion current and it is one of the main factors that affect the pipe's corrosion potential. Resistivity is a function of soil moisture and the concentration of current-carrying soluble ions. The higher the resistivity of the backfill, the higher is its resistance to the electro-chemical corrosion and, consequently, the lower is the pipe's corrosion rate.

The increase of the LPR corrosion rate with the increase of the salt concentration in soil is shown in Figure 12. The measurements were taken in samples with various concentrations of sodium chlorides in the GTI soil samples at the same moisture content.

LPR measurements of soil samples obtained from utility sites with various resistivities are shown in Figure 13. The figure shows the measurements after inserting the 3-electrode probes in soil for 24 hours. Although the figure shows a general decrease in the corrosion rate with the increase of soil resistivity, the measurements show a large variability of the LPR readings. This variability is mainly due to the sensitivity of soil resistivity, and consequently LPR measurements; to the changes of soil properties (e.g. soil moisture, chemical properties, and pH).

The LPR technology was further investigated by performing long-term measurements of corrosion rates in controlled test sections in the field.

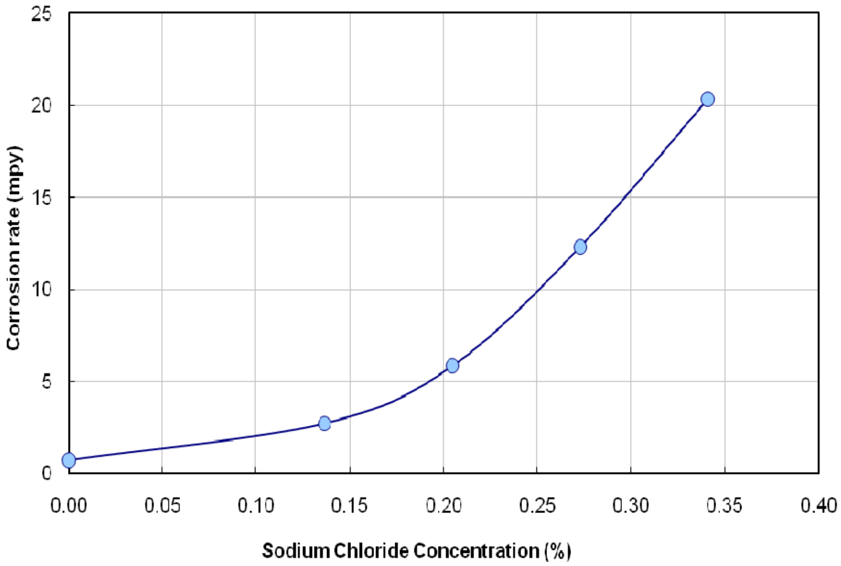


Figure 12 - Change of LPR measurements with salt concentration

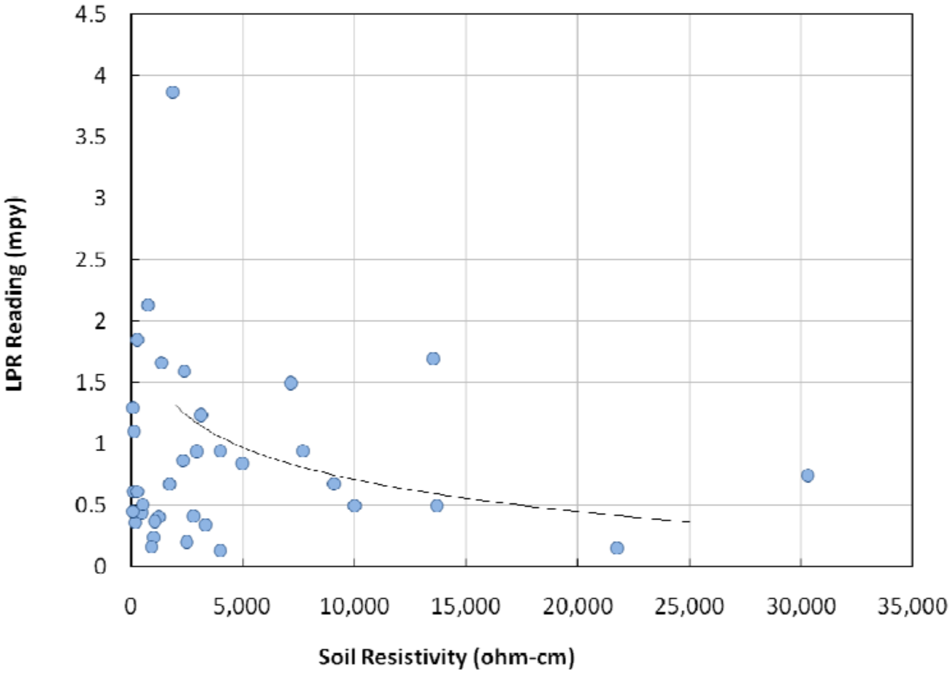


Figure 13 - LPR measurements in utility soil samples with various resistivities

Field Procedure for Measuring Corrosion Rate Using the LPR

Two LPR field units were investigated to evaluate the corrosion rate measurements in the field. The first unit is a portable LPR model '850-Aquamate Corrater'. This model allows for instantaneous readings of the corrosion rate in a readout box when the probe is inserted in soil. The second unit is model 'Rohrback Cosasco 7012' which is connected to a data acquisition system and provides a continuous field monitoring of corrosion rate.

A) The Portable LPR Aquamate

The Aquamate LPR is shown in Figure 14. It consists of LPR electrodes installed on a conical probe and a readout box that provides instantaneous reading of corrosion rate in mpy when the probe is inserted in soil (6). The device allows for quantitative measurement to be made quickly at the time of the pipe excavation with multiple readings to evaluate soil corrosivity at different locations around the pipe.

When the soil has a level of hydration that provides sufficient conductivity, corrosion-rate readings may be taken directly. When the soil is too dry, high soil resistivity may result in very low corrosion rates. In these conditions, distilled water may be added to soil to provide an estimate of corrosion rate when the soil is wet.

Figure 14 - The portable 'Aquamate Corrater' LPR probe

The procedure used to perform the LPR measurements in soil near a buried pipeline consists of:

- Take appropriate safety precautions while installing the probes or taking readings. Use insulated test clips and terminals to avoid high voltages that may be present. Follow all operator safety guidelines associated with working around pipelines.
- At the start of each survey, record the date, weather conditions, and temperature in the field notes.
- Identify a location within the excavation for obtaining the corrosion rate for the soil surrounding the pipe. It is recommended that this location be 4 to 6 inches from the pipe in undisturbed soil.
- Set the Aquamate Corrater instrument to obtain readings every 3 minutes. The time can be adjusted by using the configure button on the test instrument.
- Confirm calibration of the instrument. This is accomplished by turning the unit 'ON', installing the calibration test probe (RED) included with the instrument and pushing the "Measure" button. The meter should display the MILS/YEAR as noted on the side of the test probe.
- Create a starter hole using a screw driver or other sharp tool in order to prevent damage to the corrosion probe. This hole shall be at a slightly downward angle in the soil with a smaller diameter than the corrosion probe rod.
- Clean the corrosion probes before every use with. This will provide consistency for each new reading.
- The corrosion probe shall be inserted into the soil just enough to cover the probes at the end of the tool with soil. Completely surround the probes with soil while avoiding air gaps when inserting the probe.

- Obtain no less than 3 readings for duration of at least 3 minutes each at the location. Record all readings.
- A second reading shall be obtained at the same hole but this time filled with distilled water. Insert the corrosion probe back into the hole as outlined above and repeat the 3 test readings. This reading should the rate when soil conditions are wet.
- At the completion of the survey, typical LPR probe readings are provided as corrosion rate in mils per year (mpy). Field measurements should be made along the pipeline in intervals of about every direct exam excavation or when soil conditions differ around the pipe. Figure 15 shows the corrosion measurement using the LPR Aquamate in an excavated trench.

Figure 15 - Corrosion measurement using the LPR Aquamate soil probe

B) The Rohrback Cosasco LPR Probe

The Rohrback Cosasco LPR probe employs two replaceable, identical electrodes which are mounted at the end of the probe by threaded, insulated studs. Figure 16 shows the installation of the LPR probe in the test section.

The data logger model “9030 Plus” was used with two channels for monitoring the two LPR probes. The data logger was programmed to continuously read the data every 6 hours. The data was downloaded through a RS-232 serial port directly to a laptop computer using the device software. Figure 17 shows a view of the data logger in the test section.

Corrosion rate measurements of the LPR probes in the field are presented in Chapter 4: Field Measurements of the Corrosion Rate at GTI Test Site and Chapter 5: Field Measurements of the Corrosion Rate at Utility Sites.

Figure 16 - Installation of the 'Rohrback Cosasco' LPR sensor in test section

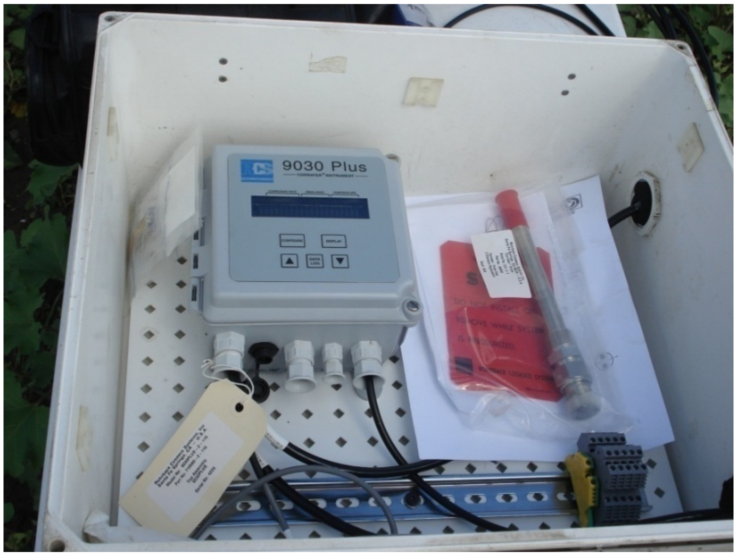


Figure 17 - View of the LPR Data Logger

CHAPTER 2

The Electrical Resistance (ER) Probe

The electrical resistance (ER) device measures the corrosion rate of a metal alloy having a composition similar to the pipe material when placed in a corrosive environment. The device is suited to corrosive environments having either poor or non-continuous electrolytes such as soil. The ER device consists of a read out instrument connected to a probe. The probe is permanently installed in soil to provide continuous information. The measuring instrument provides metal loss and corrosion rate when consecutive measurements are taken of the same probe in the field. Figure 18 shows the 'Metal Samples' ER device used in the testing program.

The ER device calculates corrosion rate from the electrical resistance of a metal probe R in the equation:

$$R = r \, . \, \frac{L}{A}$$

Where r is the specific resistance of the metal element, L and A are the element length and cross-sectional area, respectively. The element's electrical resistance is proportional to its total mass-loss due to corrosion. When two consecutive mass-loss readings ($M1$ and $M2$) are taken by the device, the corrosion rate (CR) can be expressed as:

$$CR = \frac{365 \, . \, (M1 - M2)}{\Delta t \, . \, 1000}$$

Where Δt is the time between the two readings in days.

Figure 18 - 'Metal Samples' ER sensor with Flush element and readout box

Practical measurement of the element’s corrosion rates is achieved by using ER probes equipped with an element that is freely exposed to the corrosive environment and a reference element sealed within the probe body (7). Since temperature changes affect the resistance of both the exposed and reference element equally, measuring the resistance ratio minimizes the influence of temperature changes. Accordingly, the net change in the resistance ratio is solely attributable to metal loss from the exposed element once temperature equilibrium is established.

Several probe types and sizes are available for various ER field applications (Figure 19). The two probes that are most suitable for corrosion measurements in soil are the “Flush” and the “Surface Strip” element. These elements are designed to be mounted flush against the soil; thus simulating the corrosion of the pipeline surface. The comparatively large surface area of the “Surface Strip” element allows for more representative results in non-homogeneous corrosive environments on the external surface of buried pipes.

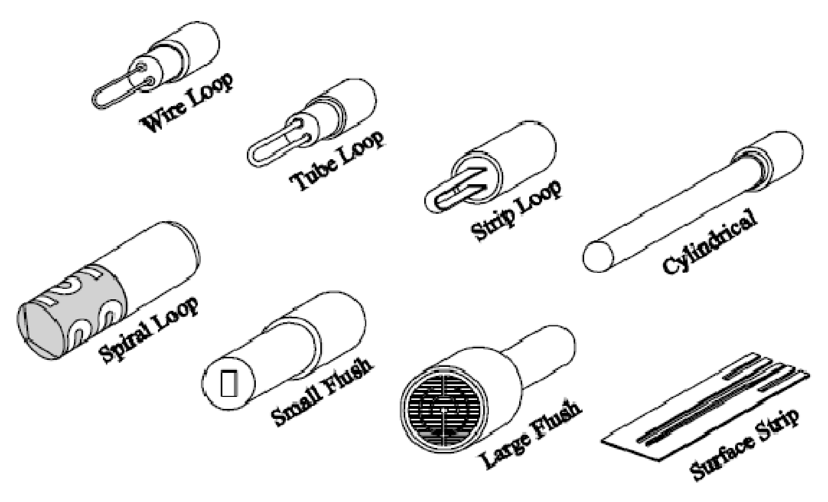


Figure 19 - Various types of the ER sensing probes (7)

Field Procedure for Measuring Corrosion Rate Using the ER Probe

An ER probe type Flush 40 and a read outbox model “Metal Samples” MS1500E were used in the field measurements of corrosion rates. The procedure used to perform LPR corrosion rate measurement in soil near a buried pipeline during routine External Corrosion Direct Assessment (ECDA) consists of:

- Take appropriate safety precautions while installing the probes or taking readings. Use insulated test clips and terminals to avoid high voltages that may be present. Follow all operator safety guidelines associated with working around gas pipelines.

- At the start of each test, record the date, weather conditions, and temperature.
- Identify a location within the excavation for the corrosion rate monitoring. It is recommended that probe is installed in undisturbed soil section.
- Two probes are used in each excavated site. The grounding lead of the first probe is connected to the cathodically protected pipe (Figure 20). The connection allows the probe to measure the effectiveness of the Cathodic Protection (CP) System. The second probe is not connected to the pipe and is used to monitor soil corrosivity.

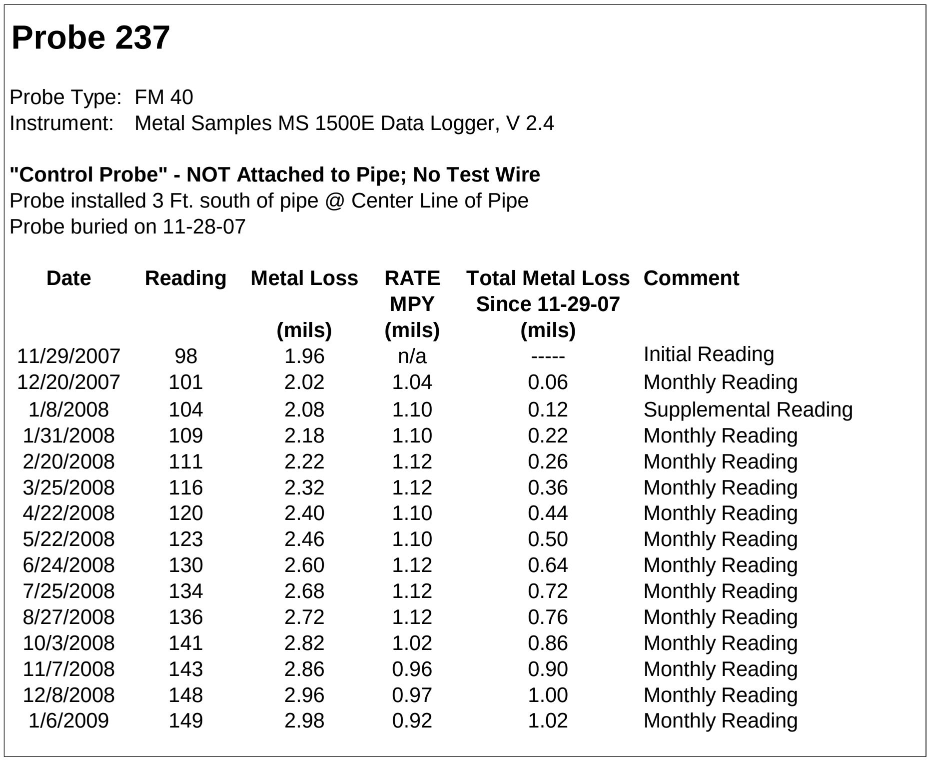
Figure 20 - Welding the ER attached wire to the pipe surface for CP monitoring

- The second probe monitors the corrosion-rate in unprotected surface due to soil and environmental conditions. This represents the conservative condition when an anomaly on the pipe surface is uncoated or unprotected by CP current.
- The ER probes are placed about 1-2 ft from the pipe and at the level of the centerline of the pipe (Figure 21). Alternatively, the probes are placed near the location of the pipe where corrosive conditions exist (e.g., at the bottom of the pipe or at a location of permanent water table).
- The ER probes are backfilled using the same backfill that is used around the pipe. The end connectors of the probes are placed in a protected case at the ground surface to allow for ER monitoring.
- Initial reading is taken after the placement of the backfill. Consequent readings are taken periodically to monitor corrosion rate. The measurements are uploaded to a

computer from the readout box for data analysis and plotting. The data output records the readout dates, metal-loss, and corrosion growth rates at each reading. Figure 23 shows an example of the data output after subsequent readings of an ER probe installed in the GI test section.

Figure 21 - Placement of the ER probe near the pipe

Figure 22 - End terminals at the ground surface for periodic monitoring



Probe 237

Probe Type: FM 40
Instrument: Metal Samples MS 1500E Data Logger, V 2.4

"Control Probe" - NOT Attached to Pipe; No Test Wire
Probe installed 3 Ft. south of pipe @ Center Line of Pipe
Probe buried on 11-28-07

Date	Reading	Metal Loss (mils)	RATE MPY (mils)	Total Metal Loss Since 11-29-07 (mils)	Comment
11/29/2007	98	1.96	n/a	-----	Initial Reading
12/20/2007	101	2.02	1.04	0.06	Monthly Reading
1/8/2008	104	2.08	1.10	0.12	Supplemental Reading
1/31/2008	109	2.18	1.10	0.22	Monthly Reading
2/20/2008	111	2.22	1.12	0.26	Monthly Reading
3/25/2008	116	2.32	1.12	0.36	Monthly Reading
4/22/2008	120	2.40	1.10	0.44	Monthly Reading
5/22/2008	123	2.46	1.10	0.50	Monthly Reading
6/24/2008	130	2.60	1.12	0.64	Monthly Reading
7/25/2008	134	2.68	1.12	0.72	Monthly Reading
8/27/2008	136	2.72	1.12	0.76	Monthly Reading
10/3/2008	141	2.82	1.02	0.86	Monthly Reading
11/7/2008	143	2.86	0.96	0.90	Monthly Reading
12/8/2008	148	2.96	0.97	1.00	Monthly Reading
1/6/2009	149	2.98	0.92	1.02	Monthly Reading

Figure 23 - Example of output data from ER probe

CHAPTER 3

Field Measurements of the Corrosion Rate at GTI Test Section

The GTI testing facility includes five test sections for the evaluation of the effect of soil on the corrosion-rate of buried steel pipes. The first test section (Trench-A) was constructed in June 2007 as a part of the OTD co-funding project. The construction of the other four test sections (Sections-1 to 4) started in May 2009 and was completed in August 2009. The following sections describe the soil properties and field instrumentations of the five GTI test sections.

A) Trench Section-A

Trench-A consists of 6 inches asphalt pavement layer and 6 inches stone base layer on the top of a uniform compacted subgrade soil. A 4-ft wide by 20-ft long trench was cut in the asphalt layer to facilitate instrumentation and corrosion measurements in the subgrade soil. Figure 24 shows a view of the trench.

The subgrade soil consisted of 80% sand and 20% silt and clay and its grain size distribution is shown in Figure 25. The soil is non-plastic and is classified as 'Loamy-Sand' according to the US Department of Agriculture (USDA) classification system and as 'Silty-Sand' according to the Unified Soil Classification System (USCS). Further discussion regarding these two soil classification systems is presented in Appendix B and the chemical properties and gradations of the GTI test sections are shown in Appendix C.

Figure 24 - Trench-A at GTI facility for corrosion monitoring

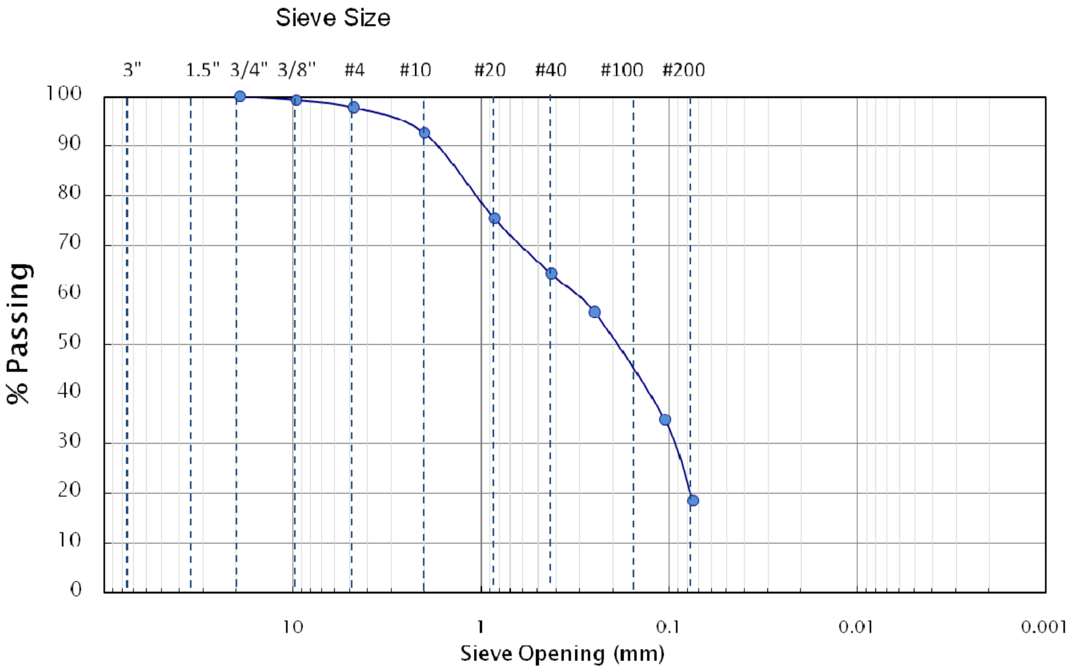


Figure 25 - Grain size distribution of the subgrade soil in Trench-A

A Test-Kit was used to measure the soil chemical components from field samples (i.e.; Chloride, Nitrate, Sulfate, pH, and soil Redox Potential). Figure 26 and Figure 27 show the components of the Test-Kit for chloride and nitrate measurements, respectively. The soil Redox potential is used to determine the anaerobic soils that could support sulfate-reducing bacterial activities. A high Redox potential measurement indicates aerobic conditions and a low potential for sulfate-reducing bacterial activities. Measurements of Redox potential were performed in the field since the removal and transportation of the samples to the laboratory cause aeration of the sample and result in inaccurate values. Figure 28 shows the Redox field measurement kit.

Soil samples were also analyzed at the GTI Chemistry lab to compare the lab results with the measurements of the Test-Kit. The results of the Chemistry lab (lab results) and the Test-Kit (field measurements) were comparable and are shown in Table 2.

The Test-Kit was used to perform periodic measurements to monitor the variations of soil properties in the test section with time. The results of one year measurements from July 2007 to August 2008 are shown in Figure 29. The results show significant seasonal variations of the chloride and sulfate contents. The corresponding changes in soil temperatures and water contents are also shown in Table 3. The results show that the average of periodic measurements provides a better representation of soil properties over the corrosion monitoring duration.

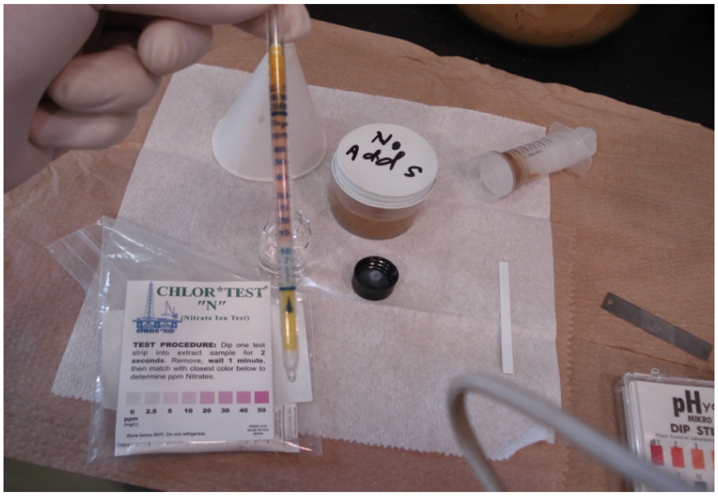


Figure 26 - Test kit for Chloride measurements

Figure 27 - Test kit for Nitrate measurements

Figure 28 - Redox Potential measurements in the field

Table 2 - Results of the field and Lab measurements in Trench-A

Parameter	Test Method	Measurement
Chloride Content [µg/g]	Lab Results	13.8
	Field Measurements (4 min)	12
	(1.5 min tests)	10
Nitrate content [µg/g]	Lab Results	<1.0
	Field Measurements	0
Sulfate content [µg/g]	Lab Results	69.8
	Field Measurements	64
pH		7

Table 3 - Seasonal changes of soil properties in the Trench-A

Test		07/27/07	11/07/07	04/15/08	08/27/08
Field Water Content (%)		16	18	19.8	15.5
Redox		234	320	214	203
Temp (F)		78	75.2	86	89.6

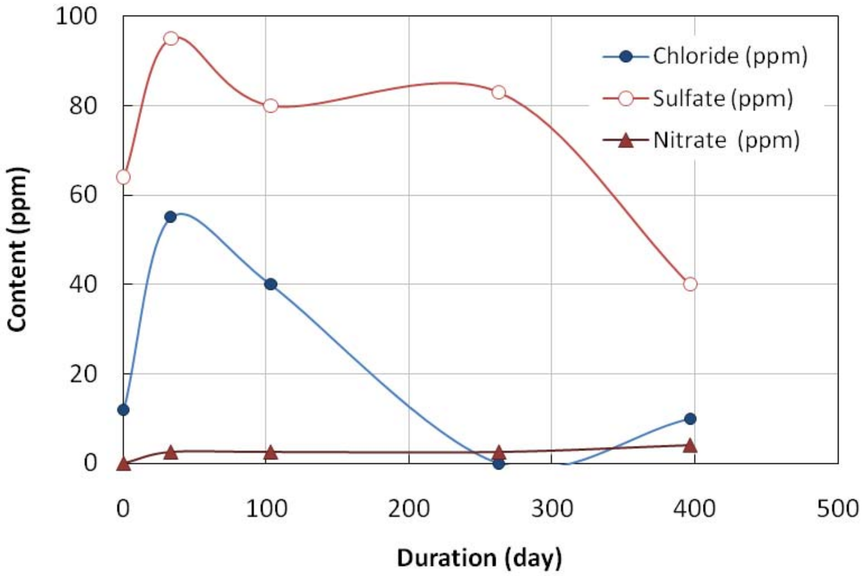


Figure 29 - Seasonal variation of chemical measurements of Trench-A

The corrosion potential of the soil in Trench-A was evaluated using the measurements of soil resistivity tests, Linear Polarization Resistance (LPR), and Electrical Resistance (ER) methods. Periodic resistivity measurements were performed using the soil resistivity box in Figure 30. The results of one year measurements from July 2007 to August 2008 are shown in Figure 31.

Figure 30 - View of the soil resistivity box for lab measurements

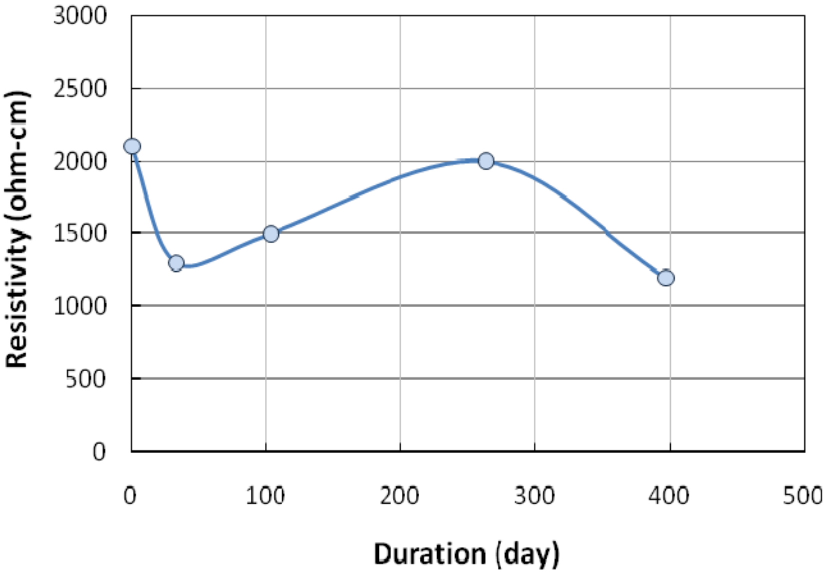


Figure 31 - Variation of soil resistivity with time in Trench-A

Laboratory measurements of the soil corrosion potential using the LPR method was performed using a 3-Electrode LPR probe model "Metal Samples" with alloy type G10100 which is equivalent to steel pipe material with 0.1% carbon steel. The readout box and the 3-electrode probe are shown in Figure 1 and Figure 2, respectively.

The LPR tests were performed on saturated soil samples in the lab. The LPR probe was left in the soil and periodic measurements were taken. At each reading, distilled water was added and the soil was left to stabilize before consistent readings are obtained from the LPR device as shown in Figure 32.

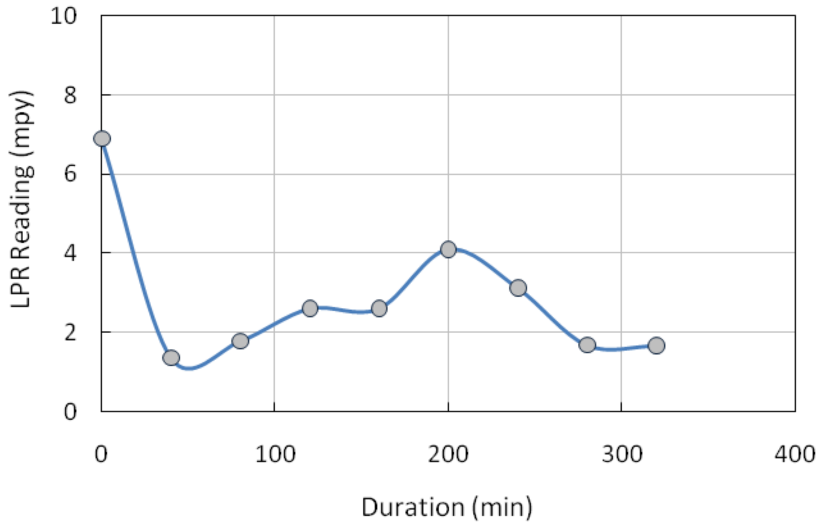


Figure 32 - LPR measurement of soil in Section-A with time

An Electrical Resistance (ER) probe type “Metal Samples Flush-40” was installed in Section-A. Measurements were taken using a readout box model “Metal Samples” MS1500E (Figure 33). Periodic field measurements of the ER probe were taken for one year. Figure 34 shows a comparison between the corrosion rates (in mpy) from the ER field probe and laboratory LPR measurements from the field samples. Both results are not comparable with significantly higher readings in the LPR method. Both readings were not expected to correlate since the LPR provides instantaneous ‘general’ corrosion estimate while the measurements of the ER probes can result from long-term ‘localized (pitting)’ corrosion on the probe.

Figure 33 - View of the ER probe and readout box before installation

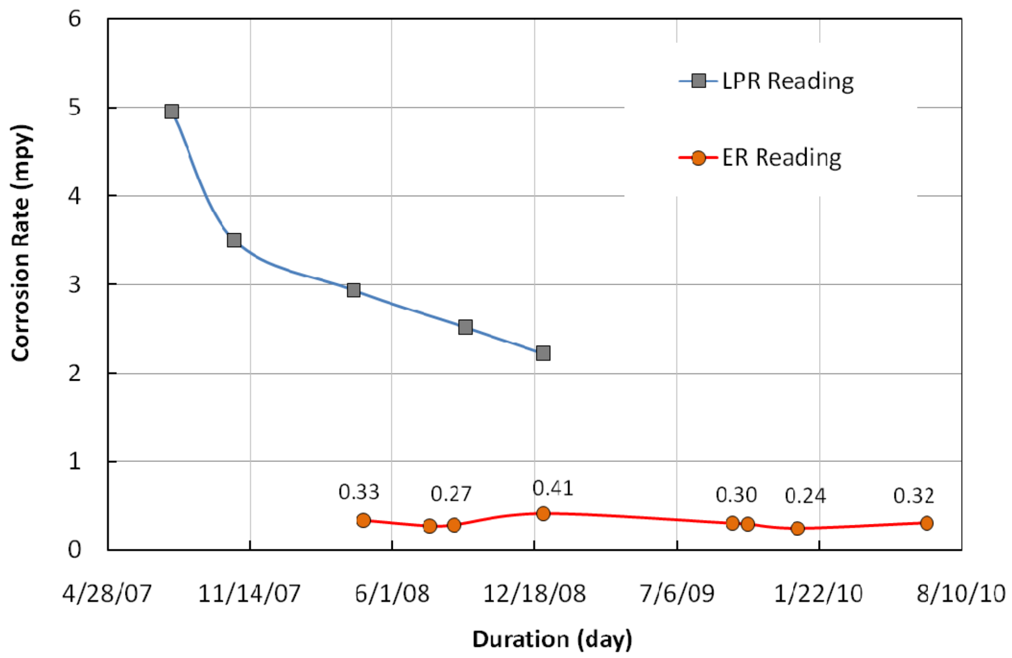


Figure 34 - LPR and ER measurement of Trench-A

Steel coupons were also placed in Trench-A to monitor corrosion rate from metal weight-loss calculations. Samples were extracted after 6 months and 18 months of installation for metal-loss calculations. Figure 35 shows the samples extracted from the test section after 6 months.

Samples preparation, cleaning, and measurements of weight loss were performed according to ASTM G1 (8) and NACE TM0169 Standards (9). The general corrosion estimates from coupons weight-loss show no correlation with the LPR measurements in Figure 36. The results show that the average corrosion rate of 0.9 mpy is lower than the LPR measurements.

Although the LPR readings provide valuable information regarding the real-time changes of corrosion rates when environmental conditions change around the probe, the device does not provide consistent and comparable corrosion rates when soil samples were tested in long-term tests. Further evaluation of the LPR was performed with the device installed in the test sections in the field to provide continuous monitoring of corrosion rate potential.

Figure 35 - View of the extracted coupons after 6 months

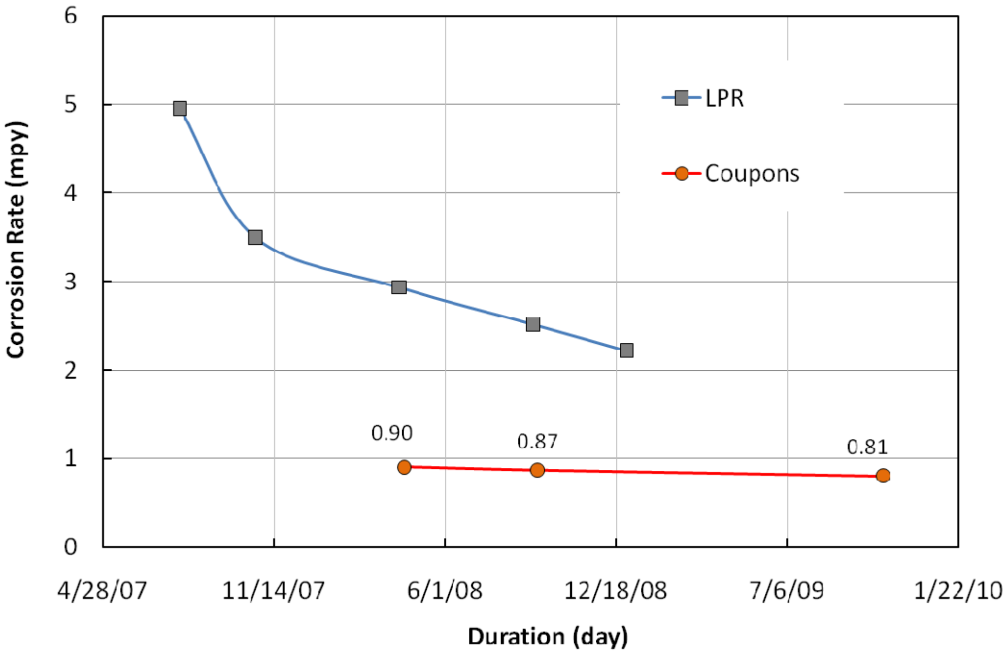


Figure 36 - Weight-loss coupon measurements and LPR data in Trench-A

B) Test Sections 1-4

Four test sections (Sections 1 to 4) were constructed at the GTI Pipeline Testing Facility from May 2009 to August 2009. Each section has an area of 9 ft by 9 ft and a depth of 4 ft. Figure 37 shows the excavation of one of the test sections. The native soils in the excavated sections were replaced by 4 different soil backfills as shown in Figure 38. Table 4 shows the gradations of the backfills and Table 5 shows the chemical properties of the soil in the tests sections.

Figure 37 - Excavation of the test section at GTI testing facility

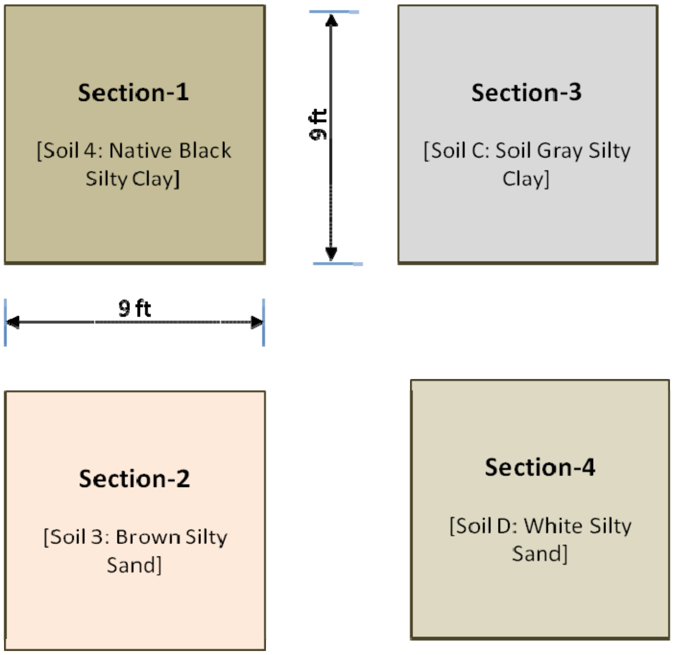


Figure 38 - Schematic of the test sections at GTI

Table 4 - Physical properties of the GTI test sections

Site No.	Description	Gradation				Plasticity Limits			Classification USCS system
		%Gravel	%Sand	%Silt	%Clay	LL	PL	PI	
Trench-A	Silty sand	0	80	20		Non-Plastic			SM
Sec-1	Black silty clay with gravel	11.4	36.5	24.1	28	35	18	17	CL
Sec-2	Brown silty sand	0.3	64.6	26.1	9	Non-Plastic			SM
Sec-3	Gray silty clay with sand	2.3	14.4	40.3	43	40	16	24	CL
Sec-4	White silty sand	3.7	75.2	19.1	2	Non-Plastic			SM

Table 5 - Chemical properties of the GTI test sections

Site No.	Description	Chloride (mg/kg)	Nitrate (mg/kg)	Sulfate (mg/kg)	pH
Trench- A	Silty sand	13	1	70	7
Sec-1	Black silty clay with sand	ND	3.4	732	7.7
Sec-2	Brown silty sand	30	ND	483	7.9
Sec-3	Gray silty clay with gravel	50	6.1	ND	7.0
Sec-4	White silty sand	50	3	ND	9.0

ND: ND - Not Detected at the Reporting Limit

Steel coupons and an ER sensor were installed in the four test sections to evaluate their corrosion potential.

Test Section-1:

The backfill in Section-1 was the native soil excavated from the test sections. The soil was cleared from the large-size gravel and was re-placed and compacted (Figure 39). The backfill is a black silty clay soil with more than 50% clay and silt contents. Laboratory tests for the physical and chemical properties of the soil are shown in Appendix C.

The soil has a high Sulfate content and plasticity index (PI) of 17 and an activity index (A) of 0.6. These parameters correlate to the chemical and physical behavior of the cohesive soils and a further discussion on these properties is presented in Appendix B.

Figure 39 - View of the backfill in Section-1

Test Section-2:

The backfill in Section-2 has 65% sand and 25% silt. The backfill is non-plastic and has a higher permeability than the silty soil in sections 1 and 3. Figure 40 shows the installation of the ER sensor at a depth of 3 ft in the test section.

Test Section-3:

The soil is section-3 is a silty clay soil with higher percentage of silt and clay than other sections. The soil is more plastic than in Section-1 with PI equals 24 and has an Activity Index of 0.55. The soil is mildly compacted to provide medium water permeability in the section. Figure 41 shows a view of the backfill in Section-3.

Test Section-4:

This section contained a coarse grained backfill consisting of about 80% sand and gravel. It is non-plastic backfill with high permeability and medium chloride content. Figure 42 shows a view of the backfill of Section-4.

Figure 40 - View of the backfill in Section-2

Figure 41 - View of the backfill in Section-3

Figure 42 - View of the backfill in Section-4

LPR Measurements in the Test Sections:

LPR corrosion probes model “Rohrback Cosasco 7012” were installed in test sections 1 and 2 to provide continuous monitoring of LPR corrosion rates in the field. The objective of these measurements was to evaluate the applicability of using the LPR for contentious measurements in the soil.

The LPR probe employs two replaceable, identical electrodes which are mounted at the end of the probe by threaded, insulated studs. Figure 16 shows the installation of the LPR probe in the test section.

The data logger model “9030 Plus” was used with two channels for monitoring the two LPR probes installed in sections 1 and 2. The data logging function is programmed to continuously read the data every 6 hours. The data is downloaded through a RS-232 serial port directly to a laptop computer using the device software. Figure 17 shows the data logger system.

The results of the long-term monitoring of the sensors in Section-1 and Section-2 are shown in Figure 43 and Figure 44. The results showed seasonal variations of the corrosion rate measurements, with significantly higher rates in the summer of 2009 and spring of 2010. These periods are characterized by higher precipitation rates and, consequently, higher soil water contents. The figures also display the average corrosion rates based on the long-term measurements.

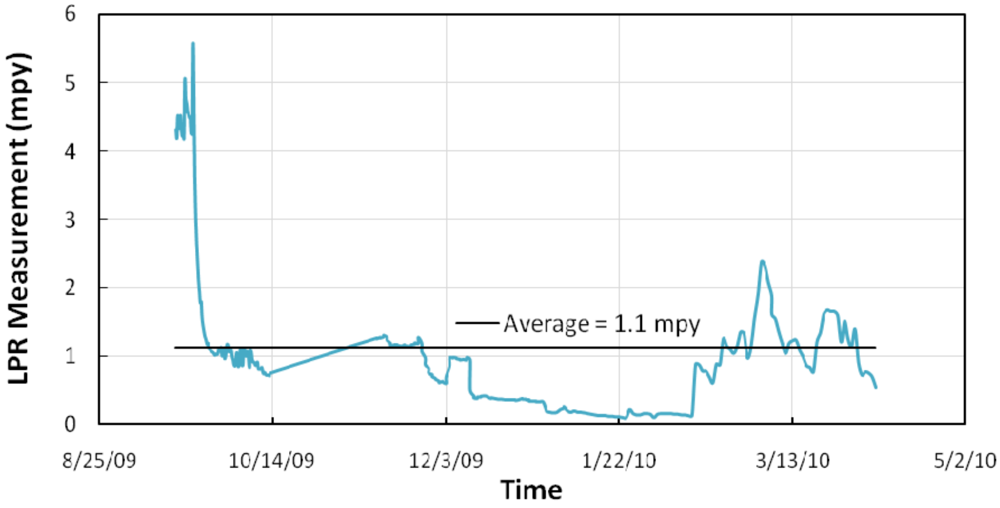


Figure 43 - LPR measurements in the native soil section -1

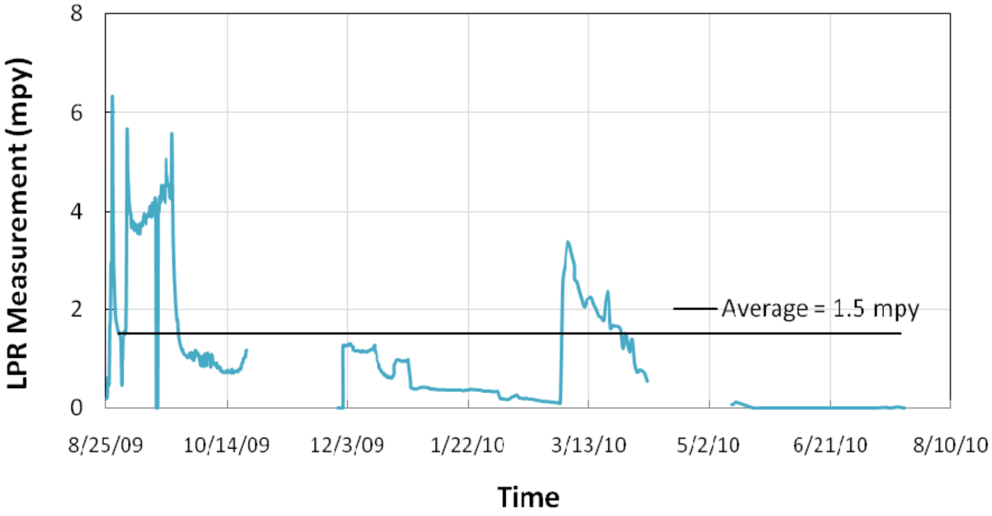


Figure 44 - LPR measurements in the granular soil section-2

ER Measurements in the Test Sections

The ER corrosion probes with 3-electodes model 'Metal Samples' were installed in four test sections and the data was monitored periodically for duration of 12 months. Figure 45 shows the results of the ER corrosion rate measurements in the test sections. A relatively higher rate was monitored in Section 4 while the other three sections had comparable low corrosion rates of about 1 mpy. The soil Section 4 is well compacted granular with medium chloride and a high pH value.

A comparison between the ER and LPR data in test sections 1 and 2 are shown in Figure 46 and Figure 47, respectively. Although the results of section-1 compare well in both devices, the average LPR reading in section 2 was higher than the ER measurements.

The test results typically show higher LPR readings than the ER and weight-loss coupon measurements. This is possibly due to the fact that the LPR device estimates 'potential' corrosion rate based on soil electro-chemical reactions. This theoretical estimate may not necessarily result in equal long-term corrosion rate in the field, which is measured by the other two devices.

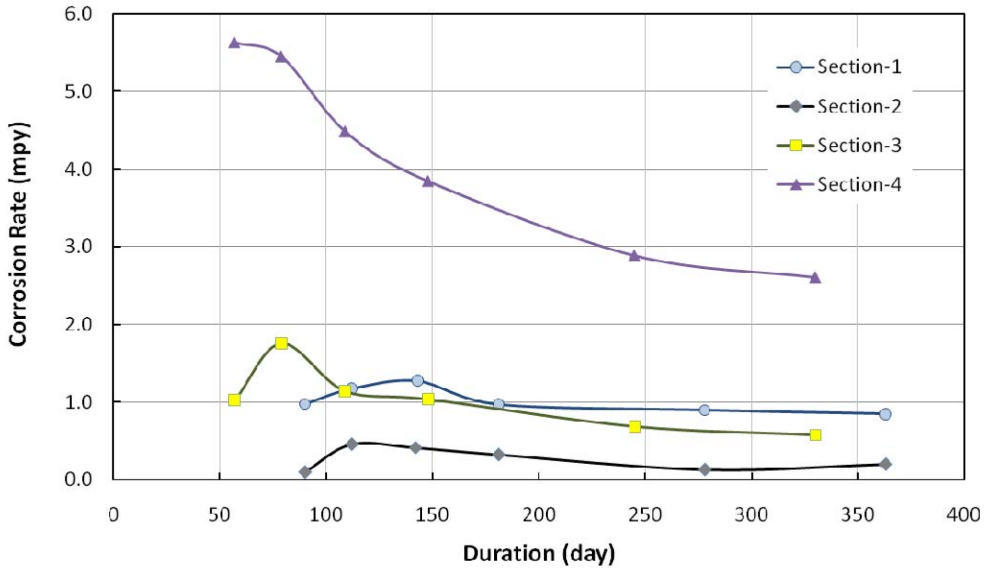


Figure 45 - Results of ER corrosion rate measurements in the GTI test sections

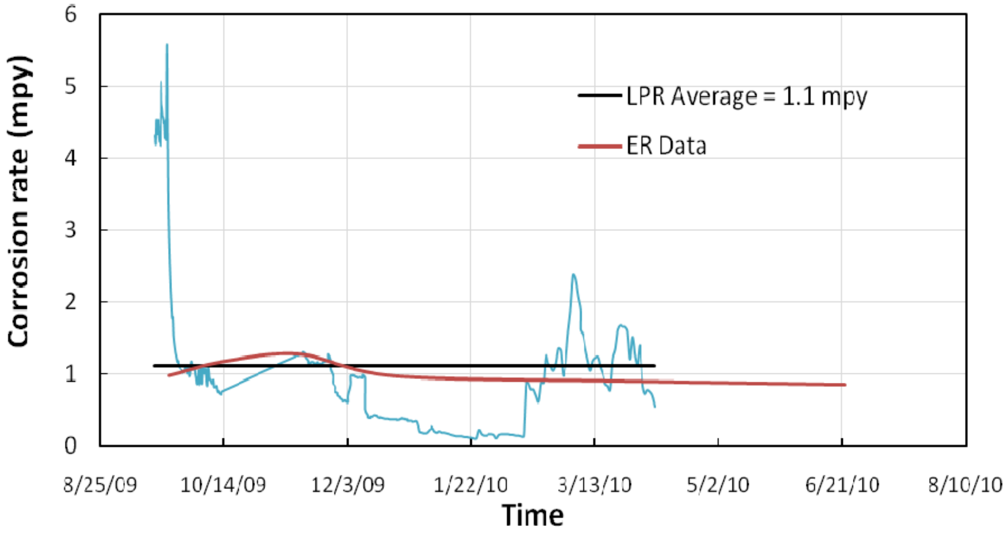


Figure 46 - ER and average LPR data with time in Test Section-1

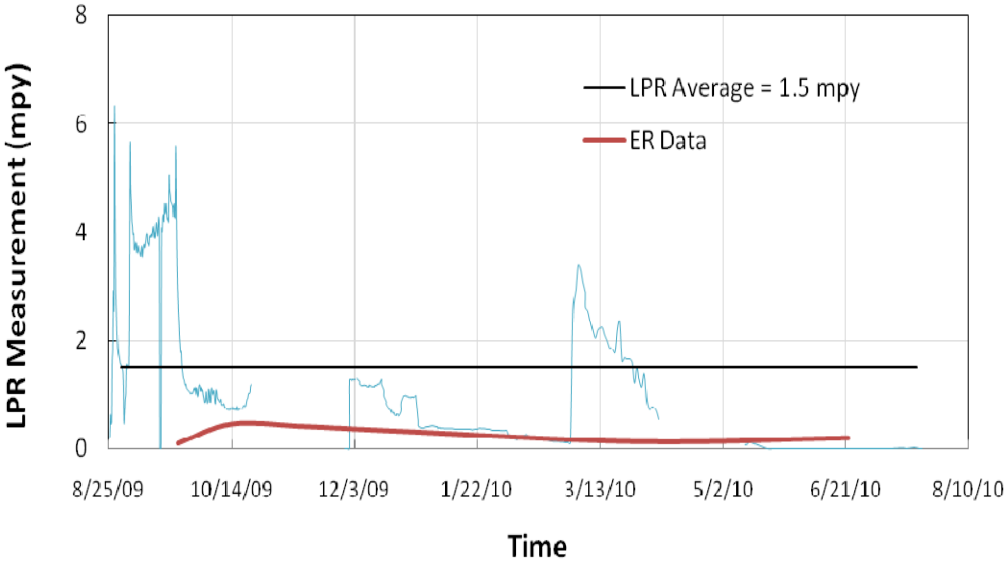


Figure 47 - ER and average LPR data with time in Test Section-2

CHAPTER 4

Field Measurements of the Corrosion Rate at Utility Sites

The Electrical Resistance probes were installed in various sites during the utilities routine External Corrosion Direct Assessment (ECDA) programs. The ER probes were installed in the summers of 2008 and 2009 and corrosion measurements continued until the spring of 2010.

A total of 5 utilities participated in the ER field installation and monitoring program. A total of 16 sites were initially selected with the participating utilities for the ER installations. Out of these sites, data from 11 sites in 4 utilities were actually collected by the end of the testing program. A list of these sites is shown in Table 6.

Most of the sites had 2 sensors installed, with one sensor connected to the cathodically protected pipe to monitor corrosion rate with a CP protection, while the other sensor is not connected to the pipe to monitor soil corrosion potential without CP protection.

A data readout box was provided to each utility for performing periodic corrosion rate measurements at their sites and soil samples were obtained during the installation of the ER probes. Out of the 16 sites with ER sensors, data was provided from 11 of these sites. The following sections provide the soil properties and the ER measurements in these sites.

A) Installation of the ER probe at Utility-A Site, NY

The ER probes were installed at a transmission line at the Utility-A test site in New York. The backfill material in the test section was sandy soil with the gradation shown in Figure 48. The results of resistivity and chemical analysis tests on the soil are shown in Table 7 which shows a high resistivity soil with pH of 6.4 and low chloride and sulfate contents.

Two ER probes were installed at the pipe level about 7 ft below surface as shown in Figure 49. One probe was connected to the cathodically-protected pipe through a lead wire and the other probe was not connected to the pipe and was placed in the backfill about 2 ft from the pipe.

The ER probes were installed in November 2007 and the results of 13-month monitoring period of the probes are shown in Figure 50. The corrosion rates of the ER probe connected to the pipe (i.e., with CP) showed zero corrosion rate readings throughout the monitoring period. The ER probe placed without CP showed a low constant corrosion rate of about 1.1 mpy during the first few months of the monitoring period. Thereafter, the measurements showed gradual reduction in the corrosion rate during the last months of the monitoring period.

Table 6 - List of ER probes installations in utility sites

Site	Utility Name	Sensor ID #	Date of installation	Notes
	GTI Test Site, IL			
1	Trench Site	#744	7/11/2007	Silty-sand native soil
2	Section -1	#255	6/24/2009	Silty-clay with organic mix
3	Section -2	#267	6/24/2009	Sandy soil
4	Section -3	#261	7/27/2009	Clay soil
5	Section -4	#268	7/27/2009	Crushed stone backfill
	Utility-A Site, NY			
6	Utility Test Site	#236-#237	November, 2007	Native sandy soil
7	Scheduled	#262-#363		No data was provided
8	Scheduled	#264-#266		No data was provided
	Utility-B Sites, UT			
9	Site-1	#743	5/5/2008	Fine sand
10	Site-2	#978	5/5/2008	Sandy backfill soil
11	Site-3	#979	5/5/2008	Sandy backfill Soil
12	Site-4	#780	5/20/2008	Coarse sand
	Utility-C Sites, NV			
13	Site 1	#Y343#Y344	11/19/2008	Sand with clay and stone
14	Site-2	#X356-#X357	09/30/2008	Well drained sand
15	Site-3	#X358-#781	06/24/2008	Well drained sand
	Utility-D, OK			
16	Site-1	#782-#783	September, 2008	No data was provided
17	Scheduled	#Y345-#Y346	N/A	No data was provided
	Utility E, IL			
18	Site-1	#265-#269	May, 2009	Clay soil
19	Site-2	#260-#258	May, 2009	Clay soil
20	Site-3	#Y347-#Y348	August, 2009	Clay soil
	Utility F, NY			
21	Scheduled	#Z507-#Z508	N/A	No data was provided

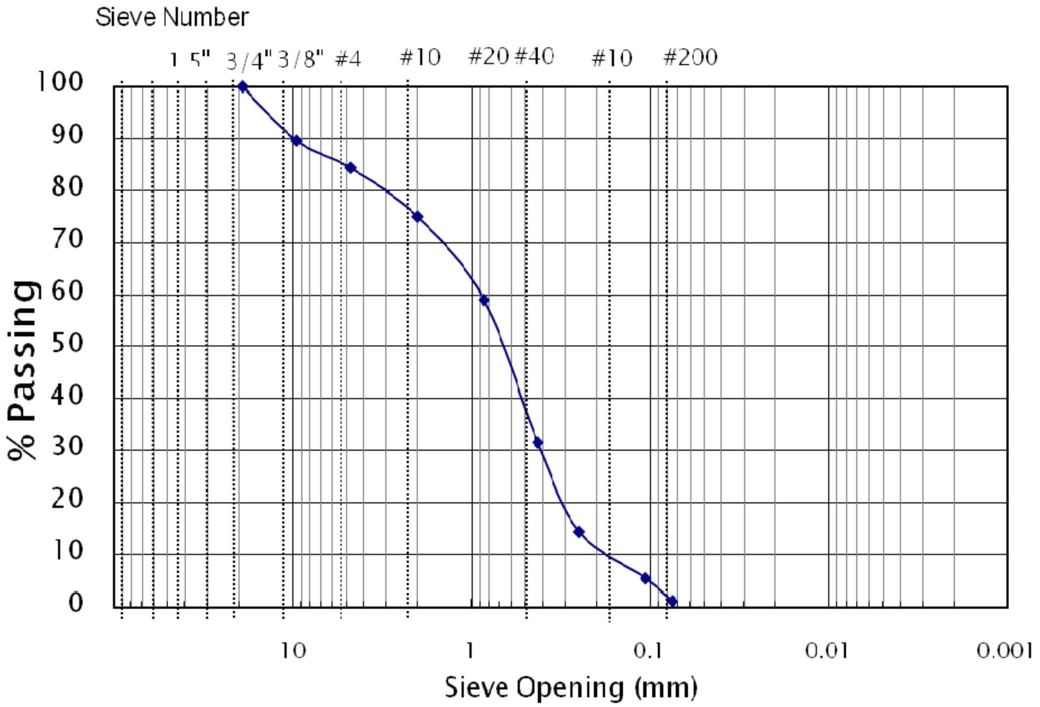


Figure 48 - Soil gradation of the backfill material at Utility-A Site, NY

Table 7 - Soil properties of the Utility-A site

Parameter		Value	Notes
Resistivity		8.8 k	(with soil moisture content from site condition)
		2.3K	(saturated)
LPR reading	(mpy)	2.74	In saturated samples in the lab
pH		6.38	
Chloride	(ppm)	45	(reading 5 min)
Sulfate	(ppm)	10	
Nitrate	(ppm)	50	
Water content	(%)	8.3	(from field sample)

Figure 49 - Installation of the ER probe on the transmission pipe in Utility-A site

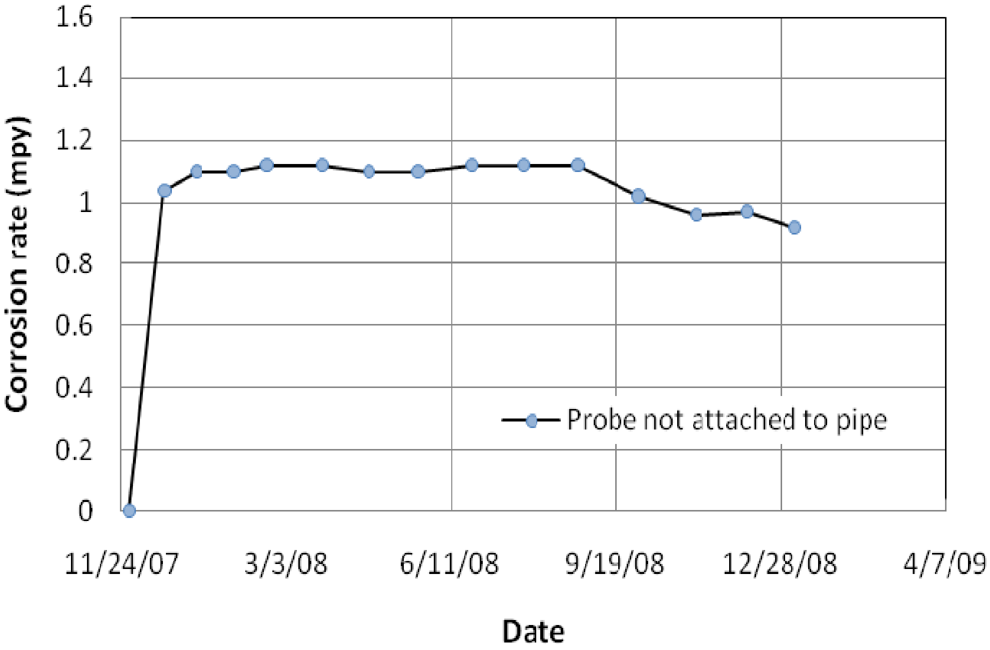


Figure 50 - Corrosion rate measurements using the ER probe in Astoria Site

B) Installation of the ER probe at Utility-B Sites, UT

ER probes were installed at four test sites at Utility-B sites during their integrity management operation of their gas transmission pipelines. The probes were installed in four sites (Sites 1 to 4) by the utility during the month of May 2008 and Initial measurements of the ER probes were recorded during installation. Figure 51 to Figure 53 show the installation of the ER probes.

Soil samples were taken from the four sites and sent to GTI for soil classification and characterization. The soils in the four sites were sandy soil with no plasticity. All soils had less than 10% clay and silt fines (i.e., soil passing sieve #200). The soil in Site-1 had finer granular material (with about 70% passing sieve #40) than Soil 4 which had about 30% passing sieve #40. Figure 54 shows the grain size analysis of the soils. Table 8 shows the chemical analysis of the soils in the four sites. The soils had low mineral components with the exception of the high Chloride content in Site-1. Chloride ions can increase the corrosion current and resultant corrosion by increasing the anode to cathode voltage and reducing the backfill resistivity.

Corrosion rate measurements of the sites are shown in Figure 55. The results show that low corrosion rates below 1 mpy in the four sites with reduction in the rate measurements with time.

Figure 51 - View of the test section at Site-1

Figure 52 - Installation of the ER probe in Site-4

Figure 53 - View of the ER probe installation in the backfill

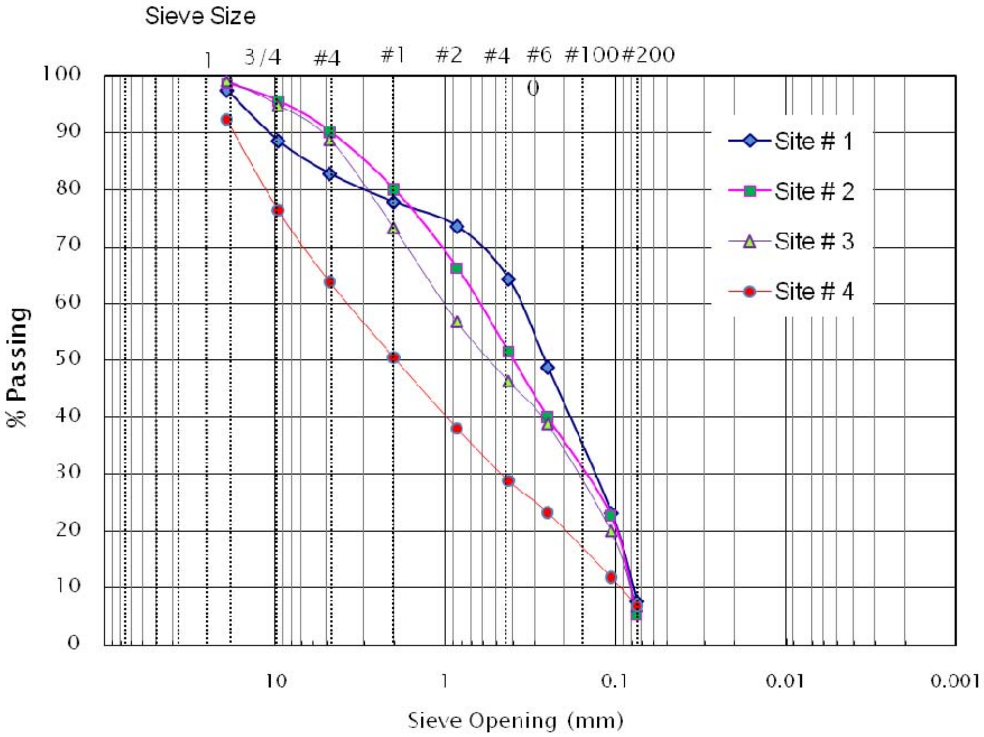


Figure 54 - Grain size distribution of the Utility-B soils

Table 8 - Results of the chemical analysis of Utility-B soils

Chemical Analysis, Dry Soil Basis

Sample Number	Sample Description	Chloride, µg/g	Nitrate, µg/g	Sulfate, µg/g
081431-001	Site #1	389	2.3	26.8
081431-002	Site #2	3.7	41.4	12.6
081431-003	Site #3	47.4	5.4	24.0
081431-004	Site #4	4.0	< 1.0	6.3

Chemical Analysis, Dry Soil Basis

Sample Number	Sample Description	Moisture, wt%	Chloride, µg/g	Nitrate, µg/g	Sulfate, µg/g
081431-001	Site #1	11.0	437	2.6	30.1
081431-002	Site #2	13.6	4.3	48.0	14.6
081431-003	Site #3	8.5	51.8	5.9	26.2
081431-004	Site #4	5.0	4.2	< 1.0	6.3

The moisture content was determined by drying to constant weight at 107°C.

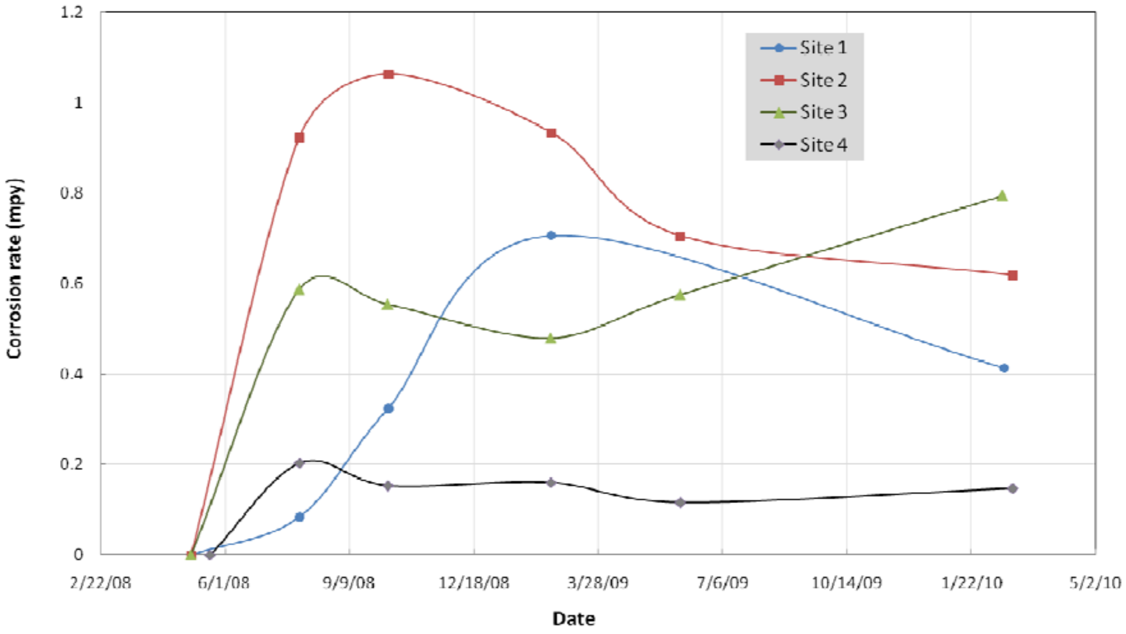


Figure 55 - Corrosion rate measurements of the test sites

C) Installation of the ER probe at Utility-C Sites, NV

The probes were installed in three test sites by the utility personnel during the period of June to November 2008. The three sites had granular soils with clay and gravel contents in Site 3. Soil properties and gradations of the three test sections are shown in Figure 56 and Table 9.

Two ER probes were installed at each site. One probe was connected to the cathodically-protected pipe through a lead wire and the other probe was not connected to the pipe and was placed in the backfill around the pipe. Corrosion rate measurements of the three sites are shown in Figure 57 to Figure 59. The results show a drop of the corrosion rate after relatively high initial corrosion rate measurements in sites 1 and 2.

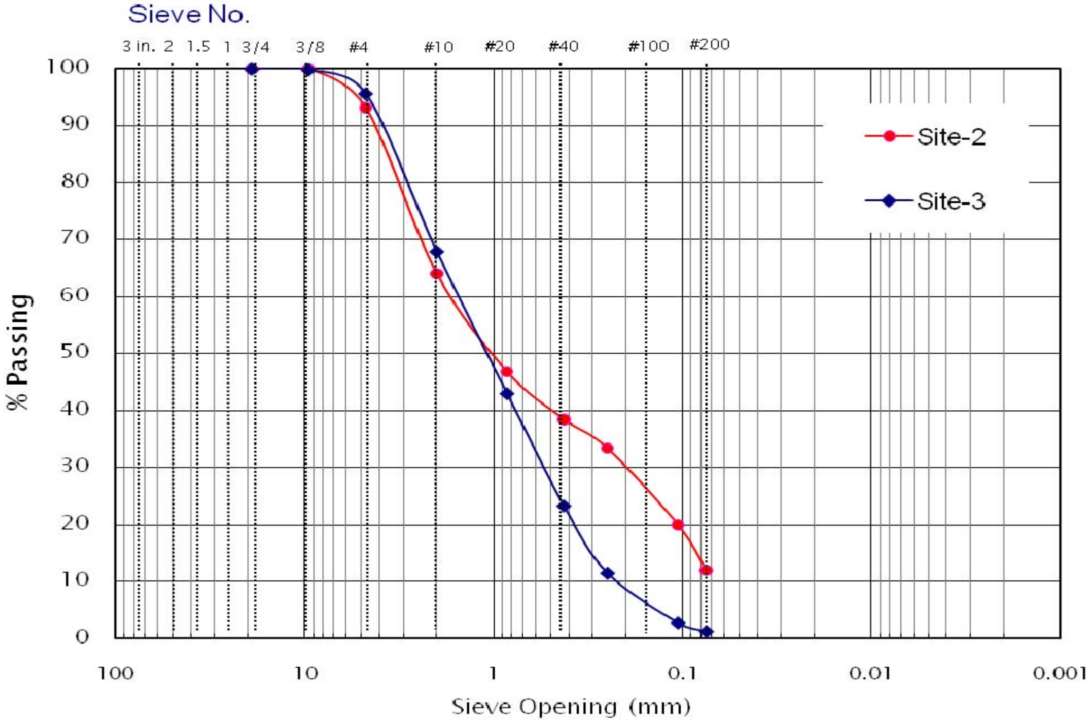


Figure 56 - Grain size distribution of Soil in Utility-C sites

Table 9 - Soil properties of Utility-C sites

Site	Soil type	Resistivity (ohm-cm)	pH	Chloride (mg/g)	Nitrate (mg/g)	Sulfate (mg/g)
Site-1	Sandy-clay with gravel	-	8.6	30	2.6	10
Site-2	Sandy Soil	22,000	3.6	15	3	45
Site-3	Sandy Soil	17,500	4.4	3	3	12

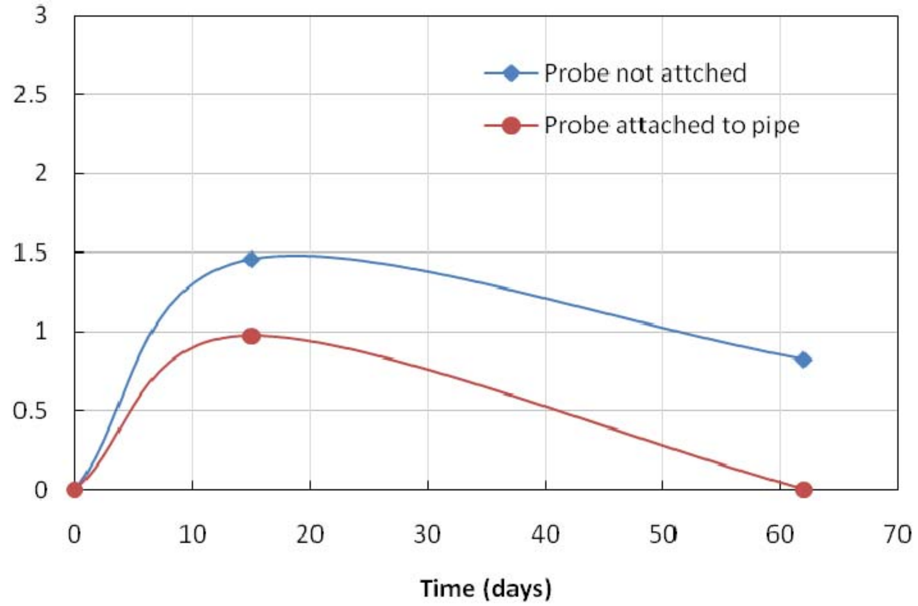


Figure 57 - Corrosion rate measurements of Site 1

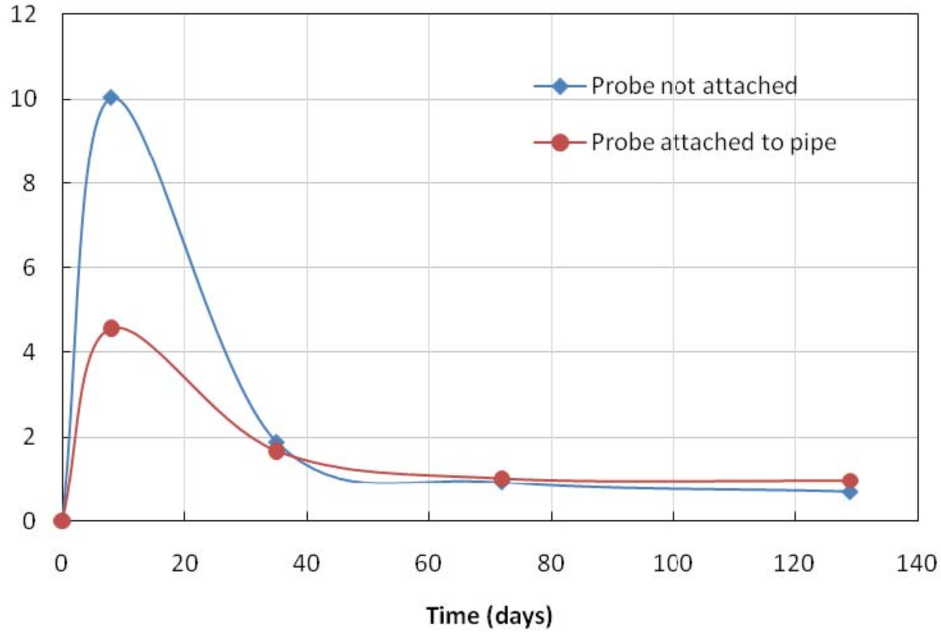


Figure 58 - Corrosion rate measurements of Site-2

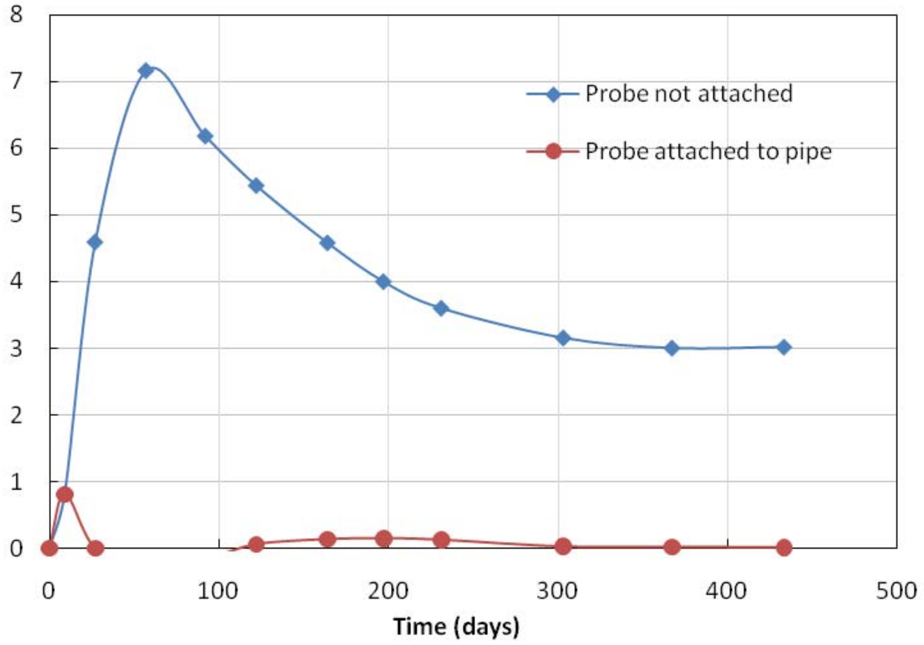


Figure 59 - Corrosion rate measurements of Site-3

E) Field Installation at Utility-E Test Site, IL

The probes were installed at transmission lines in three sites during the period of May to August 2009. The soils in the three sites were medium plasticity clay-silt soil. Site-1 had 50% clay content and a high water table at the time of excavation. Figure 60 shows the excavation of Site-1. The soil had a chloride content of 370 ppm and a pH value of 8. Figure 61 shows the ER measurement at the ground surface in the site.

Site-2 had medium plasticity soil with about 40% clay content and a higher chloride content of 750 ppm and pH value of 8. Figure 62 and Figure 63 show the excavation and ER measurements of Sites 2, respectively. Figure 64 shows the excavation in Site-3. The soil properties and gradations of the test sections are shown Appendix D.

Two ER probes were installed at each site. One probe was connected to the cathodically-protected pipe through a lead wire and the other probe was placed in the backfill around the pipe. The measurements of the ER probes in the soil are shown in Figure 65. A high corrosion rate of about 8 mpy was recorded in the high chloride clay soil in Site 2.

Figure 60 - ECDA excavation at the Utility E Site-1

Figure 61 - ER measurements in the Utility-E Site-1

Figure 62 - ECDA excavation at the Utility-E Site-2

Figure 63 - ER measurement at the Utility-E Site-2

Figure 64 - Site preparation at the Utility-E Site-3

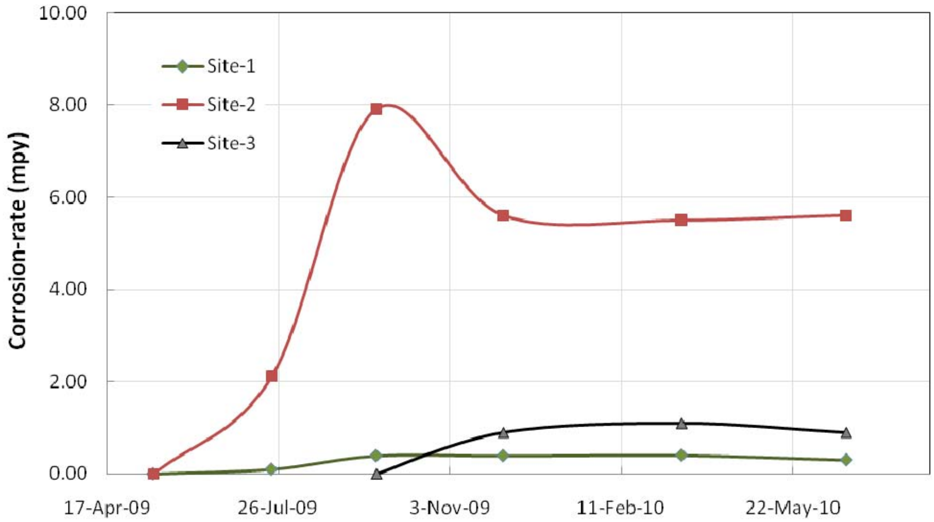


Figure 65 - ER measurements in Utility-E three sites

Summary

Measurements of corrosion rates were performed using the LPR on soil samples from the GTI test sections and several utility sites. Long-term field monitoring of corrosion rate was also performed with the LPR in two GTI test sections.

The LPR measurements demonstrated its sensitivity to the varying testing parameters (e.g., monitoring duration and changes of water content) and it was difficult to obtain a reliable estimate of the corrosion rate in dry soil. The average long-term measurements of the LPR in the field were higher than the corrosion rates from the ER device and weight-loss measurements. The LPR measurements estimate the potential variations of corrosion due to the changes in the electro-chemical environment in the soil while the ER and weight-loss measurements reflect the actual metal loss in the field.

The ER probes were installed in a total of 17 utility sites and the corrosion rate measurements and soil properties were obtained from 11 of these sites.

The electrical resistance (ER) measurements showed that the ER device provides consistent long-term measurements of corrosion rate and it is an efficient method to obtain the long-term corrosion growth rate of the pipe without the need for field excavation. The probe measurements typically model the localized metal loss at the surface as reflected by the change of the probe’s electrical resistance. These measurements differ from the general corrosion estimates commonly obtained from the weight-loss measurements.

CHAPTER 5

Estimation of Corrosion Rate from Soil Properties

A) Introduction

The rate of external corrosion is influenced by a significant number of soil and environmental parameters which makes it difficult to determine a realistic estimate. In the field, external corrosion rate may be estimated from the following measurements:

1. Direct measurements of pitting depth as a function of time during repetitive excavations,
2. Measurements of wall thickness as a function of time during repetitive in-line inspection (ILI) runs,
3. Measurements of corrosion-rate from Linear Polarization Resistance (LPR) and Electrical Resistance (ER) probes.

Methods to estimate the general corrosion-rate also include measurements of weight-loss from field coupons. Several models have been developed to estimate corrosion-rates based on soil and environmental parameters (10), (11), (12), and (13). These models provided several methodologies for quantifying corrosion-rates and comparisons with field measurements such as ILI runs.

In the absence of corrosion-rate measurements, NACE recommends using a high pitting corrosion-rate of 16 mpy (0.4 mm/year) to determine the re-inspection intervals for external corrosion direct assessment (ECDA) (1). This rate represents the upper 80% confidence level from long-term corrosion tests of unprotected steel in various soils.

The objective of this task of the research project is to develop: (a) an effective procedure to determine the locations of high corrosion potential for monitoring corrosion rate, and (b) a simplified method to estimate the external corrosion rate based on soil and environmental parameters. The procedure is further discussed in Chapter 6 and it is incorporated into a web-based computer program presented in Chapter 7 to provide an estimate of corrosion growth rate based on the measured soil parameters.

The objective of the computer program is to provide the field engineer with a tool to make an informed estimate of corrosion growth rate in a particular pipeline region. This will result in the proper selection of reassessment intervals. The estimate also identifies potential sites where high rates are anticipated and further field monitoring is required.

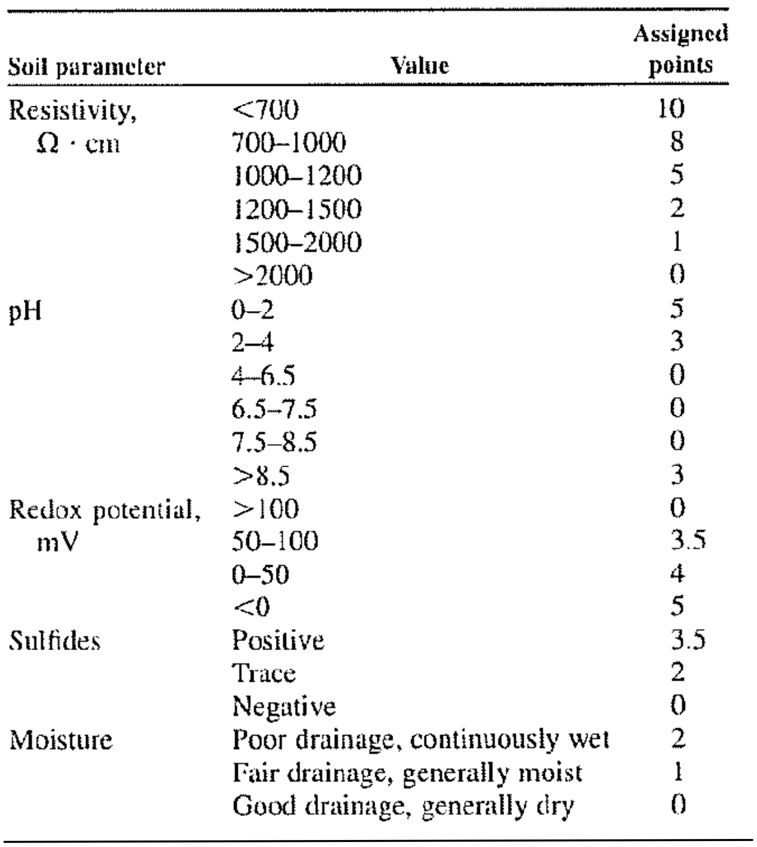
The estimation of corrosion-rates from soil properties builds on the following data:

- Corrosion estimates based on the American Water Works Association (AWWA) guidelines,
- Historical data of corrosion-rate predictions based on soil parameters,
- Utility measurements of corrosion-rates in various soils,
- NIST database of field corrosion-rate measurements in various soil types and conditions.

B) Corrosion Estimation from AWWA Guideline (14)

The American Water Works Association (AWWA) C-105 guideline assigns point rating to five soil parameters and the cumulative total of these points is used to judge the backfill corrosion potential. Table 10 shows the AWWA guideline for the effect of backfill parameters on corrosion potential. A total sum of 10 or higher indicates that the backfill has a high corrosion potential.

Table 10 - Point System for soil corrosivity (14)



Soil parameter	Value	Assigned points
Resistivity, Ω · cm	<700	10
	700–1000	8
	1000–1200	5
	1200–1500	2
	1500–2000	1
	>2000	0
pH	0–2	5
	2–4	3
	4–6.5	0
	6.5–7.5	0
	7.5–8.5	0
	>8.5	3
Redox potential, mV	>100	0
	50–100	3.5
	0–50	4
	<0	5
Sulfides	Positive	3.5
	Trace	2
	Negative	0
Moisture	Poor drainage, continuously wet	2
	Fair drainage, generally moist	1
	Good drainage, generally dry	0

The AWWA guidelines conservatively specifies soils with pH greater than 8.5 as moderately corrosive due to presence of dissolved salts that could lead to reduced resistivity and possibly react with the pipe.

The AWWA test criterion does not include two important factors; namely chloride concentration and stray current. A soil chloride concentration higher than 500 ppm is considered corrosive. The influence of stray current which causes a shift in the polarized pipe-to-earth potential greater than ±50 mV versus a copper-copper sulfate reference cell may also result in corrosion of a buried pipe [(15).

C) Corrosion Estimates from Soil Properties

Soil corrosion is affected by a significant number of soil and environmental parameters including soil resistivity, water content, pH, soluble salts, oxygen concentration, soil chemistry, and microbial activities. Accordingly, corrosion-rate in soil may change along the length of the pipe and it makes it difficult to obtain a single rate. The estimation of corrosion-rate estimate in a specific pipe segment may be based on the uniform soil or backfill properties that are representative of the segment. The most significant soil parameters based on the historical data from the literature are:

1. Soil Electrical Resistivity

Resistivity indicates the ability of the soil to carry corrosion current. It is a function of soil moisture and the concentration of current-carrying soluble ions. The higher the resistivity of the backfill, the higher is its resistance to the electro-chemical corrosion of the pipe. Conversely, low resistivity environment increases corrosion rates. Table 11 and Table 12 show typical corrosion classifications based on soil resistivity. The steel pipeline industry considers resistivity less than 1,000 ohm-cm to be very corrosive.

Table 11 - Steel pipe corrosion classification (16)

Resistivity (ohm-cm)	Classification
0 to 1,000	Very severely corrosive
1,001 to 2,000	Severely corrosive
2,001 to 5,000	Moderately corrosive
5,001 to 10,000	Mildly corrosive
> 10,000	Very mildly corrosive

Table 12 - Corrosivity classification based on soil resistivity (17)

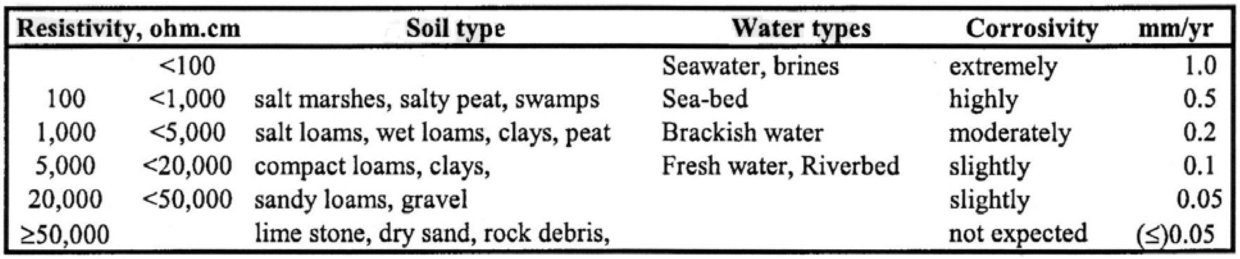
Resistivity (ohm-cm)	Classification
<1000	Extremely corrosive
1,000-3,000	Highly corrosive
3,000-5,000	Corrosive
5,000-10,000	Moderately corrosive
10,000-20,000	Mildly corrosive
>20,000	Essentially non-corrosive

Several correlations between corrosion-rate and soil resistivity have been presented in the literature. ASME B31.8S (18) contains guidelines on estimating corrosion-rates based on soil resistivity as shown in Table 13. Several relationships of correlation-rates with soil resistivity are shown in Table 14 and Table 15. Figure 66 and Figure 67 show comparisons of several correlations with NACE recommended practice and ASME B31.8S guidance.

Table 13 - Corrosion-rate related to soil resistivity (18)

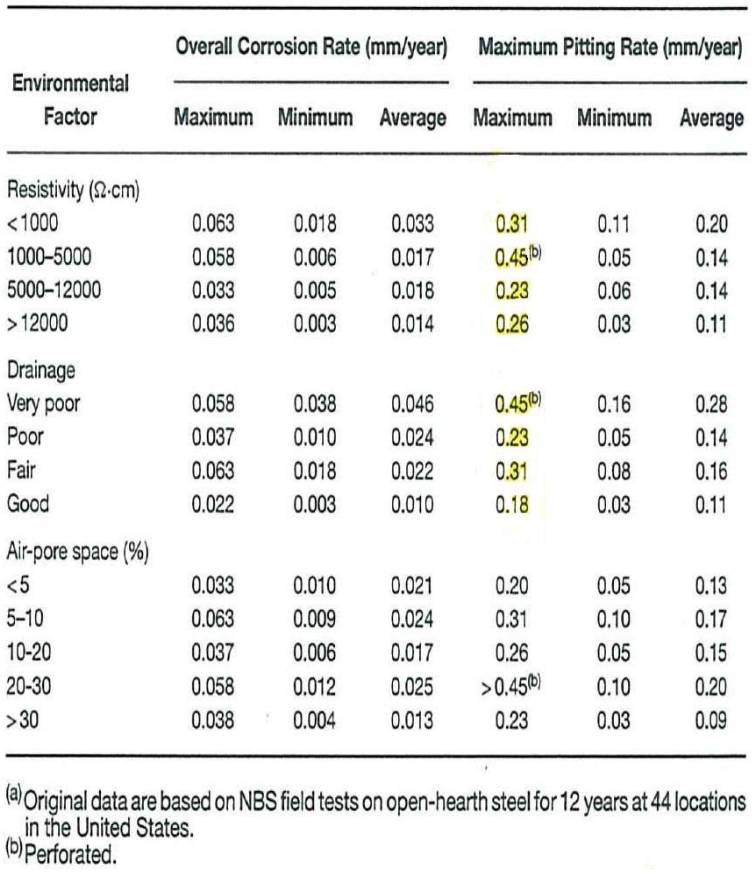
Corrosion rate (mils/year)	Soil Resistivity, ohm-cm
3	>15,000 and no active corrosion
6	1,000 –15,000 and/or active corrosion
12	<1000 (worst case)

Table 14 - Corrosion rate estimate with resistivity and soil type (11)



Resistivity, ohm.cm		Soil type	Water types	Corrosivity	mm/yr
	<100		Seawater, brines	extremely	1.0
100	<1,000	salt marshes, salty peat, swamps	Sea-bed	highly	0.5
1,000	<5,000	salt loams, wet loams, clays, peat	Brackish water	moderately	0.2
5,000	<20,000	compact loams, clays,	Fresh water, Riverbed	slightly	0.1
20,000	<50,000	sandy loams, gravel		slightly	0.05
≥50,000		lime stone, dry sand, rock debris,		not expected	(≤)0.05

Table 15 - Effect of soil characteristics on corrosion rate (19)



Environmental Factor	Overall Corrosion Rate (mm/year)			Maximum Pitting Rate (mm/year)		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Resistivity (Ω·cm)						
<1000	0.063	0.018	0.033	0.31	0.11	0.20
1000–5000	0.058	0.006	0.017	0.45[(b)]	0.05	0.14
5000–12000	0.033	0.005	0.018	0.23	0.06	0.14
>12000	0.036	0.003	0.014	0.26	0.03	0.11
Drainage						
Very poor	0.058	0.038	0.046	0.45[(b)]	0.16	0.28
Poor	0.037	0.010	0.024	0.23	0.05	0.14
Fair	0.063	0.018	0.022	0.31	0.08	0.16
Good	0.022	0.003	0.010	0.18	0.03	0.11
Air-pore space (%)						
<5	0.033	0.010	0.021	0.20	0.05	0.13
5–10	0.063	0.009	0.024	0.31	0.10	0.17
10-20	0.037	0.006	0.017	0.26	0.05	0.15
20-30	0.058	0.012	0.025	>0.45[(b)]	0.10	0.20
>30	0.038	0.004	0.013	0.23	0.03	0.09

[(a)] Original data are based on NBS field tests on open-hearth steel for 12 years at 44 locations in the United States.

[(b)] Perforated.

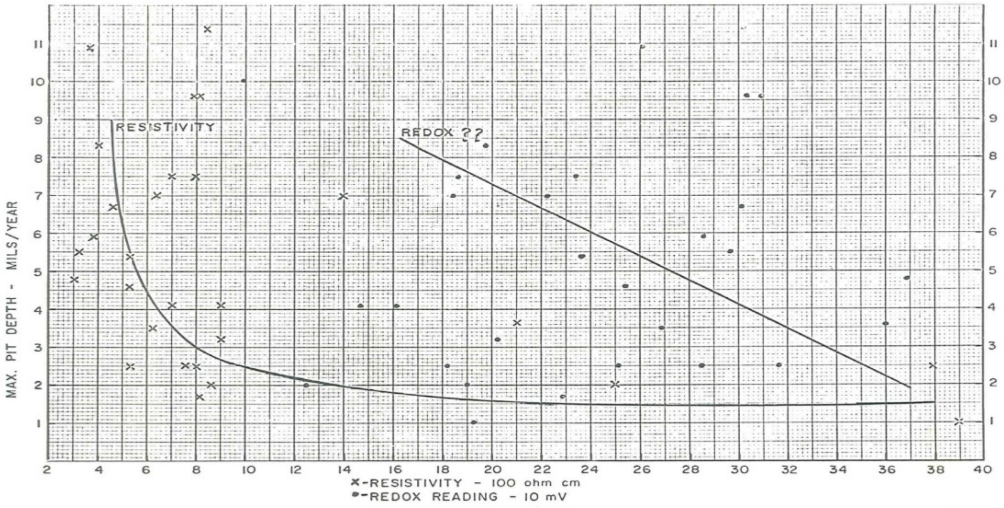


Figure 66 - Correlation of soil resistivity with pit-depth rate (20)

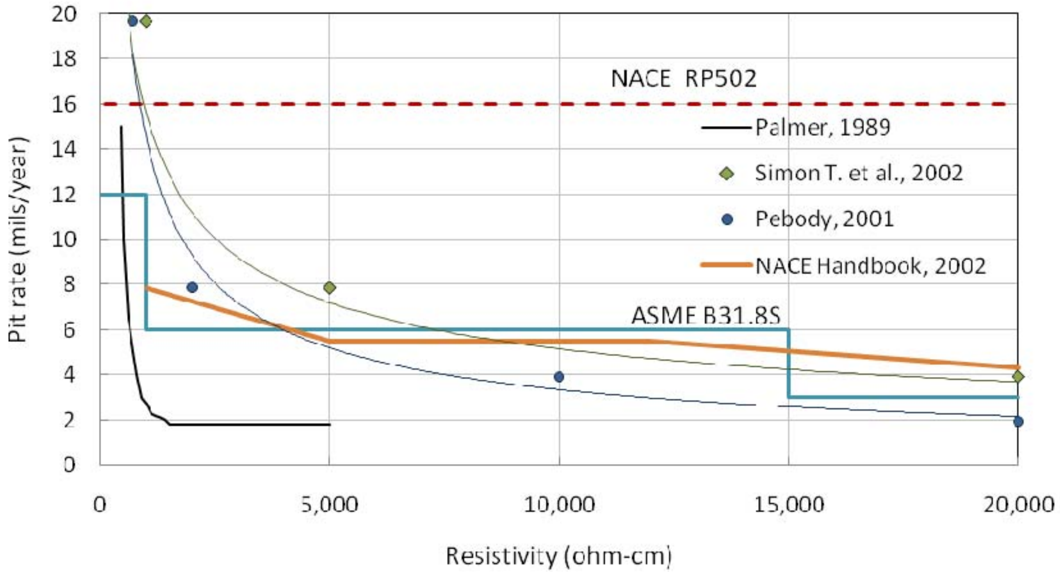


Figure 67 - Various models for estimating corrosion-rate from soil resistivity

2. Mineral Components

The corrosivity of a soil can be affected by the presence of certain ion components. Chloride ions can increase the corrosion current and resultant corrosion by increasing the anode to cathode voltage and reducing the backfill resistivity. Sulfate level can lead to increased corrosion activity as it plays an important role in Microbiological Induced Corrosion (MIC) when the Redox potential of the backfill is relevant (less than +100mV). Table 16 and Table 17 show the effect of chlorides and sulfates on sol corrosivity.

Table 16 - Effect of chloride on soil corrosively (21)

Chloride (ppm)	Corrosivity rating
> 5,000	Severe
1,500 - 5,000	Considerable
500 - 1,500	Corrosive
100-500	***Threshold***

Table 17 - Effect of Sulfate on soil corrosively (21)

Sulfate (ppm)	Corrosivity rating
> 10,000	Severe
1,500 - 10,000	Considerable
150 - 1,500	Detectible
100-500	*Negligible*

3. Soil pH Value

Soils and water had little to minimum impact on the corrosion of ferrous materials when their pH ranges between 4 and 8.5. Above 8.5, pH value has little effect on corrosion rate until it reaches 12. If the pH value is too low (below 4) or too high (above 12) it may lead to metal corrosion and/or coating degradation (20).

Table 18 - Change of soil corrosivity with pH (22)

pH of Soil	Acid/Alkaline	Corrosivity rating
<5.5	Acidic Soil	Severe
5.5-6.5	Slightly Acidic	Moderate
6.5-7.5	Neutral	Neutral (low)
>7.5	**Alkaline Soil**	**None (Low)**

4. Soil Texture

Clay has minimum particle size and minimum pore volume between the particles. Accordingly, clay's low permeability results in low air and water flow and can also result in a higher saturation. Sand has higher permeability and results in increased aeration and moisture fluctuation. The high drainage characteristics of sand can improve drainage of soil and result in drier soil. The effect of soil drainage characteristics on corrosion potential is shown in Table 19.

Table 19 - Effect of soil drainage on corrosion rate (23)

Soil Drainage	General Corrosion (mpy)	Maximum Pitting Rate (mpy)
Very poor	2.3	>17.7
Poor	1.5	12.2
Fair	2.5	9.1
Good	**0.86**	**7.1**

5. Soil Temperature

Soil temperature has a minimum effect on soil resistivity when temperature is above freezing. Below freezing point, soil resistivity increases sharply (Figure 68). Accordingly, resistivity measurements at frozen soil near the surface will not correctly reflect conditions at higher temperature near the pipe. Temperature also affects oxygen solubility in the soil. Because temperature increase and oxygen solubility have opposing effects on resistivity, temperature effect is minimized.

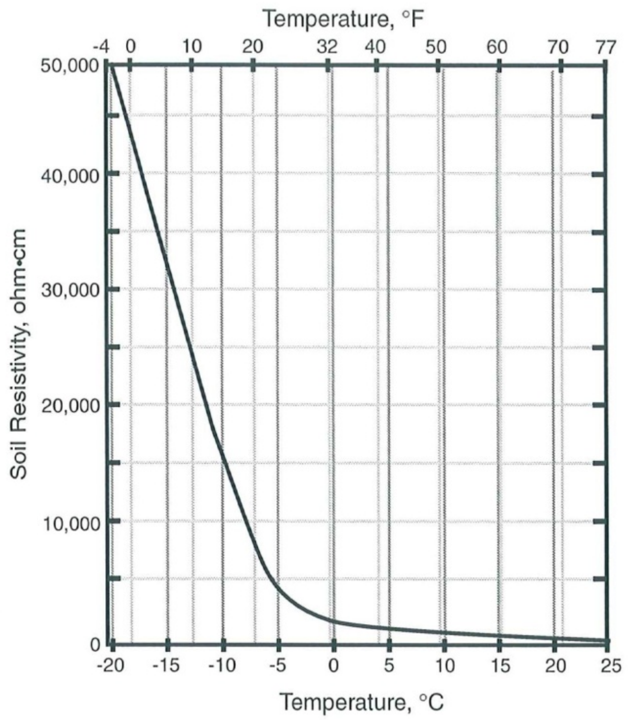


Figure 68 - Effect of Soil temperature on resistivity (24)

6. Soil Oxidation-Reduction (Redox) Potential

The Redox potential is used to determine the anaerobic soils that could support sulfate-reducing bacterial activities. A high Redox potential measurement indicates aerobic conditions and, consequently, a low potential for sulfate-reducing bacterial activities.

Table 20 and Table 21 show the relationship between Redox potential and corrosion potential. Measurements of Redox potential are usually performed in the field since the removal and transportation of the samples to the laboratory cause aeration of the sample and result in inaccurate values.

Table 20 - Relationship between Redox potential and corrosivity (25)

Classification of corrosion	Redox Potential (mV)
severely corrosive	< 100 mV
moderate corrosion	100 to 200 mV
Slight corrosion	200 to 400 mV
Non-corrosive	> 400 mV

7. Soil Type and Drainage

Soil corrosivity differs in undisturbed soil and in disturbed soils. Corrosion in undisturbed soil is limited by the availability of oxygen necessary for the cathodic reaction and it is commonly lower than corrosion in disturbed soil. Disturbed soil conditions during backfilling of gas pipes may result in corrosion rates that are highly affected by soil types and conditions (e.g. electrical resistivity, mineral composition and dissolved salts).

Table 21 - Soil Aeration and Redox potentials (24)

Redox Potential	Soil Aeration	Soil Corrosivity
Negative	Not Aerated	Extremely sever
0 – 100 mV	None to weak	Severe
100 to 200 mV	Weakly aerated	Moderate
200 – 400 mV	Aerated	Slight
>400 mV	**Strongly aerated**	**Noncorrosive**

CHAPTER 6

Correlation of Pipe Corrosion with Soil Properties

A) NIST Field Corrosion Rate Measurements

The National Institute of Standards and Technology (NIST) conducted an analysis of a large number of corrosion measurements of pipe samples installed in various sites nationwide (26) . The field study was conducted earlier on bare steel and wrought iron pipes buried underground at 47 different sites representing different soil types across the United States. One of the objectives of the study was to determine if soil properties could be used to predict corrosion.

The study performed multiple regressions of corrosion damage data against measured soil properties and concluded that relationships can be developed from these data. However, the scatter inherited in the measurements limited the ability of the corrosion predictions. The relationship between the steel pipes corrosion rates and soil resistivities from the NIST study was incorporated with other published relationships and the recent ER field measurements to establish a procedure to estimate correlation rate from soil properties.

The NIST results of the average pitting rate measurements with various soil properties are shown in Figure 69 and Figure 70 for pH<7 and pH>7, respectively. The figures show higher R^2 vales when the data was categorized into these two sets. Since soil parameters interact together so that a change of a single parameter may affect the contributions of the other ones, lower correlations are observed when the corrosion rate is plotted with other soil properties as shown in Figure 71 and Figure 72 for soil chloride and sulfate contents, respectively.

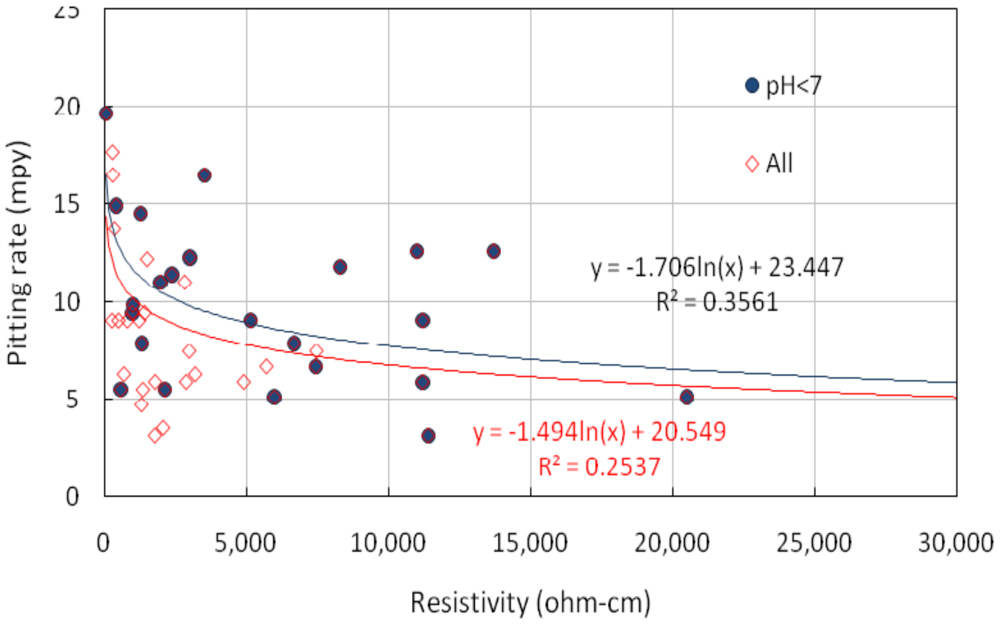


Figure 69 - Average steel pitting rate with resistivity of pH < 7 in the NIST data

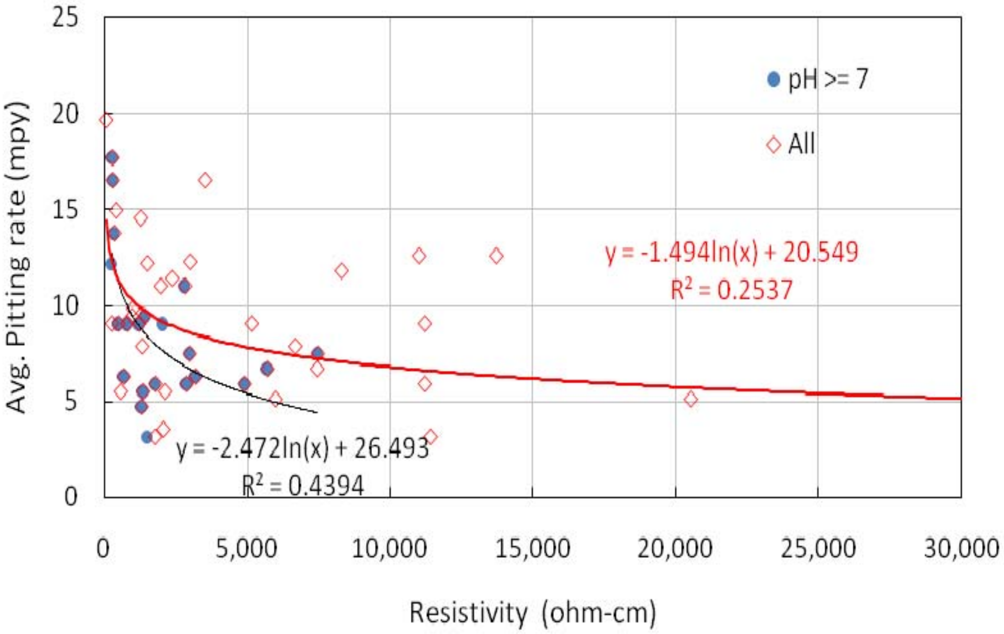


Figure 70 - Average steel pitting rate with resistivity for pH >= 7 in the NIST data

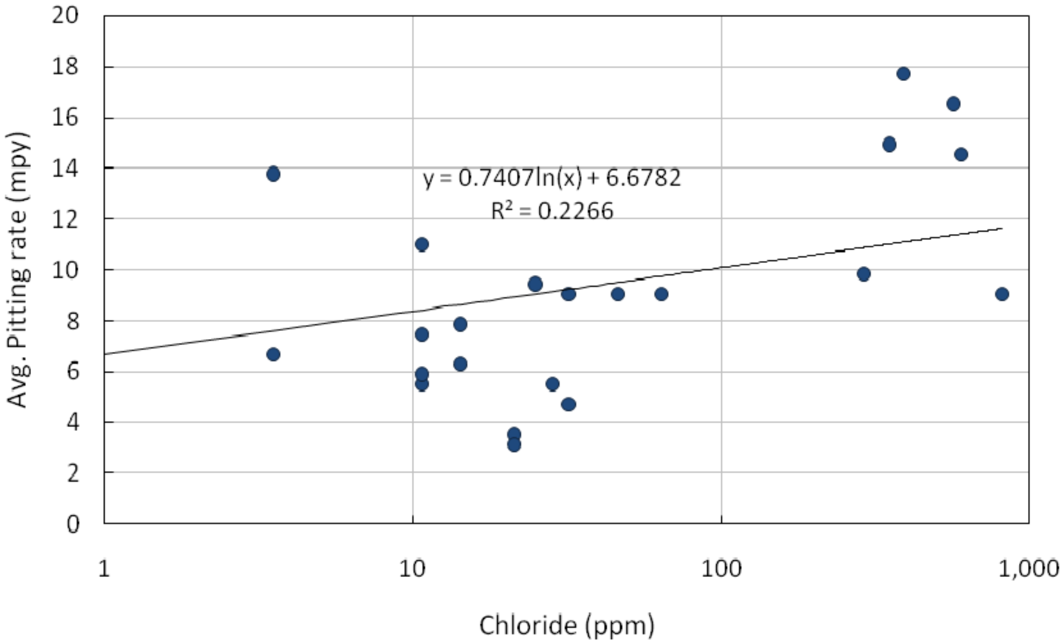


Figure 71 - Average steel pitting rate with chloride in the NIST data

In general, the NIST data show significant change of the steel localized corrosion with soil types. Figure 73 shows higher rate for cohesive soils (i.e., clay and clay-loam) in comparison to the pitting rate in sand.

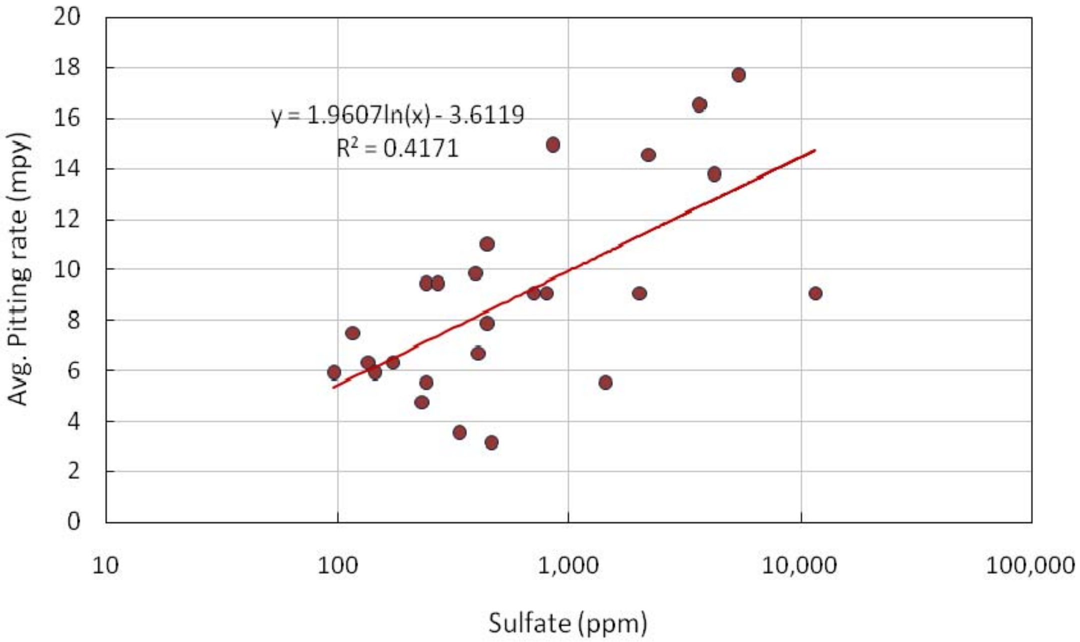


Figure 72 - Average steel pitting rate with sulfate in the NIST data

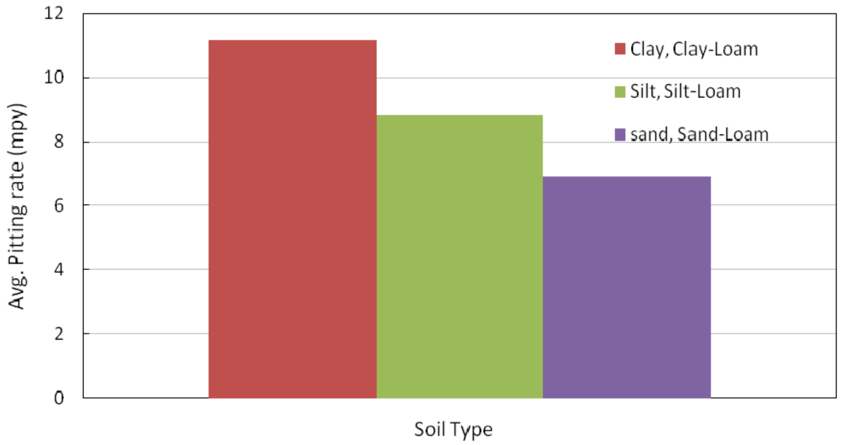


Figure 73 - Change of pitting rate with soil type in the NIST data

B) Procedure for Estimating "Unprotected" Corrosion Rate

The procedure used in estimating corrosion rate from soil properties is as follows:

a. The rate of pitting corrosion is correlated to the change of soil resistivity: The relationships in Figure 74 present various models that correlate corrosion rate to soil resistivity. The relationship between average pitting corrosion and soil resistivity from the NIST database was selected since it represents actual field measurements and is more conservative than other recommended relationships (i.e., ASME B31.8S and NACE 2002) as shown in the figure. This relationship can be written as:

Average pitting-rate (mils/year), $Y_{Rate} = -1.494\ Ln(x) + 20.55$ (1)

Where, x is the soil resistivity.

In reality, corrosion-rates are influenced by a combination of several soil parameters along with soil resistivity. Soil parameters interact together so that each parameter is affected by the contributions of the other ones. A simplified approach to include the effect of the other soil parameters is to build a ranking approach that incorporates these parameters based on their significance to corrosion mechanism.

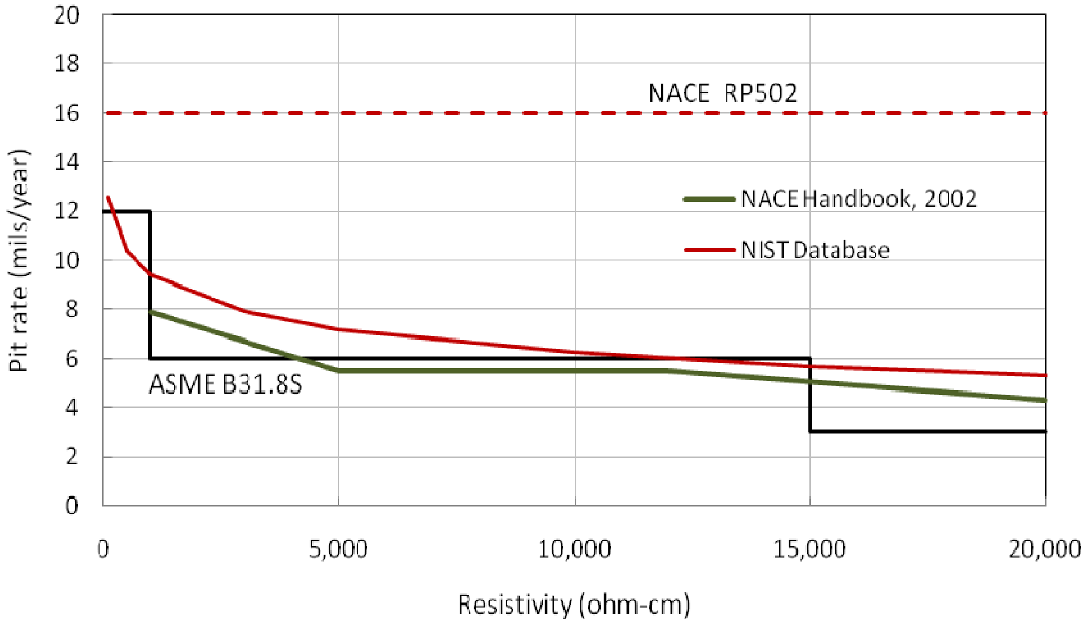


Figure 74 - Correlation between pitting rate and resistivity

b. Establish weighted values for soil parameters: Unlike the binary forms of the corrosiveness measure, such as the AWWA 10-point system, the procedure determines the corrosion-rate based on weighted values for soil properties. This procedure implements ranking values to determine the influence of each property. This approach is based on several previous studies in references: (10), (11), and (13). The influencing factors of soil parameters is represented as follows:

$$CR_{model} = Y_{Rate} *(\sum W_i \times F_i) \qquad (2)$$

Where, CR_{model} is the 'unprotected' corrosion-rate from the model based on soil parameters,

Y_{Rate} is the initial estimate of the rate based on soil-resistivity model in equation *(1)*,

W_i is a weighing factor from (0 to 1) assigned for each soil parameter, $\sum W_i = 1$,

F_i is the parameter score to estimate of the severity of corrosion due to a soil parameter (*i*), from historical data.

c. Define soil properties that are implemented in the above equation. Table 22 shows the list of the parameters used in the development of the CR_{model} in equation (2).

Table 22 - Parameters used in Equation (2)

Parameter *(i)*	Soil parameter	Weighting factor W_i	Parameter Scores (F_i)
1	Soil Resistivity	0.45	1
2	pH	0.1	Section (e)
3	Redox Potential	0.1	Section (f)
4	Chloride	0.1	Section (g)
5	Sulfate	0.1	Section (g)
6	Drainage	0.15	Section (h)

d. The weighting factors W_i are based on the weights of soil parameters in the AWWA point system (namely, resistivity, Redox, pH, sulfate, and drainage). The chloride parameter is added, with a weighting factor equals to the Sulfate, due to the significant effect of chloride on corrosion potential.

e. Parameter Scores for pH: The parameter scores for pH are shown in Table 23.

Table 23 - Parameter scores for pH

pH of Soil	Corrosivity rating	Parameter score
<5.5	Severe	1.5
5.6-6.5	Moderate	1.2
6.5-7.5	Neutral (low)	1.0
>7.5	None (Low)	0.9

f. Parameter Score for Redox Potential: The *parameters* for Redox potential are shown in Table 24.

Table 24 - Parameter scores for Redox

Redox Potential (mV)	Classification of corrosion	Parameter Score
< 100 mV	severely corrosive	1.3
100 to 200 mV	moderate corrosion	1.1
200 to 400 mV	Slight corrosion	1.0
> 400 mV	Non-corrosive	0.9

g. Parameter Scores for Chloride and Sulfate: The parameter scores are based on correlations obtained from the relationships between ion contents and pitting rates in Figure 71 and Figure 72 in the NIST data. The relationships were normalized as multipliers of corrosion rates from reference corrosion at low ion content as plotted in Figure 75.

h. Parameter Scores for Drainage: The drainage scoring parameters are the multiplication of several parameters that affect the drainage properties of the soil around the pipeline, namely, soil type (e.g., sand, silt, and clay), cover type (e.g., asphalt pavement, unpaved, and grass), pipe immersion condition (e.g., immersed all year, periodically, or dry all year), and soil moisture content.

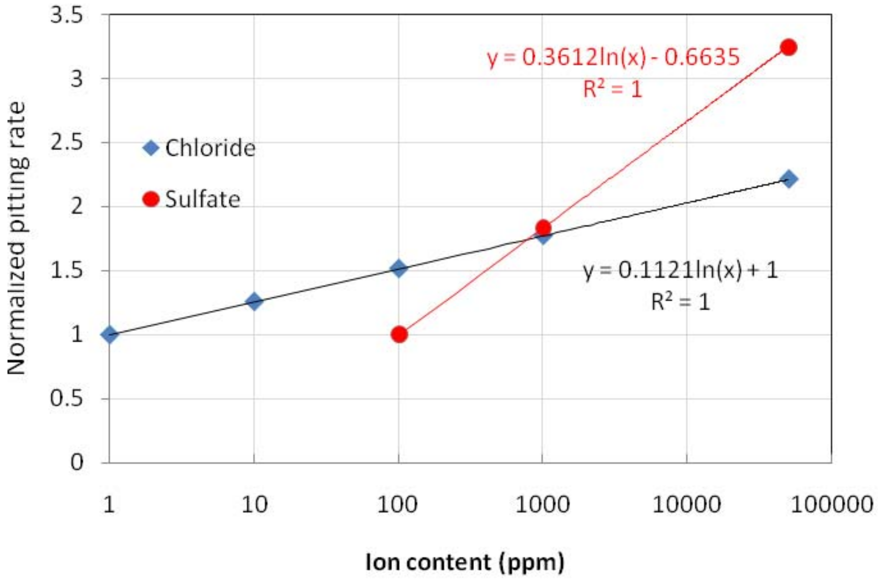


Figure 75 - Normalized pitting-rate with chloride and sulfate in NIST data

C) Procedure for Estimating 'Protected' Corrosion-Rate

The estimates of the 'un-protected' 'corrosion rates are used to establish an estimation of the 'protected' corrosion-rate due to coating and cathodic protection. The procedure is based on an earlier study (11) and is as follows:

a. Determine the unprotected corrosion rate (CR_{model}) based on soil corrosivity from the soil-corrosivity model in equation (*2*).

b. Determine the Corrected external corrosion-rate, taking into consideration the condition of the coating and the cathodic protection. The corrected corrosion rate (CR_{corr}) can be written as follows:

$$CR_{corr} = F \times CR_{protected} + (1-F) \times CR_{model} \qquad (3)$$

Where, $CR_{protected}$, is the corrosion-rate estimated for coated and CP-protected pipe.

F *is* the multiplication of cathodic protection and coating factors shown in the following section.

Accordingly, the corrected corrosion-rate is an estimate for the rate taking into consideration the performance of the CP system and the condition of the coating system.

c. Combine calculated corrosion-rate from the above step with corrosion-rate data measured from field inspection tools. The two corrosion-rate values are assigned weight factors. The weight factors depend on the reliability of the corrosion monitoring data. The 'predicted' corrosion-rate can be written in the form:

$$CR_p = f_m \, CR_{corr} + f_i \, CR_i \qquad (4)$$

Where CR_i *is corrosion-rate measured from field inspection, and* $f_m + f_i = 1$ and their selection depends on the utilities' field experience and judgment of the corrosion monitoring quality and reliability and history of the pipeline segment.

d. <u>Coating Factors:</u> Coating failure is defined as the disbonding of the coating or the occurrence of large holiday such that the efficiency of the CP system to protect the pipeline is reduced. The susceptibility of a pipeline coating to failure is dependent on the type of coating, application procedure, and how well the coating is maintained. A predictive model for external corrosion, from Reference (10), assigned several parameter weights to determine coating susceptibility to failure as follows:

$SF_{(coating)}$ = 50% application procedures (field or factory applied) + 30% coating type + 20% survey frequency

Where, $SF_{(coating)}$ is the susceptibility of coating type to failure.

The contribution of the above parameters were assigned scores between 0 to 1 to allow for $SF_{(coating)}$ to be calculated. A high assigned score for a coating type indicates its high susceptibility to coating failure. Coating deterioration depends also on the age of the installation and the estimation of corrosion rate.

Table 25 - Typical parameter scores for coating type (11)

Coating type	Parameter Score
3-Layer PE/PP	0.1
FBE, liquid epoxy	0.3
Asphalt, coal tar, double wrapped tape	0.8
Single wrap tapes	1.0

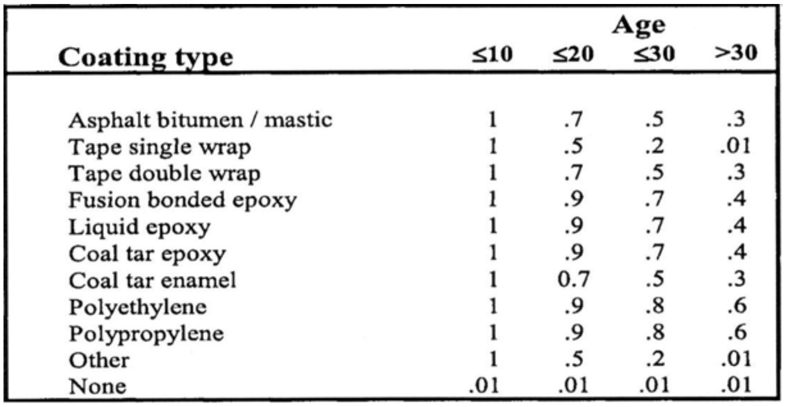
e. <u>Cathodic Protection Factor</u>: The estimated total corrosion rate CR_{total} in a pipeline section is the sum of the protected rate CRprotected and the unprotected corrosion CRunprotected of the system as follows (11):

$$CR_{Total} = F \times CR_{protected} + (1-F) \times CR_{unprotected} \qquad (5)$$

Where, F is a factor between 0 and 1 which indicates the efficiency of the CP system.

Table 26 shows the Coating Factors ($F_{coating}$) used in the theoretical estimation of corrosion rate. An adequate CP system to protect the pipeline reduces corrosion to a much lower rate with *F* equals 1 for a 100% efficient system.

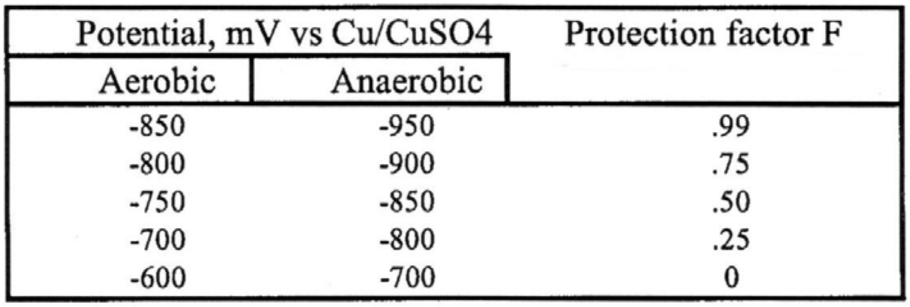
Table 26 - Pipe coating factors as function of age (11)



	Age			
Coating type	**≤10**	**≤20**	**≤30**	**>30**
Asphalt bitumen / mastic	1	.7	.5	.3
Tape single wrap	1	.5	.2	.01
Tape double wrap	1	.7	.5	.3
Fusion bonded epoxy	1	.9	.7	.4
Liquid epoxy	1	.9	.7	.4
Coal tar epoxy	1	.9	.7	.4
Coal tar enamel	1	0.7	.5	.3
Polyethylene	1	.9	.8	.6
Polypropylene	1	.9	.8	.6
Other	1	.5	.2	.01
None	.01	.01	.01	.01

The soil-pipeline potential measurement is an indication of the CP efficiency of the CP system. An off-potential measurement of -850mV, as measured by a copper-copper sulfate reference electrode, is an indication that the CP system is effective. Table 27 shows the cathodic protection factors.

Table 27 - Cathodic protection factor (F) as a function of soil potential (11)



Potential, mV vs Cu/CuSO4		Protection factor F
Aerobic	Anaerobic	
-850	-950	.99
-800	-900	.75
-750	-850	.50
-700	-800	.25
-600	-700	0

Summary

A simplified approach was developed to assess corrosion growth rates based on soil parameters and environmental conditions around the pipe. The method assigns weighted parameters to represent the contribution of various soil properties based on correlations presented in the literature. The model presents a simplified approach since it adds the effects of the various soil parameters independently. In reality, soil parameters interact together so that a change of a single parameter may affect the contributions of the other ones.

While the accuracy of the model was verified with results from the NIST database and with limited field measurements using the ER probe, further field measurements of corrosion-rates at utility sites will be needed to enhance model validation and improve the weights assigned to the various input parameters.

It should be noted that corrosion-rates of samples in identical testing conditions in the NIST database have high degrees of variability. For this purpose, comparison with a single value of the average or maximum corrosion growth rate may not represent the corrosion condition in a pipeline in similar soil and environmental conditions.

While the estimation of corrosion-rate is based on several soil and environmental properties, many other factors may affect corrosion-rate estimates. These factors include:

- Pipeline metallurgy and presence of dissimilar metals,
- Stress level on the pipe,

- Presence of stray DC current,
- Microbial corrosion,
- Soil disturbance and excavation and compaction activities,
- Levels of cations in the soil,
- Stress-corrosion cracking and hydrogen embrittlement.

Several other issues beyond the scope of this procedure should be considered when correlating the results with field measurements. These issues include:

- Seasonal variability of environment conditions,
- Corrosion growth rate mostly decreases with time,
- Field measurements of corrosion rates are difficult with regards to defining the initial corrosion time,
- Environmental changes during the exposure period (e.g., spillage, introduction of corrosion substances, and placement of adjacent pipes),
- Microbiological influenced corrosion (MIC),
- Corrosion caused by stray direct current (DC) and induced alternating current (AC).

CHAPTER 7

Modeling Pipe External Corrosion from Soil Properties

A) Introduction

A web-based computer program was developed to estimate the localized external corrosion rates of buried steel pipes based on measured soil parameters and environmental conditions around the pipe. The program ranks these parameters according to their effect on corrosion potential. The ranking is based on the correlations from the studies presented in the previous chapter and consists of assigning weighted values to quantify the contributions of these parameters.

In reality, soil parameters interact together and have high degrees of variability so that a change of a single parameter may affect the contributions of the other ones. For this purpose, determining a single value of corrosion rate may not represent the corrosion state in a pipeline in similar soil and environmental conditions. Further field measurements of corrosion rates should be performed to enhance the corrosion growth rate estimates.

While the estimation of corrosion rate is based on the several soil and environmental properties listed earlier, many other parameters beyond the scope of this project may affect corrosion rate estimates. These parameters include:

- Pipeline metallurgy and presence of dissimilar metals,
- Stress level on the pipe,
- Stray direct current (DC) and induced alternating current (AC),
- Microbiological influenced corrosion (MIC),
- Soil disturbance, excavation and compaction activities,
- Levels of cations and other ions in the soil,
- Stress-corrosion cracking and hydrogen embrittlement.

Several other factors should also be considered when correlating the results with field measurements. These factors include:

- Seasonal variability of environment conditions,
- Corrosion growth rate mostly decreases with time,
- Corrosion rates in the field are difficult to determine with regards to defining the initial corrosion time,

- Field conditions during the exposure period (e.g., spillage, introduction of corrosion substances, and placement of adjacent pipes).

The output of the program provides the following:

a) A point rating of soil corrosion potential based on the American Water Works Association (AWWA) guideline (14),

b) An estimate of localized corrosion potential of "unprotected" pipe based on soil properties,

c) An estimate of the improvement in corrosion rate in "protected" pipe based on cathodic protection level and coating type and condition,

d) A list of the corrosion rate measurements in the same State and in similar soil type or resistivity from the NIST field study (26).

The program combines the user's input data with historical correlations to provide a realistic pipe corrosion rate. The estimated corrosion rate can be used to determine the reassessment interval for the External Corrosion Direct Assessment (ECDA) of transmission pipelines. The output of the program can also be used to identify potential sites for field monitoring, where soil and environmental condition prompts pipe corrosion.

B) Data Input

The program is located at the web address: http://apps.gastechnology.org/pipecorrosion

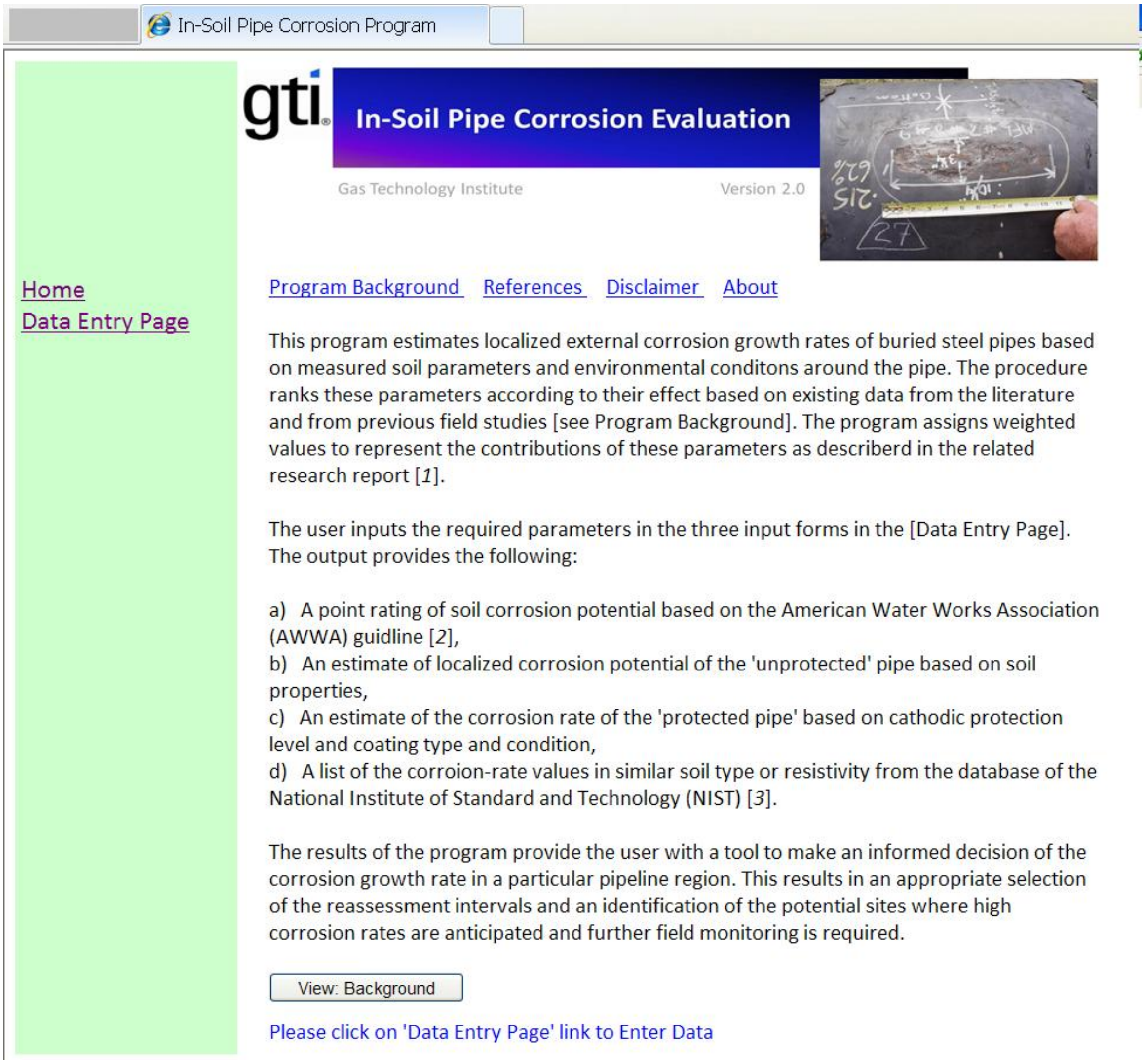
The access to the program is secured and the user may contact the e-mail address provided at the 'Log In' page to obtain the required User ID and a Password.

A view of the 'Home Page' of the program is shown in Figure 76. The page contains an introduction and a list of references used in the program development. In the 'Data Entry Page', the user inputs pipe, soil, and environmental data in three input forms.

The first input form is the Site Information form shown in Figure 77 . The entries for Ground Surface Type (Figure 78), Soil Type (Figure 79), and Pipe Immersion Condition provide drop-down lists for the users. These entries are used with weighted factors to establish the drainage condition of the site as discussed in the previous chapter. If left unchanged, the default values of these parameters will result in conservative estimate of corrosion rate.

The second form of the page is the Pipeline Information form shown in Figure 80. In this form, pipe dimensions are only used for site identification and are not used in the program. The entry for Pipe Coating Type provides a drop-down list as shown in Figure 81 and is used in estimating the protected corrosion rate. When the user selects Pipe Cathodic Protection as "None" and Pipe Coating Type as "Uncoated", only corrosion rates for 'unprotected pipes" are estimated.

The third input form is the Soil Data form and it is shown in Figure 82. If the user does not enter a value for soil resistivity, it is estimated based on soil type. Similarly, if user does not enter a value for any of the other soil properties, conservative values will be estimated for the calculation of the corrosion rate. These values will be shown in the output page. It should be also noted that the Nitrate content is not used in the program calculations.



This program estimates localized external corrosion growth rates of buried steel pipes based on measured soil parameters and environmental conditons around the pipe. The procedure ranks these parameters according to their effect based on existing data from the literature and from previous field studies [see Program Background]. The program assigns weighted values to represent the contributions of these parameters as describerd in the related research report [*1*].

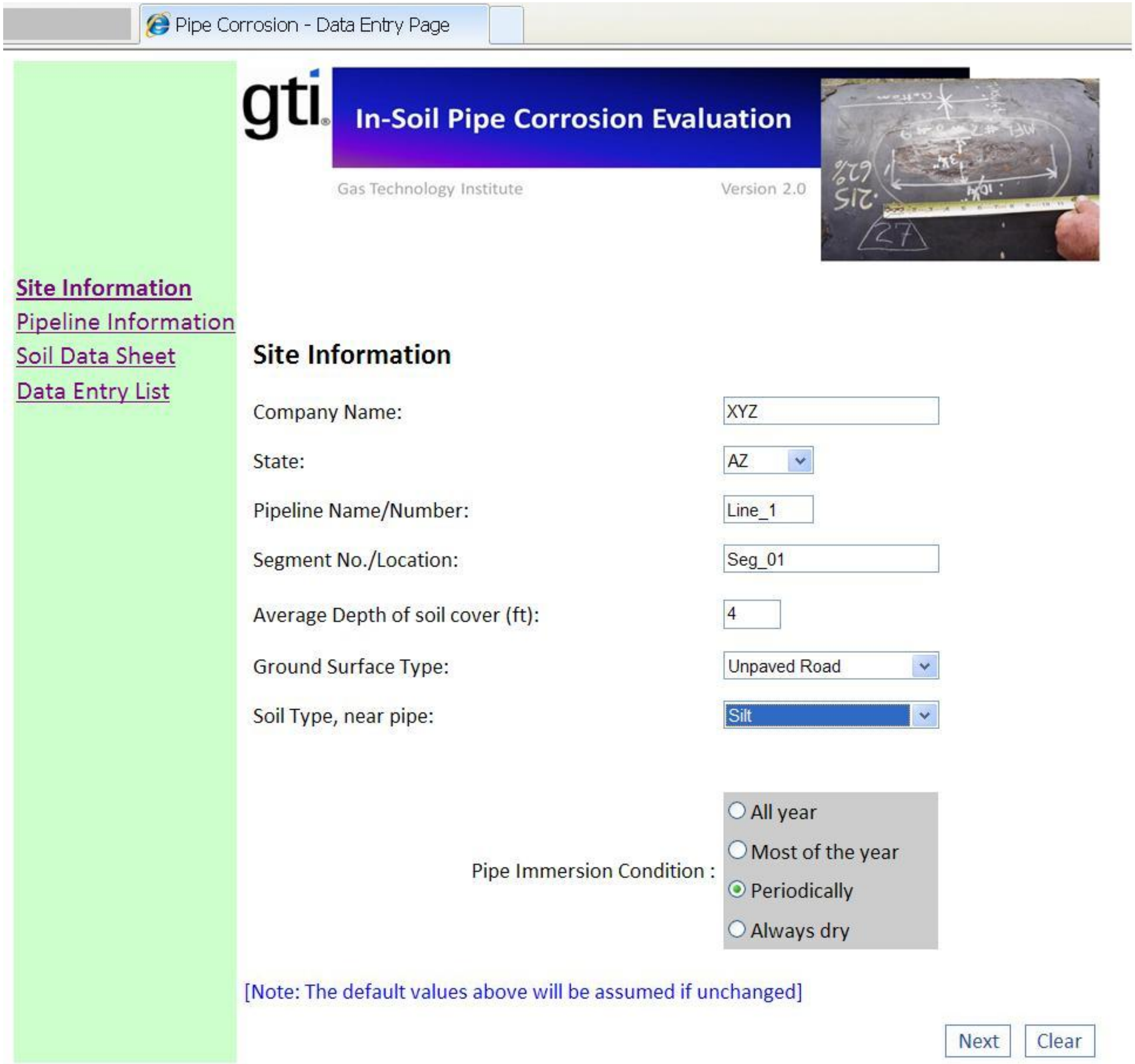
The user inputs the required parameters in the three input forms in the [Data Entry Page]. The output provides the following:

a) A point rating of soil corrosion potential based on the American Water Works Association (AWWA) guidline [*2*],
b) An estimate of localized corrosion potential of the 'unprotected' pipe based on soil properties,
c) An estimate of the corrosion rate of the 'protected pipe' based on cathodic protection level and coating type and condition,
d) A list of the corroion-rate values in similar soil type or resistivity from the database of the National Institute of Standard and Technology (NIST) [*3*].

The results of the program provide the user with a tool to make an informed decision of the corrosion growth rate in a particular pipeline region. This results in an appropriate selection of the reassessment intervals and an identification of the potential sites where high corrosion rates are anticipated and further field monitoring is required.

Please click on 'Data Entry Page' link to Enter Data

Figure 76 - View of the 'Home Page' of the web-based program



Site Information

Company Name: XYZ

State: AZ

Pipeline Name/Number: Line_1

Segment No./Location: Seg_01

Average Depth of soil cover (ft): 4

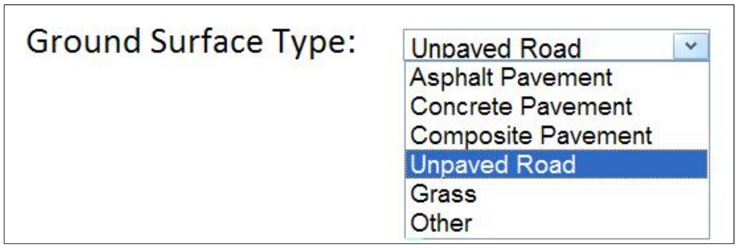
Ground Surface Type: Unpaved Road

Soil Type, near pipe: Silt

Pipe Immersion Condition :
○ All year
○ Most of the year
● Periodically
○ Always dry

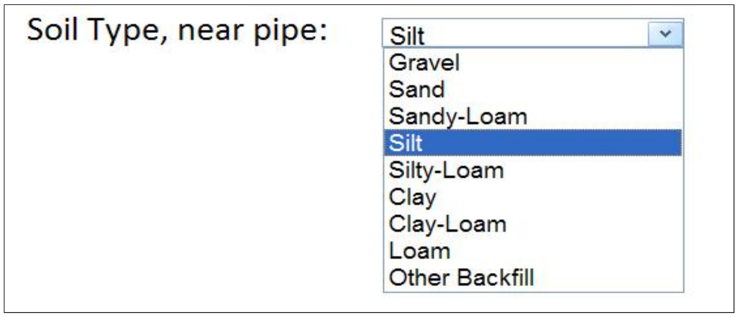
[Note: The default values above will be assumed if unchanged]

Figure 77 - View of the ‘Site Information’ form of the Data Entry Page



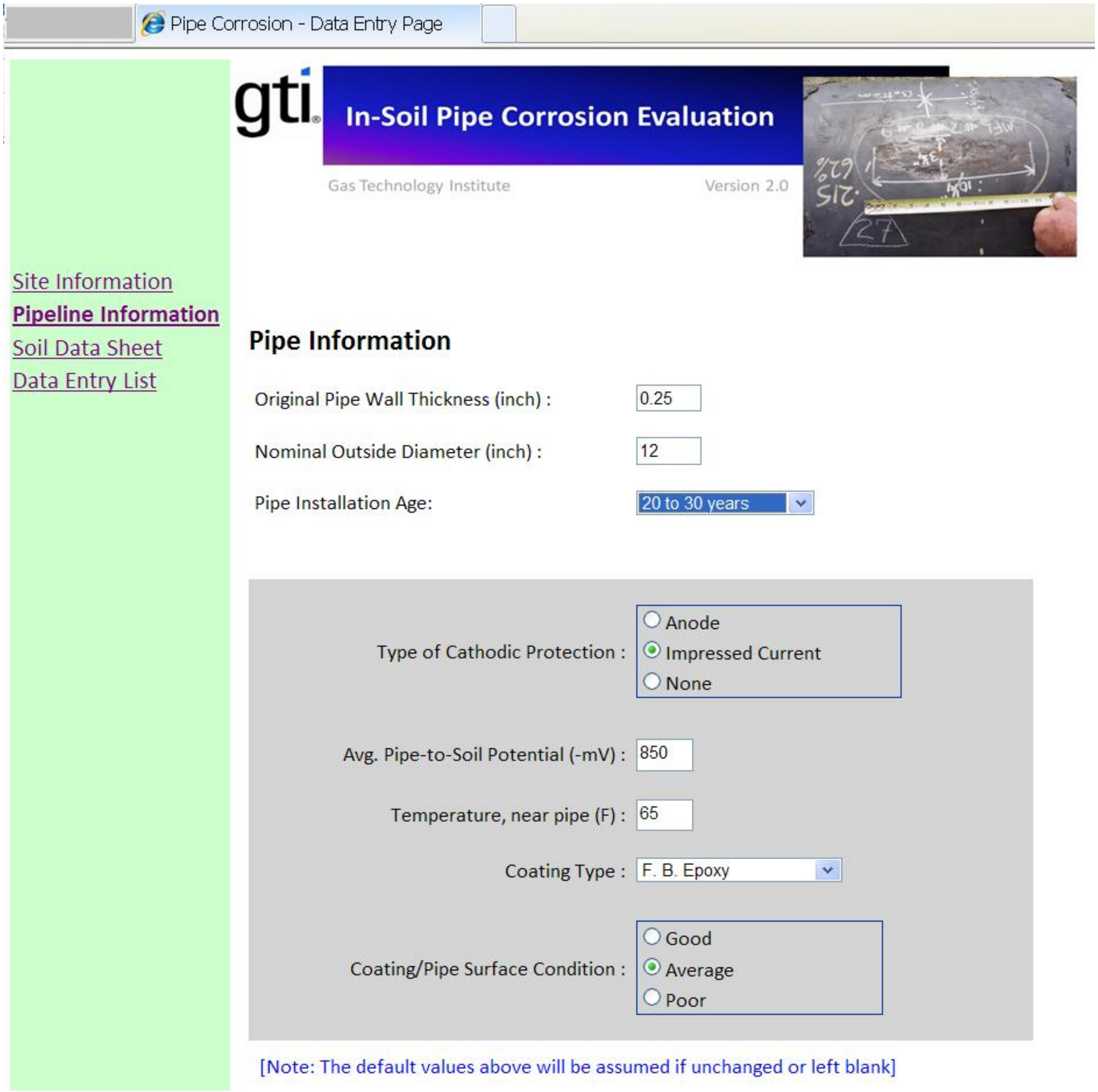
Ground Surface Type: Unpaved Road

Figure 78 - Drop-down list of the ‘Ground Surface Type’ selection



Soil Type, near pipe: Silt

Figure 79 - Drop-down list of the ‘Soil Type’ selection



Pipe Information

Original Pipe Wall Thickness (inch) : 0.25

Nominal Outside Diameter (inch) : 12

Pipe Installation Age: 20 to 30 years

Type of Cathodic Protection :
○ Anode
● Impressed Current
○ None

Avg. Pipe-to-Soil Potential (-mV) : 850

Temperature, near pipe (F) : 65

Coating Type : F. B. Epoxy

Coating/Pipe Surface Condition :
○ Good
● Average
○ Poor

[Note: The default values above will be assumed if unchanged or left blank]

Figure 80 - View of the ‘Pipeline Information’ form of the Data Entry Page

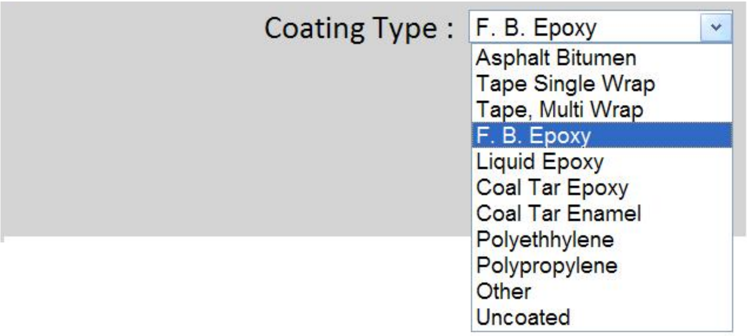
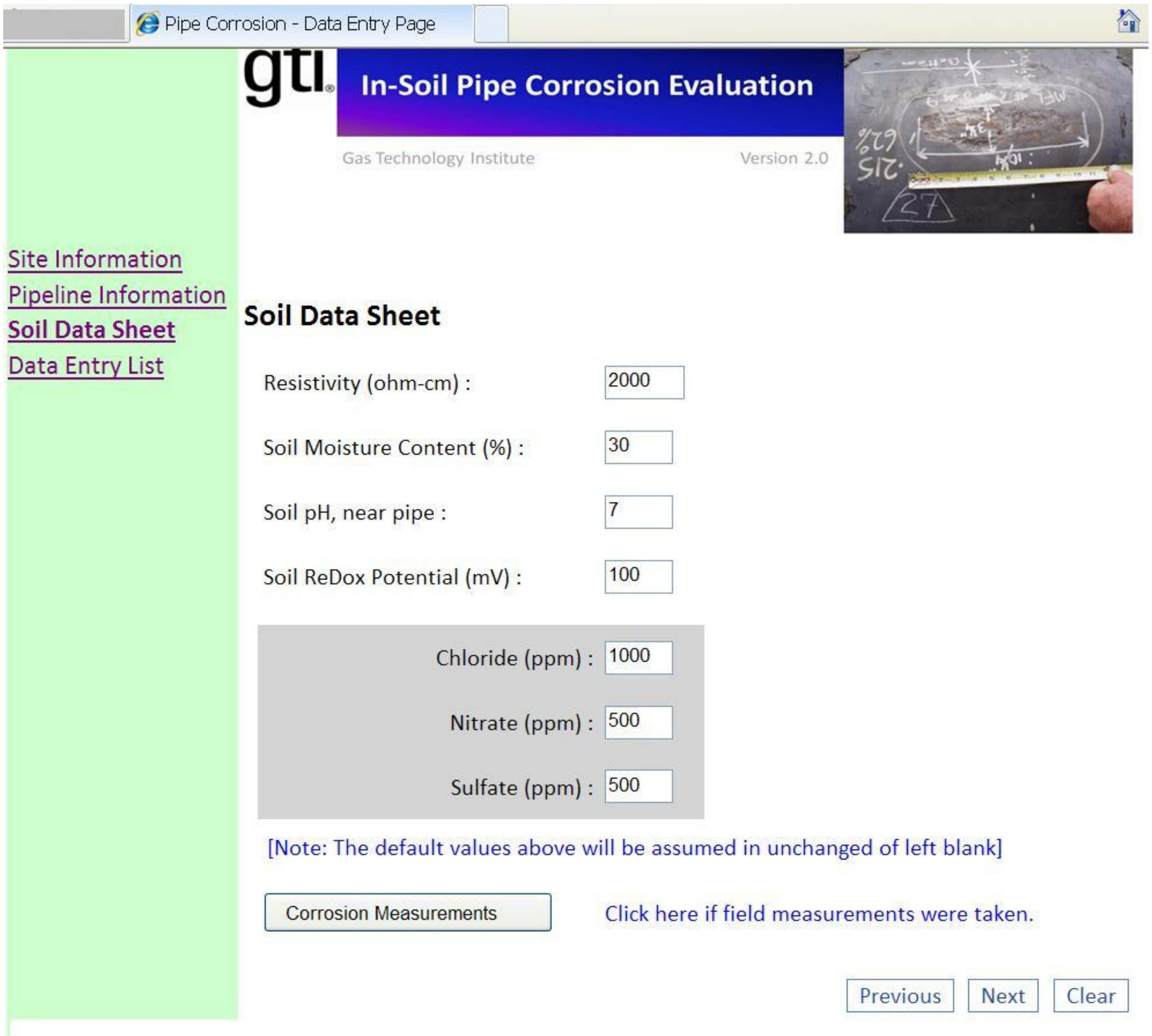

Coating Type : F. B. Epoxy

Figure 81 - Drop-down list of the 'Coating Type' selection



Soil Data Sheet

Resistivity (ohm-cm) : 2000

Soil Moisture Content (%) : 30

Soil pH, near pipe : 7

Soil ReDox Potential (mV) : 100

Chloride (ppm) : 1000

Nitrate (ppm) : 500

Sulfate (ppm) : 500

[Note: The default values above will be assumed in unchanged of left blank]

Click here if field measurements were taken.

Figure 82 - View of the Soil Data form of the Data Entry Page

C) Program Output

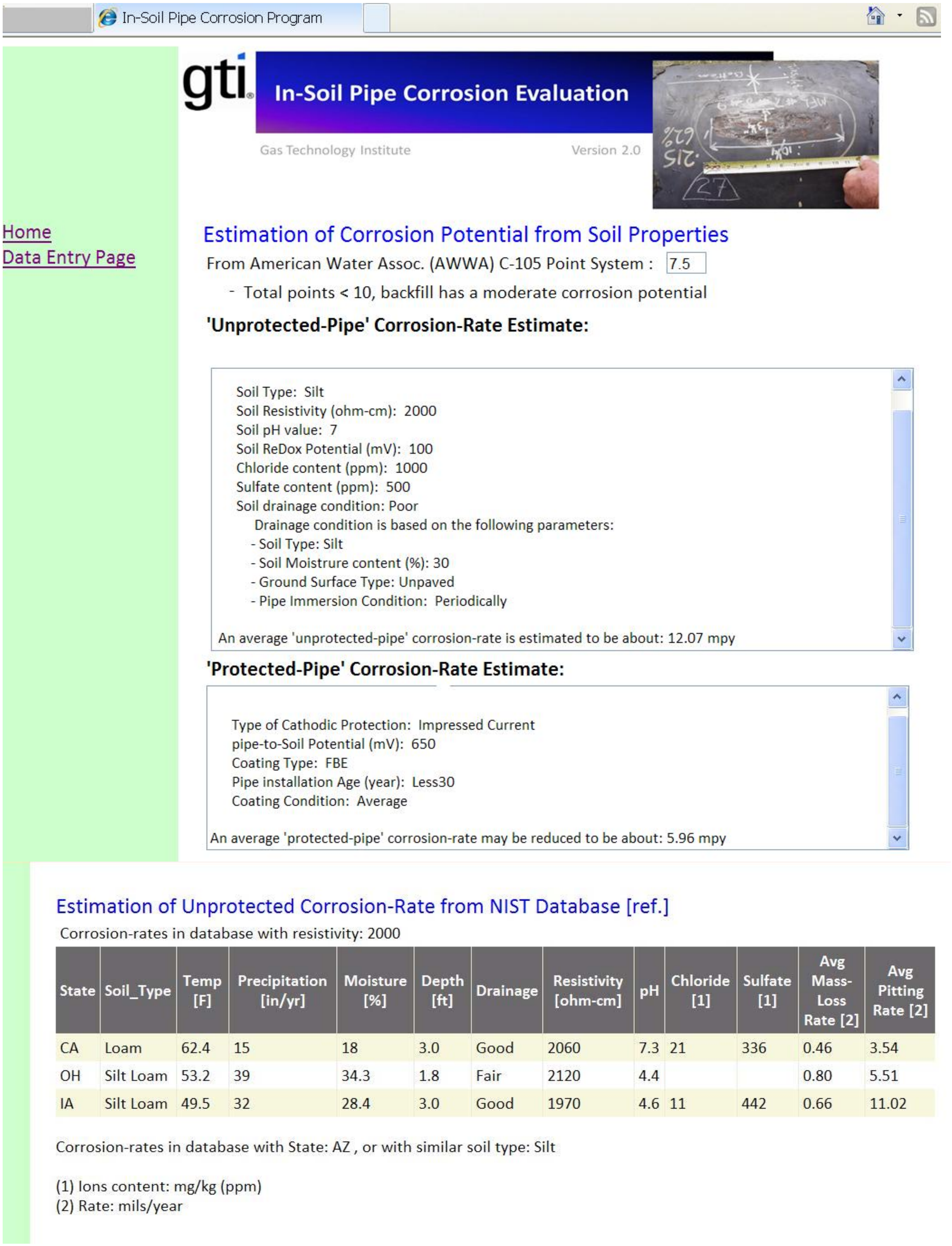
The program output lists the data entered by the user or the default ones if the user does not enter a value. The results page displays the following:

a) A point rating of soil corrosion potential based on the AWWA guideline,

b) An estimate of localized corrosion potential of “unprotected” pipe based on soil properties,

c) An estimate of the corrosion rate in “protected” pipe based on cathodic protection level and coating type and condition,

Additionally, a list of the corrosion-rates from the NIST field is displayed for the tests in the same State and in soils with similar type or resistivity. Figure 83 shows the data output page.



Estimation of Corrosion Potential from Soil Properties

From American Water Assoc. (AWWA) C-105 Point System : 7.5

- Total points < 10, backfill has a moderate corrosion potential

'Unprotected-Pipe' Corrosion-Rate Estimate:

Soil Type: Silt
Soil Resistivity (ohm-cm): 2000
Soil pH value: 7
Soil ReDox Potential (mV): 100
Chloride content (ppm): 1000
Sulfate content (ppm): 500
Soil drainage condition: Poor
Drainage condition is based on the following parameters:
- Soil Type: Silt
- Soil Moistrure content (%): 30
- Ground Surface Type: Unpaved
- Pipe Immersion Condition: Periodically

An average 'unprotected-pipe' corrosion-rate is estimated to be about: 12.07 mpy

'Protected-Pipe' Corrosion-Rate Estimate:

Type of Cathodic Protection: Impressed Current
pipe-to-Soil Potential (mV): 650
Coating Type: FBE
Pipe installation Age (year): Less30
Coating Condition: Average

An average 'protected-pipe' corrosion-rate may be reduced to be about: 5.96 mpy

Estimation of Unprotected Corrosion-Rate from NIST Database [ref.]

Corrosion-rates in database with resistivity: 2000

State	Soil_Type	Temp [F]	Precipitation [in/yr]	Moisture [%]	Depth [ft]	Drainage	Resistivity [ohm-cm]	pH	Chloride [1]	Sulfate [1]	Avg Mass-Loss Rate [2]	Avg Pitting Rate [2]
CA	Loam	62.4	15	18	3.0	Good	2060	7.3	21	336	0.46	3.54
OH	Silt Loam	53.2	39	34.3	1.8	Fair	2120	4.4			0.80	5.51
IA	Silt Loam	49.5	32	28.4	3.0	Good	1970	4.6	11	442	0.66	11.02

Corrosion-rates in database with State: AZ , or with similar soil type: Silt

(1) Ions content: mg/kg (ppm)
(2) Rate: mils/year

Figure 83 - View of the program output

References

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6. *Aquamate User Manual.* Rohrback Cosasco Systems, Inc., 1999.

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18. *ASME B31.8S, Managing System Integrity of Gas Pipelines.* American Society of Mechcanical Engineers, 2004.

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21. *ACI-318 Building Code, 2002.*

22. *Romanoff, M., Underground Corrosion.* NIST, 1967.

23. *Romanoff, M., Underground Corrosion.* NIST, 1967.

24. *Bradford, S., Practical Handbook of Corrosion Control in Soils.* CASTI, 2000.

25. *Starkey, R., and Wight, K., Anaerobic Corrosion of Iron in Soil.* American Gas Association, 1945.

26. *Analysis of Pipeline Steel Corrosion Data from NBS (NIST) Studies Conducted Between 1922-1940 and Relevance to Pipeline Management.* National Institute of Standards and Technology (NIST), Report 7415, 2007.

APPENDIX A – LPR Measurements in Soil Samples from ECDA Sites

Table A1 - LPR Readings of Soil Samples from Utility Sites

Dig No.	First Reading mils/yr	Second Reading mils/yr	Third Reading mils/yr	Average	Probe	soil Resistivity ohm/cm	Soil pH
1	0.23	0.23	0.25	0.24	2 prong probe	1010.10	8.4
1	0.22 (10 min interval)	0.23 (10 min interval)	0.25 (10 min interval)	0.23	2 prong probe	1010.10	8.4
1	0.06 (15 min interval)	0.08 (15 min interval)	0.08 (15 min interval)	0.07	3 prong probe LPR3A	1010.10	8.4
1	0.08 (15 min interval)	0.07 (15 min interval)	0.07 (15 min interval)	0.07	3 prong probe LPR3A	1010.10	8.4
1	0.06 (5 min interval)	0.06 (5 min interval)	0.08 (5 min interval)	0.07	3 prong probe LPR3A	1010.10	8.4
2	0.24	0.27	0.24	0.25	2 prong probe	1724.14	7.8
2	0.25 (10 min interval)	0.25 (10 min interval)	0.28 (10 min interval)		2 prong probe	1724.14	7.8
3	0.05	0.03	0.04	0.04		112.36	9.6
3	0.58	0.59	0.66	0.61	2 prong probe	112.36	9.6
3	0.52	0.41	0.23	0.39		112.36	9.6
4	4.43	2.02	1.57	2.67		285.71	8.9
5	1.10	1.08	1.12	1.10	2 prong probe	142.86	9.8
5	1.25 (10 min interval)	1.30 (10 min interval)	1.38 (10 min interval)		2 prong probe	142.86	9.8
5	1.33	1.38	1.44	1.38	2 prong probe	142.86	9.8
5	1.47	1.51	1.44	1.47	2 prong probe	142.86	9.8
6	1.58	1.40	1.94	1.64	2 prong probe	109.89	9.7
7	1.75	1.43	1.33	1.50	2 prong probe	500.00	8.7
8	1.38	1.11	1.03	1.17	2 prong probe	149.25	9.4
9	1.46	1.15	0.99	1.20	2 prong probe	588.24	8.1
10	0.76	0.46	0.41	0.54	2 prong probe	769.23	9.0
11	2.35	1.14	1.04	1.51	2 prong probe	1333.33	9.3
12	1.04	1.03	0.98	1.02	2 prong probe	294.12	9.1
13	1.12	1.12	1.09	1.11	2 prong probe	434.78	9.2
14	1.51	1.37	1.47	1.45		625.00	8.5
15	1.47	1.52	1.51	1.50		1098.90	8.0
15	0.40	0.42	0.39	0.40	2 prong probe	1250.00	8.4
15	0.39 (10 min interval)	0.39 (10 min interval)	0.36 (10 min interval)		2 prong probe	1250.00	8.4
15	0.41 (10 min interval)	0.40 (10 min interval)	0.39 (10 min interval)		2 prong probe	1250.00	8.4

Table A1 [Continued]

Dig No.	First Reading mils/yr	Second Reading mils/yr	Third Reading mils/yr	Average	Probe	soil Resistivity ohm/cm	Soil pH
16	2.08	2.01	2.07	2.05		1234.57	8.3
16	3.81	3.87	3.91	3.86	2 prong probe	1851.85	7.5
16	4.09 (10 min interval)	4.05 (10 min interval)	4.08 (10 min interval)		2 prong probe	1851.85	7.5
16	4.07 (10 min interval)	4.07 (10 min interval)	4.07 (10 min interval)		2 prong probe	1851.85	7.5
17	0.44 (10 min interval)	0.43 (10 min interval)	0.45 (10 min interval)	0.44	2 prong probe	476.19	7.2
18	4.36	3.31	3.16	3.61		1265.82	9.0
19	3.95	4.09	3.57	3.87		769.23	8.6
19	2.19	2.07	2.13	2.13	2 prong probe	769.23	8.6
19	1.65	1.36	1.26	1.42		769.23	8.6
20	0.16	0.15	0.17	0.16	2 prong probe	909.09	8.0
20	0.15 (10 min interval)	0.17 (10 min interval)	0.17 (10 min interval)		2 prong probe	909.09	8.0
21	0.36	0.36	0.35	0.36	2 prong probe	208.33	7.4
21	0.36 (10 min interval)	0.36 (10 min interval)	0.34 (10 min interval)		2 prong probe	208.33	7.4
22	1.15 (10 min interval)	1.14 (10 min interval)	1.20 (10 min interval)	1.16	2 prong probe	714.29	8.0
23	0.65	0.67	0.62	0.65		454.55	9.0
24	1.10	1.03	0.94	1.02		526.32	8.4
25	1.56	1.79	1.79	1.71		113.64	11.0
26	1.59 (10 min interval)	1.59 (10 min interval)	1.60 (10 min interval)	1.59	2 prong probe	2380.95	8.4
27	0.35 (10 min interval)	0.35 (10 min interval)	0.32 (10 min interval)	0.34	2 prong probe	3333.33	7.8
28	0.86	0.85	0.88	0.86	2 prong probe	2325.58	8.7
28	0.89 (10 min interval)	0.90 (10 min interval)	0.85 (10 min interval)		2 prong probe	2325.58	8.7
29	0.14 (10 min interval)	0.15 (10 min interval)	0.10 (10 min interval)	0.13	2 prong probe	4000.00	7.6
29	0.63 (15 min interval)	0.48 (15 min interval)	0.48 (15 min interval)	0.53	3 prong probe LPR3A	4000.00	7.6
30	1.29	1.28	1.31	1.29	2 prong probe	76.92	10.7
30	1.33 (10 min interval)	1.34 (10 min interval)	1.31 10 min interval)		2 prong probe	76.92	10.7
31	2.31	2.34	2.25	2.30		1190.48	8.0
32	2.05	2.05	2.02	2.04		769.23	8.1
33	2.50	2.84	2.88	2.74		172.41	9.6
34	3.47	2.34	2.34	2.72		1886.79	8.0
35	2.90	2.97	2.92	2.93		2272.73	8.2

Table A1 [Continued]

Dig No.	First Reading mils/yr	Second Reading mils/yr	Third Reading mils/yr	Average	Probe	soil Resistivity ohm/cm	Soil pH
36	2.88	2.93	2.79	2.87		1136.36	8.2
37	2.79	2.13	2.11	2.34		149.25	9.2
38	1.07	1.05	1.09	1.07		1612.90	8.1
39	1.03	1.01	1.04	1.03		270.27	9.6
39	1.80	1.88	1.86	1.85	2 prong probe	270.27	9.6
39	1.87 (10 min interval)	1.89 (10 min interval)	1.89 (10 min interval)		2 prong probe	270.27	9.6
40	2.04	1.93	1.81	1.93		2564.10	7.4
41	1.49	1.62	1.65	1.59		1204.82	7.5
42	0.67	0.66	0.69	0.67	2 prong probe	9090.91	6.6
42	0.65 (10 min interval)	0.67 (10 min interval)	0.67 (10 min interval)		2 prong probe	9090.91	6.6
43	1.71	1.69	1.66	1.69	2 prong probe	1351.35	7.9
43	1.65 (10 min interval)	1.67 (10 min interval)	1.67 (10 min interval)		2 prong probe	1351.35	7.9
44	0.62	0.60	0.61	0.61	2 prong probe	277.78	7.7
44	0.59 (10 min interval)	0.59 (10 min interval)	0.58 (10 min interval)		2 prong probe	277.78	7.7
45	0.44	0.45	0.46	0.45	2 prong probe	83.33	9.9
45	0.45 (10 min interval)	0.43 (10 min interval)	0.45 (10 min interval)		2 prong probe	83.33	9.9
46	0.50	0.51	0.51	0.51	2 prong probe	526.32	8.1
46	0.53 (10 min interval)	0.51 (10 min interval)	0.50 (10 min interval)		2 prong probe	526.32	8.1
47	0.50	0.49	0.49	0.49	2 prong probe	10000.00	6.2
47	0.51 (10 min interval)	0.52 (10 min interval)	0.51 (10 min interval)		2 prong probe	10000.00	6.2
48	2.33	2.33	2.32	2.33	2 prong probe	21739.13	5.7
48	2.34 (10 min interval)	2.34 (10 min interval)	2.32 (10 min interval)		2 prong probe	21739.13	5.7
48	0.15 (15 min interval)	0.17 (15 min interval)	0.13 (15 min interval)	0.15	3 prong probe LPR3A	21739.13	5.7
48	0.13 (5 min interval)	0.12 (5 min interval)	0.13 (5 min interval)	0.13	3 prong probe LPR3A	21739.13	5.7
48	1.40 (10 min interval)	1.37 (10 min interval)	1.35 (10 min interval)	1.37	2 prong probe	21739.13	5.7
48	0.02 (15 min interval)	0.02 (15 min interval)	0.03 (15 min interval)	0.03	3 prong probe LPR3A	21739.13	5.7
48	0.03 (5 min interval)	0.03 (5 min interval)	0.01 (5 min interval)		3 prong probe LPR3A	21739.13	5.7
48	0.00 (15 min interval)	0.03 (15 min interval)	0.03 (15 min interval)		3 prong probe LPR3C	21739.13	5.7

Table A1 [Continued]

Dig No.	First Reading mils/yr	Second Reading mils/yr	Third Reading mils/yr	Average	Probe	soil Resistivity ohm/cm	Soil pH
48	1.25	1.26	1.28	1.26	2 prong probe	21739.13	5.7
48	1.30 (10 min interval)	1.30 (10 min interval)	1.30 (10 min interval)	1.30	2 prong probe	21739.13	5.7
49	1.69	1.70	1.69	1.69	2 prong probe	13513.51	5.9
49	1.72 (10 min interval)	1.70 (10 min interval)	1.72 (10 min interval)		2 prong probe	13513.51	5.9
50	0.62	0.69	0.67	0.67	2 prong probe	1724.14	
50	0.66 (10 min interval)	0.67 (10 min interval)	0.67 (10 min interval)		2 prong probe	1724.14	
51	0.21	0.19	0.20	0.20	2 prong probe	2500.00	8.2
51	0.22 (10 min interval)	0.20 (10 min interval)	0.21 (10 min interval)		2 prong probe	2500.00	8.2
52	1.48	1.49	1.51	1.49	2 prong probe	7142.86	5.6
52	1.54 (10 min interval)	1.54 (10 min interval)	1.52 (10 min interval)		2 prong probe	7142.86	5.6
53	0.74	0.73	0.76	0.74	2 prong probe	30303.03	6.3
53	0.73 (10 min interval)	0.76 (10 min interval)	0.75 (10 min interval)		2 prong probe	30303.03	6.3
54	0.36	0.37	0.37	0.37	2 prong probe	1063.83	6.9
54	0.36 (10 min interval)	0.36 (10 min interval)	0.37 (10 min interval)		2 prong probe	1063.83	6.9
55	3.33	2.41	2.24	2.66	2 prong probe	2777.78	7.7
55	0.41	0.41	0.41	0.41	2 prong probe	2777.78	7.7
56	5.18	4.00	3.28	4.15		3125.00	7.5
56	1.27	1.23	1.20	1.23	2 prong probe	3125.00	7.5
56	1.81	1.74	1.72	1.76		3125.00	7.5
57	0.83	0.83	0.85	0.84	2 prong probe	5000.00	8.0
57	0.85 (10 min interval)	0.88 (10 min interval)	0.84 (10 min interval)		2 prong probe	5000.00	8.0
58	2.40	2.29	2.05	2.25		1333.33	7.5
59	2.67	2.66	2.55	2.63		833.33	7.2
60	3.11	2.68	2.56	2.78		1851.85	7.2
61	0.50	0.49	0.49	0.49	2 prong probe	13698.63	7.3
61	0.55 (10 min interval)	0.50 (10 min interval)	0.52 (10 min interval)		2 prong probe	13698.63	7.3

Table A1 [Continued]

Dig No.	First Reading mils/yr	Second Reading mils/yr	Third Reading mils/yr	Average	Probe	soil Resistivity ohm/cm	Soil pH
62	0.94	0.96	0.93	0.94	2 prong probe	4000.00	7.9
62	0.92 (10 min interval)	0.97 (10 min interval)	0.91 (10 min interval)		2 prong probe	4000.00	7.9
63	0.99	0.97	0.97	0.98	2 prong probe	2941.18	4.6
63	0.94 (10 min interval)	0.94 (10 min interval)	0.94 (10 min interval)		2 prong probe	2941.18	4.6
64	0.94	0.95	0.94	0.94	2 prong probe	7692.31	7.1
64	0.99 (10 min interval)	0.99 (10 min interval)	0.99 (10 min interval)	0.99	2 prong probe	7692.31	7.1
64	0.94 (10 min interval)	0.98 (10 min interval)	0.99 (10 min interval)	0.96	2 prong probe	7692.31	7.1
1	0.07 (15 min interval)	0.09 (15 min interval)	0.08 (15 min interval)	0.08	3 prong probe LPR3A	1010.10	8.4
6	0.57	0.55	0.58	0.57	2 prong probe	109.89	9.7
6	0.60 (10 min interval)	0.62 (10 min interval)	0.60 (10 min interval)	0.61	2 prong probe	109.89	9.7

APPENDIX B - A Summary of Soil Classification Systems

The soils in the field test sections were classified according to the following two classification systems:

1. The U.S. Department of Agriculture (USDA) System,
2. The Unified Soil Classification System (USCS).

These classification systems are based on the gradation of the soil particles and its plasticity. Further discussions regarding these two soil classification and properties are presented in the following sections:

A. The USDA Soil Classification System

The USDA system identifies soil based on its textural classification and it classifies the soil into three groups (sand, silt and clay) according to their particle size and the soils are named after their principal components. The chart in Figure B-1 is used in the USDA system to classify the soil as percentages of each of these three groups. The particle sizes for these three groups are (1):

- Sand size: 2.0 to 0.05 mm in diameter
- Silt size: 0.05 to 0.002 mm in diameter
- Clay size: smaller than 0.002 mm in diameter.

The use of this system is relatively simple. However, the classification is based entirely on the particle-sixe distribution. Since the amount of the clay minerals in the soil has a significant effect on the soil characteristics, the Unified Soil Classification System (USCS) is more utilized to account for the effect of clay minerals on soil characteristics.

B. The USCS Soil Classification System

This system was developed by the U.S. Army Corps of Engineers and is widely used by engineers as it incorporates a wide range of soil properties in its classification. It is based on the ASTM standard D-2489 (2) and it classifies the soils according to:

- Coarse-grained soil: Soils with less than 50% passing sieve No. 200 are gravel (G) and sand (S),
- Fine-grained soil: Soils with more than 50% passing sieve No. 200 are inorganic silt (M), inorganic clay (C), and organic soil (O),
- Gradation: Coarse-grained soils are well graded (W) or poorly graded (P),
- Plasticity: Fine-grained soils are low plasticity soil (L) with liquid limit less than 50% or High plasticity soil (H).

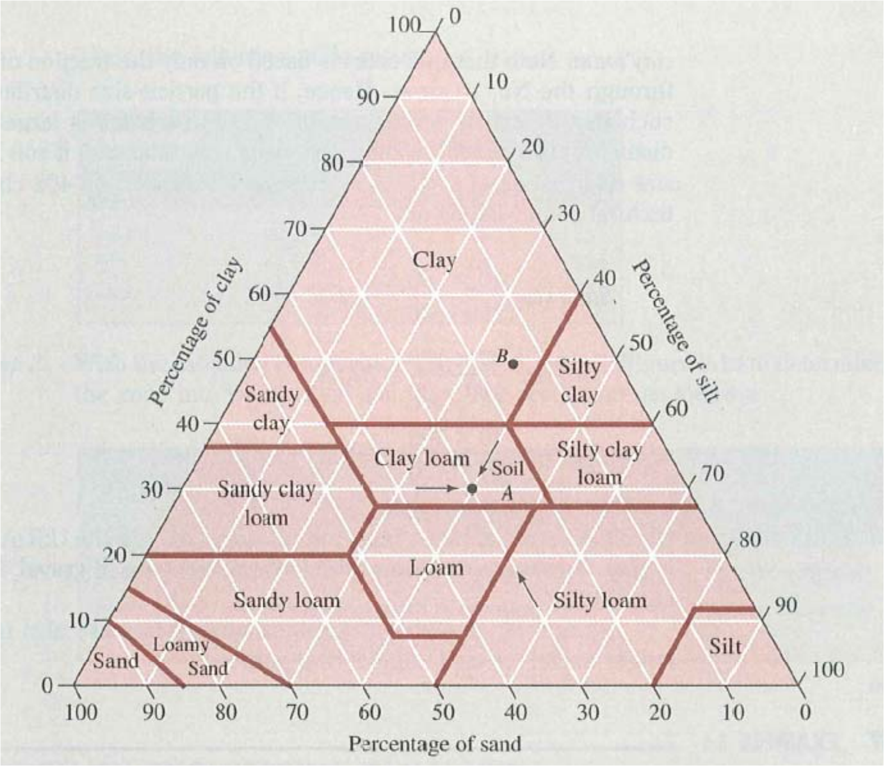


Figure B1 - The USDA Soil Classification System

The USCS system utilizes a combination of the above symbols to identify soil components. It also utilizes soil plasticity properties for fine-grained soils to classify the soil as shown in the following section.

Soil Plasticity and its effect on Soil Chemical and Physical Properties

Soil plasticity properties of cohesive soils (i.e., silt and clay soils) identify the surface areas of its particles, which control how much wetting can be absorbed by the soil. It is also used to identify the dominant clay type present in a soil sample. These soil plasticity properties are:

- The plastic limit (PL) property of the soil, which is the water content where soil starts to exhibit plastic behavior. It is the lower limit of the plastic stage of cohesive soil.
- The Liquid Limit (LL) property, which is the water content where soil changes from plastic to liquid behavior. It specifies the upper limit of the plastic stage of the soil.
- The plasticity index (PI) is a measure of the plasticity of a soil. The plasticity index is the range of water contents where the soil exhibits plastic properties. The PI is the difference between the liquid limit and the plastic limit (i.e., PI = LL-PL). Soils with a high PI tend to be clay while those with a lower PI tend to be silt. Granular soils (gravel and sand) are non-plastic (i.e., their LL and PL are 0).

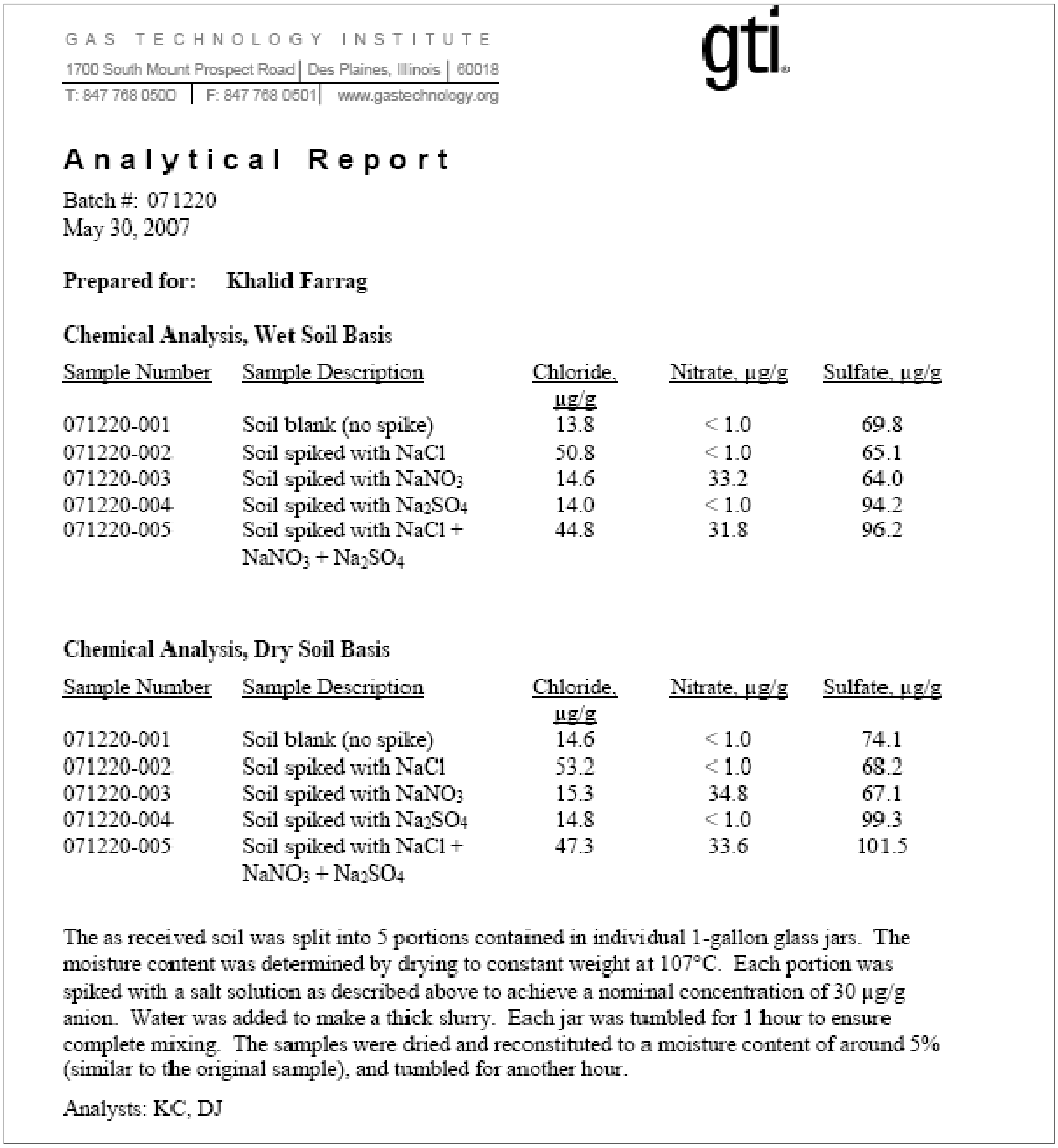
- Soil Activity (A) is the soil PI divided by the percent of clay-size particles in the soil. Normally, activity of clay is between 0.75 and 1.25. Clay is considered active when A is greater than 1.25.

The plasticity indices of the soil (LL, PL, and PI) are determined according to the ASTM standard D-4318 (3). The values of these limits are commonly used in empirical correlations to determine soil permeability and compressibility. Since the various types of clays have different surface areas, these parameters control how much water can be absorbed by soil particles. High activity parameter signifies the influence of the clay fraction of soil on its properties and its susceptibility to change its cations and its pore fluid composition (4). Consequently, it is expected that high activity soils exhibit low resistivity and may increase the corrosion potential of metal pipes.

References of Appendix B

1. Das, B., *Principles of Geotechnical Engineering*, 1990.
2. ASTM D 2487, *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*, American Society of Testing and Materials, 2010.
3. ASTM D 4318, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*, American Society of Testing and Materials, 2010.
4. Mitchell, J., *Fundamentals of Soil Behavior*, 1993.

APPENDIX C - Physical and Chemical Properties of the GTI Test Sections



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Analytical Report

Batch #: 071220
May 30, 2007

Prepared for: **Khalid Farrag**

Chemical Analysis, Wet Soil Basis

Sample Number	Sample Description	Chloride, µg/g	Nitrate, µg/g	Sulfate, µg/g
071220-001	Soil blank (no spike)	13.8	< 1.0	69.8
071220-002	Soil spiked with NaCl	50.8	< 1.0	65.1
071220-003	Soil spiked with $NaNO_3$	14.6	33.2	64.0
071220-004	Soil spiked with Na_2SO_4	14.0	< 1.0	94.2
071220-005	Soil spiked with NaCl + $NaNO_3$ + Na_2SO_4	44.8	31.8	96.2

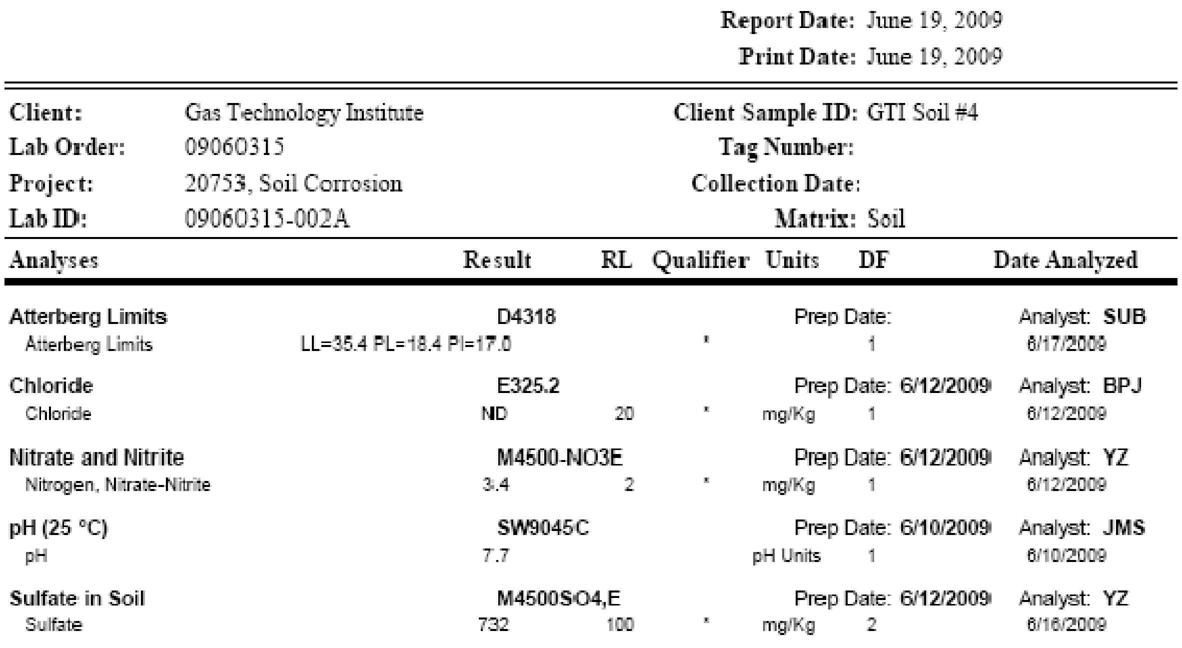
Chemical Analysis, Dry Soil Basis

Sample Number	Sample Description	Chloride, µg/g	Nitrate, µg/g	Sulfate, µg/g
071220-001	Soil blank (no spike)	14.6	< 1.0	74.1
071220-002	Soil spiked with NaCl	53.2	< 1.0	68.2
071220-003	Soil spiked with $NaNO_3$	15.3	34.8	67.1
071220-004	Soil spiked with Na_2SO_4	14.8	< 1.0	99.3
071220-005	Soil spiked with NaCl + $NaNO_3$ + Na_2SO_4	47.3	33.6	101.5

The as received soil was split into 5 portions contained in individual 1-gallon glass jars. The moisture content was determined by drying to constant weight at 107°C. Each portion was spiked with a salt solution as described above to achieve a nominal concentration of 30 µg/g anion. Water was added to make a thick slurry. Each jar was tumbled for 1 hour to ensure complete mixing. The samples were dried and reconstituted to a moisture content of around 5% (similar to the original sample), and tumbled for another hour.

Analysts: KC, DJ

Figure C1 - Chemical properties of the subgrade in Trench-A

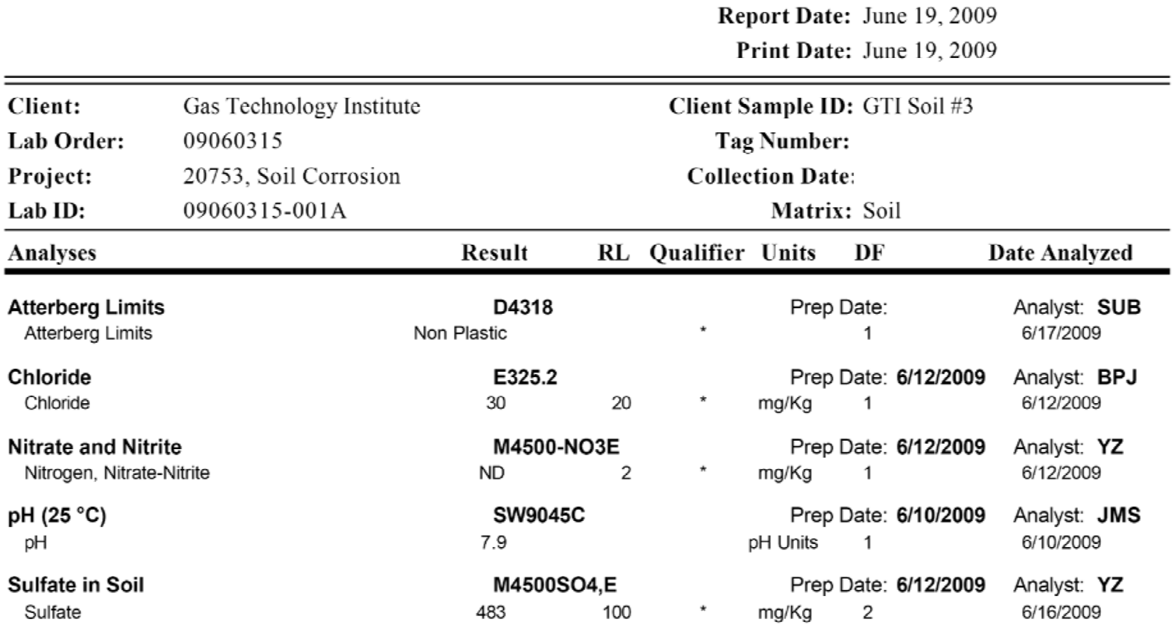


Report Date: June 19, 2009
Print Date: June 19, 2009

Client:	Gas Technology Institute	**Client Sample ID:**	GTI Soil #4
Lab Order:	09060315	**Tag Number:**	
Project:	20753, Soil Corrosion	**Collection Date:**	
Lab ID:	09060315-002A	**Matrix:**	Soil

Analyses	Result	RL	Qualifier	Units	DF	Date Analyzed
Atterberg Limits	**D4318**			Prep Date:		Analyst: **SUB**
Atterberg Limits	LL=35.4 PL=18.4 PI=17.0		*		1	6/17/2009
Chloride	**E325.2**			Prep Date: **6/12/2009**		Analyst: **BPJ**
Chloride	ND	20	*	mg/Kg	1	6/12/2009
Nitrate and Nitrite	**M4500-NO3E**			Prep Date: **6/12/2009**		Analyst: **YZ**
Nitrogen, Nitrate-Nitrite	3.4	2	*	mg/Kg	1	6/12/2009
pH (25 °C)	**SW9045C**			Prep Date: **6/10/2009**		Analyst: **JMS**
pH	7.7			pH Units	1	6/10/2009
Sulfate in Soil	**M4500SO4,E**			Prep Date: **6/12/2009**		Analyst: **YZ**
Sulfate	732	100	*	mg/Kg	2	6/16/2009

Figure C2 - Chemical properties of backfill in Section-1

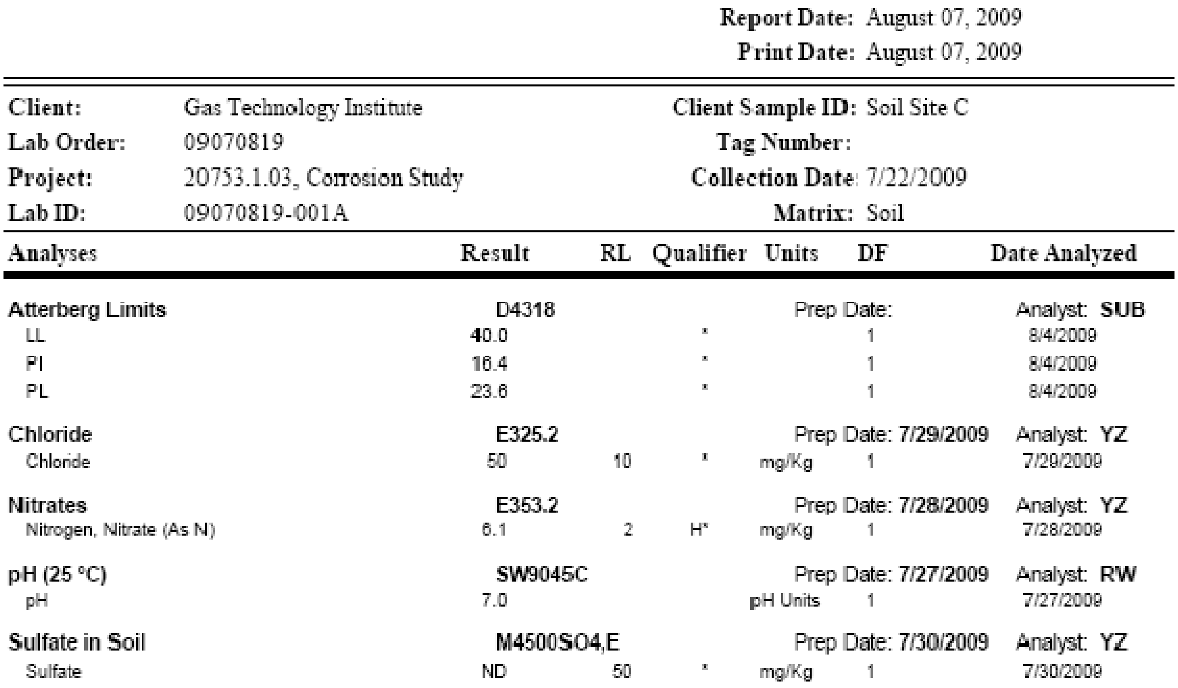


Report Date: June 19, 2009
Print Date: June 19, 2009

Client:	Gas Technology Institute	**Client Sample ID:**	GTI Soil #3
Lab Order:	09060315	**Tag Number:**	
Project:	20753, Soil Corrosion	**Collection Date:**	
Lab ID:	09060315-001A	**Matrix:**	Soil

Analyses	Result	RL	Qualifier	Units	DF	Date Analyzed
Atterberg Limits	**D4318**			Prep Date:		Analyst: **SUB**
Atterberg Limits	Non Plastic		*		1	6/17/2009
Chloride	**E325.2**			Prep Date: **6/12/2009**		Analyst: **BPJ**
Chloride	30	20	*	mg/Kg	1	6/12/2009
Nitrate and Nitrite	**M4500-NO3E**			Prep Date: **6/12/2009**		Analyst: **YZ**
Nitrogen, Nitrate-Nitrite	ND	2	*	mg/Kg	1	6/12/2009
pH (25 °C)	**SW9045C**			Prep Date: **6/10/2009**		Analyst: **JMS**
pH	7.9			pH Units	1	6/10/2009
Sulfate in Soil	**M4500SO4,E**			Prep Date: **6/12/2009**		Analyst: **YZ**
Sulfate	483	100	*	mg/Kg	2	6/16/2009

Figure C3 - Chemical properties of backfill in Section-2

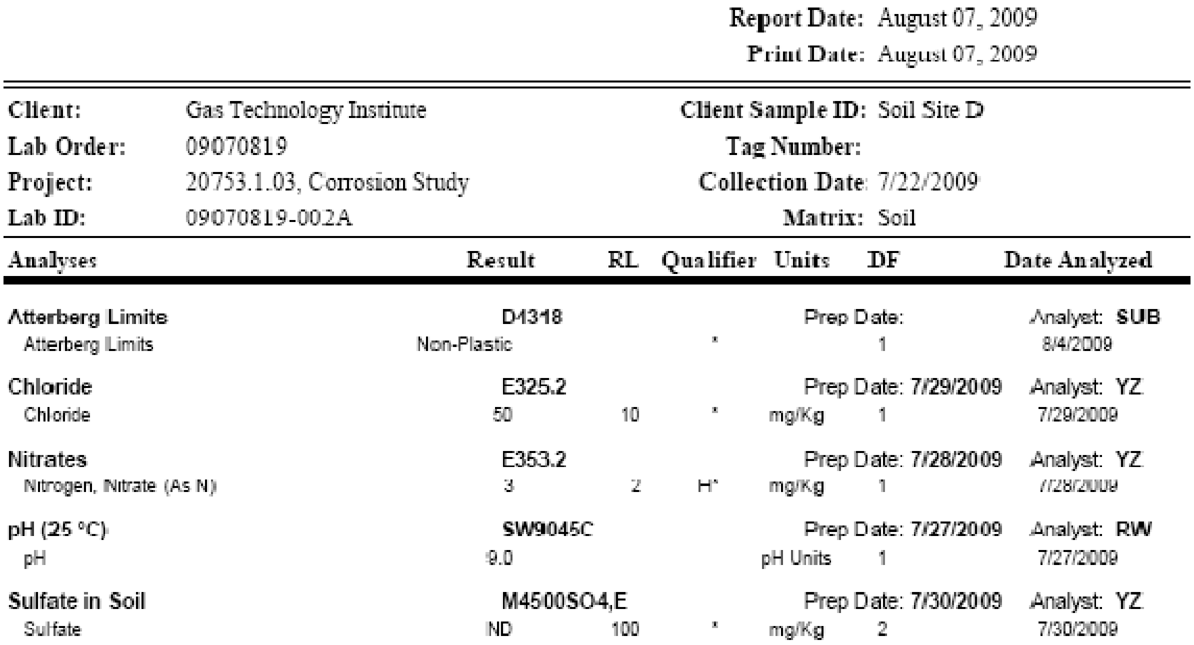


Report Date: August 07, 2009
Print Date: August 07, 2009

Client:	Gas Technology Institute	**Client Sample ID:**	Soil Site C
Lab Order:	09070819	**Tag Number:**	
Project:	20753.1.03, Corrosion Study	**Collection Date:**	7/22/2009
Lab ID:	09070819-001A	**Matrix:**	Soil

Analyses	Result	RL	Qualifier	Units	DF	Date Analyzed
Atterberg Limits	**D4318**			Prep Date:		Analyst: **SUB**
LL	40.0		*		1	8/4/2009
PI	16.4		*		1	8/4/2009
PL	23.6		*		1	8/4/2009
Chloride	**E325.2**			Prep Date: **7/29/2009**		Analyst: **YZ**
Chloride	50	10	*	mg/Kg	1	7/29/2009
Nitrates	**E353.2**			Prep Date: **7/28/2009**		Analyst: **YZ**
Nitrogen, Nitrate (As N)	6.1	2	H*	mg/Kg	1	7/28/2009
pH (25 °C)	**SW9045C**			Prep Date: **7/27/2009**		Analyst: **RW**
pH	7.0			pH Units	1	7/27/2009
Sulfate in Soil	**M4500SO4,E**			Prep Date: **7/30/2009**		Analyst: **YZ**
Sulfate	ND	50	*	mg/Kg	1	7/30/2009

Figure C4 - Chemical properties of backfill in Section-3



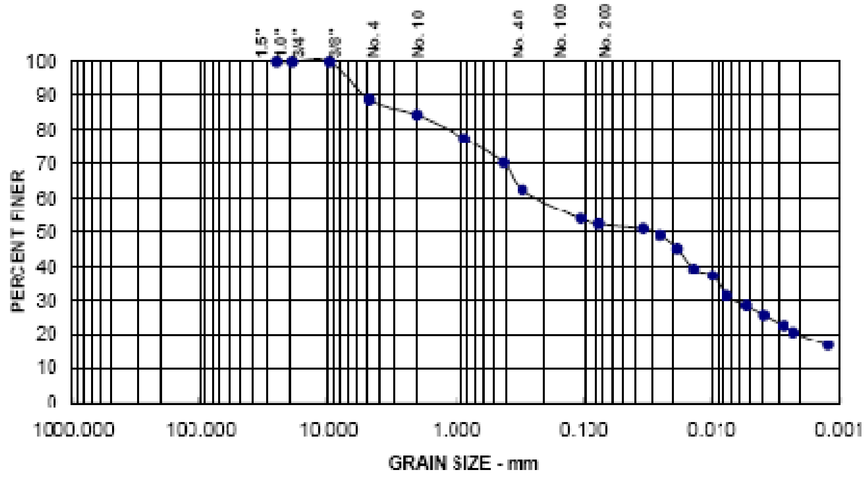
Report Date: August 07, 2009
Print Date: August 07, 2009

Client:	Gas Technology Institute	**Client Sample ID:**	Soil Site D
Lab Order:	09070819	**Tag Number:**	
Project:	20753.1.03, Corrosion Study	**Collection Date:**	7/22/2009
Lab ID:	09070819-002A	**Matrix:**	Soil

Analyses	Result	RL	Qualifier	Units	DF	Date Analyzed
Atterberg Limits	**D4318**			Prep Date:		Analyst: **SUB**
Atterberg Limits	Non-Plastic		*		1	8/4/2009
Chloride	**E325.2**			Prep Date: **7/29/2009**		Analyst: **YZ**
Chloride	50	10	*	mg/Kg	1	7/29/2009
Nitrates	**E353.2**			Prep Date: **7/28/2009**		Analyst: **YZ**
Nitrogen, Nitrate (As N)	3	2	H*	mg/Kg	1	7/28/2009
pH (25 °C)	**SW9045C**			Prep Date: **7/27/2009**		Analyst: **RW**
pH	9.0			pH Units	1	7/27/2009
Sulfate in Soil	**M4500SO4,E**			Prep Date: **7/30/2009**		Analyst: **YZ**
Sulfate	ND	100	*	mg/Kg	2	7/30/2009

Figure C5 - Chemical properties of backfill in Section-4

GRAIN SIZE ANALYSIS (ASTM D422)	SAMPLE:GTI-SOIL # 4



% + 3"	% Gravel	% Sand	% Silt	% Clay
0.0	11.4	36.5	24.1	28.0

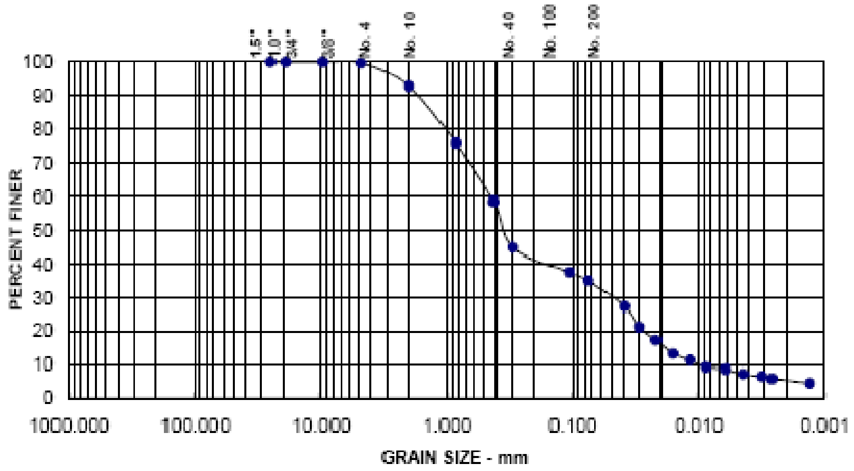
Sieve Size	Percent Passing
1"	100.0
3/4"	100.0
3/8"	100.0
#4	88.6
#10	84.3
#20	77.3
#40	70.2
#60	62.4
#140	53.7
#200	52.1

D60 (mm)	D30 (mm)	D10 (mm)	Cu	Cc
0.24	0.0065	-	-	-

Visual Soil Description:	Black silty clay and coarse to fine sand, little fine gravel
Soil Classification:	CL
System:	USCS

Figure C6 - Physical properties of backfill in Section-1

GRAIN SIZE ANALYSIS (ASTM D422)	**SAMPLE:GT1-SOIL# 3**



% + 3"	% Gravel	% Sand	% Silt	% Clay
0.0	0.3	64.6	26.1	9.0

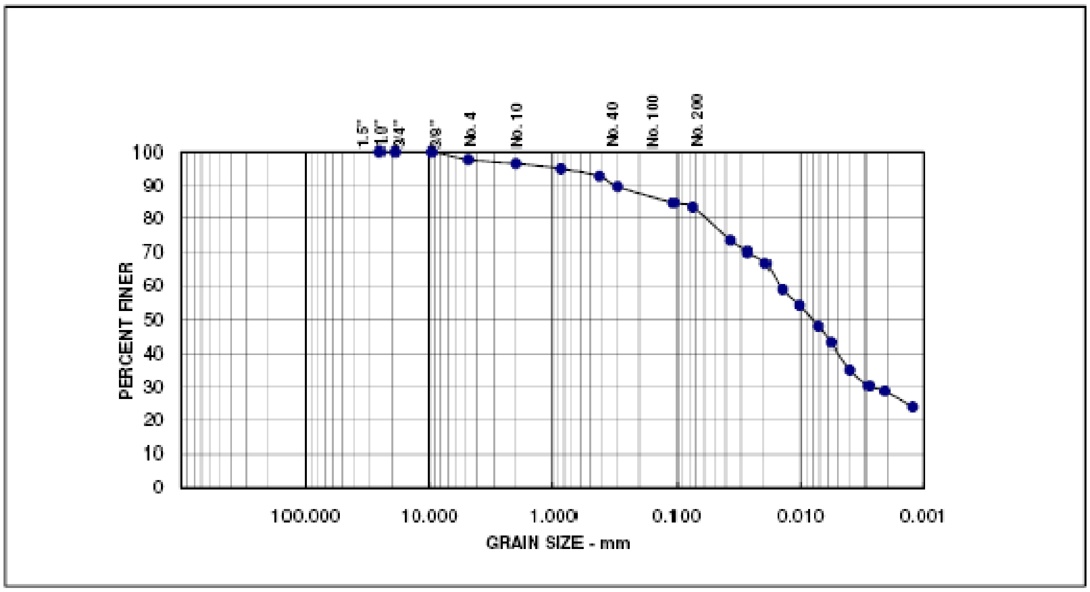
Sieve Size	Percent Passing
1"	100.0
3/4"	100.0
3/8"	100.0
#4	99.7
#10	92.8
#20	76.0
#40	58.6
#60	44.7
#140	37.6
#200	35.1

D60 (mm)	D30 (mm)	D10 (mm)	Cu	Cc
0.48	0.046	0.0086	55.81	0.51

Visual Soil Description:	Brown silty to clayey sand, trace fine gravel
Soil Classification:	SM
System:	USCS

Figure C7 - Physical properties of backfill in Section-2

GRAIN SIZE ANALYSIS (ASTM D422)	SAMPLE: SITE C



% + 3"	% Gravel	% Sand	% Silt	% Clay
0.0	2.3	14.4	40.3	43.0

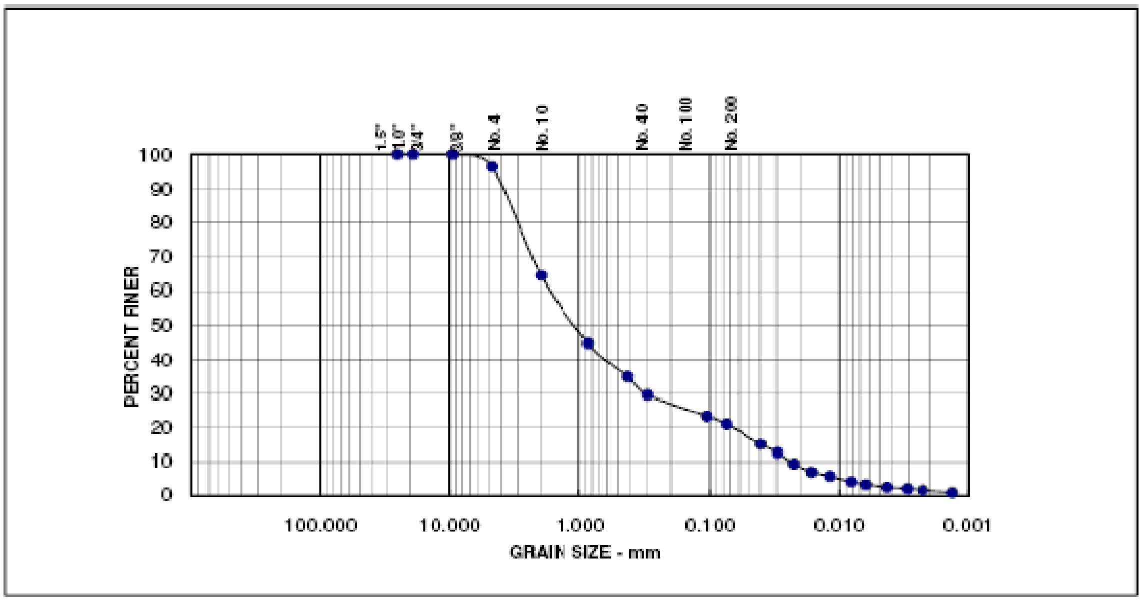
Sieve Size	Percent Passing
1"	100.0
3/4"	100.0
3/8"	100.0
#4	97.7
#10	96.6
#20	95.0
#40	92.8
#60	89.6
#140	84.6
#200	83.3

D60 (mm)	D30 (mm)	D10 (mm)	Cu	Cc
0.015	0.003	-	-	-

Visual Soil Description:	Gray silty clay, some coarse to fine sand, trace fine gravel
Soil Classification:	CL
System:	USCS

Figure C8 - Physical properties of backfill in Section-3

GRAIN SIZE ANALYSIS (ASTM D422)	**SAMPLE: SITE D**



% + 3"	% Gravel	% Sand	% Silt	% Clay
0.0	3.7	75.2	19.1	2.0

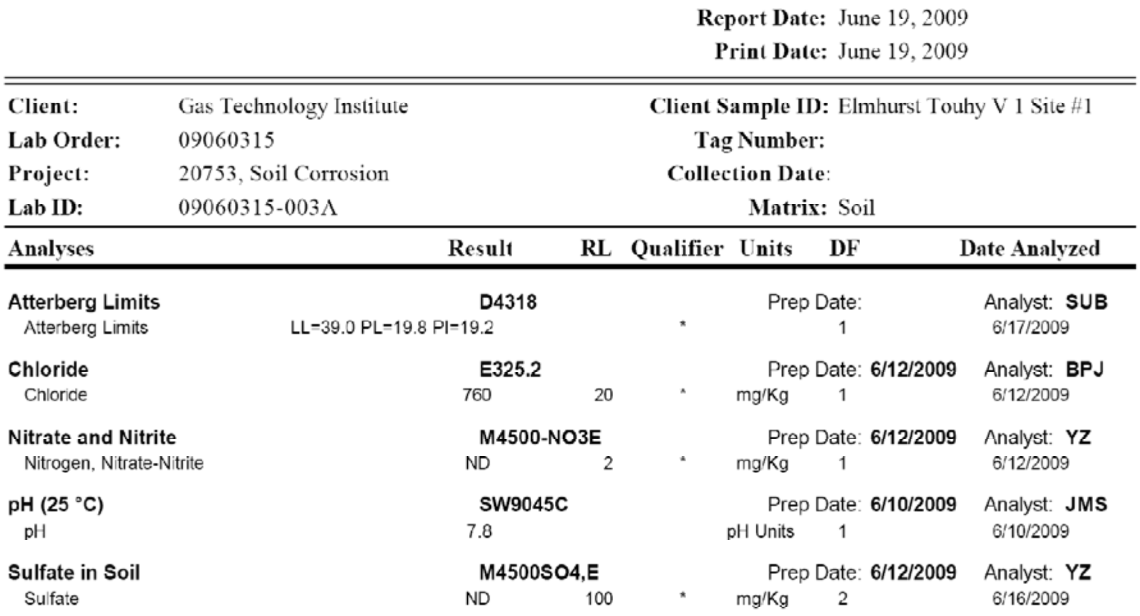
Sieve Size	Percent Passing
1"	100.0
3/4"	100.0
3/8"	100.0
#4	96.3
#10	64.5
#20	44.7
#40	34.9
#60	29.6
#140	23.4
#200	21.1

D60 (mm)	D30 (mm)	D10 (mm)	Cu	Cc
1.8	0.3	0.0220	81.82	2.27

Visual Soil Description:	White silty sand, trace fine gravel
Soil Classification:	SM
System:	USCS

Figure C9 - Physical properties of backfill in Section-4

APPENDIX D - Physical and Chemical Properties of Utility-E Sites

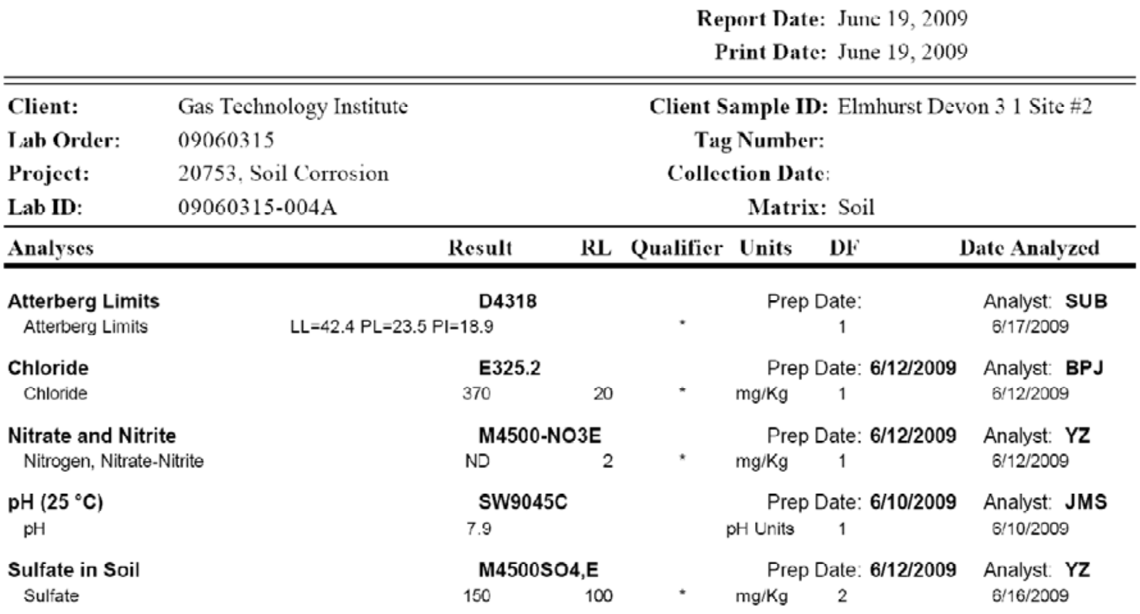


Report Date: June 19, 2009
Print Date: June 19, 2009

Client:	Gas Technology Institute	**Client Sample ID:**	Elmhurst Touhy V 1 Site #1
Lab Order:	09060315	**Tag Number:**	
Project:	20753, Soil Corrosion	**Collection Date:**	
Lab ID:	09060315-003A	**Matrix:**	Soil

Analyses	Result	RL	Qualifier	Units	DF	Date Analyzed
Atterberg Limits	**D4318**			Prep Date:		Analyst: **SUB**
Atterberg Limits	LL=39.0 PL=19.8 PI=19.2		*		1	6/17/2009
Chloride	**E325.2**			Prep Date:	**6/12/2009**	Analyst: **BPJ**
Chloride	760	20	*	mg/Kg	1	6/12/2009
Nitrate and Nitrite	**M4500-NO3E**			Prep Date:	**6/12/2009**	Analyst: **YZ**
Nitrogen, Nitrate-Nitrite	ND	2	*	mg/Kg	1	6/12/2009
pH (25 °C)	**SW9045C**			Prep Date:	**6/10/2009**	Analyst: **JMS**
pH	7.8			pH Units	1	6/10/2009
Sulfate in Soil	**M4500SO4,E**			Prep Date:	**6/12/2009**	Analyst: **YZ**
Sulfate	ND	100	*	mg/Kg	2	6/16/2009

Figure D1 - Chemical properties of backfill of Utility-E Site-1

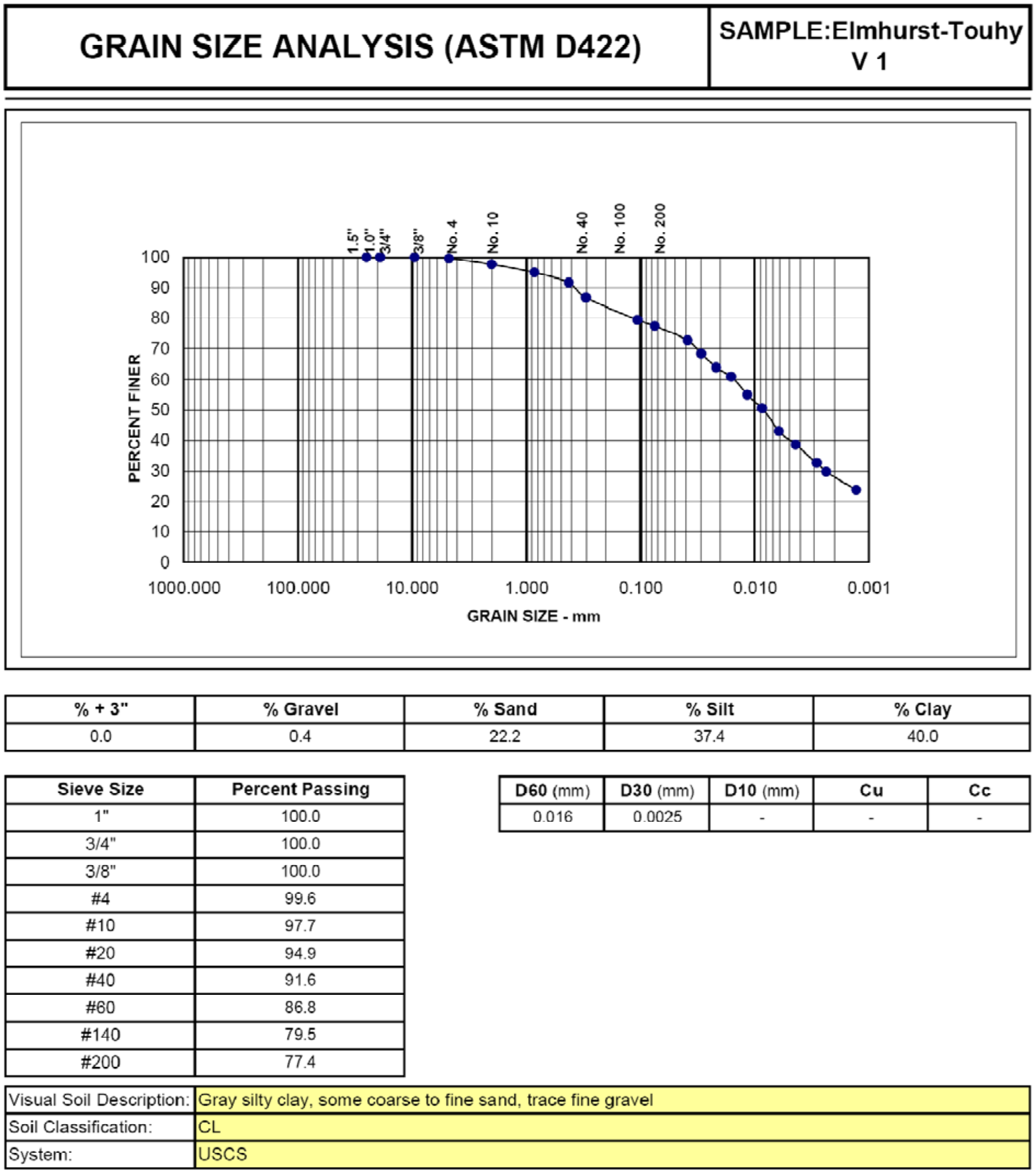


Report Date: June 19, 2009
Print Date: June 19, 2009

Client:	Gas Technology Institute	**Client Sample ID:**	Elmhurst Devon 3 1 Site #2
Lab Order:	09060315	**Tag Number:**	
Project:	20753, Soil Corrosion	**Collection Date:**	
Lab ID:	09060315-004A	**Matrix:**	Soil

Analyses	Result	RL	Qualifier	Units	DF	Date Analyzed
Atterberg Limits	**D4318**			Prep Date:		Analyst: **SUB**
Atterberg Limits	LL=42.4 PL=23.5 PI=18.9		*		1	6/17/2009
Chloride	**E325.2**			Prep Date:	**6/12/2009**	Analyst: **BPJ**
Chloride	370	20	*	mg/Kg	1	6/12/2009
Nitrate and Nitrite	**M4500-NO3E**			Prep Date:	**6/12/2009**	Analyst: **YZ**
Nitrogen, Nitrate-Nitrite	ND	2	*	mg/Kg	1	6/12/2009
pH (25 °C)	**SW9045C**			Prep Date:	**6/10/2009**	Analyst: **JMS**
pH	7.9			pH Units	1	6/10/2009
Sulfate in Soil	**M4500SO4,E**			Prep Date:	**6/12/2009**	Analyst: **YZ**
Sulfate	150	100	*	mg/Kg	2	6/16/2009

Figure D2 - Chemical properties of backfill in Utility-E Site-2



GRAIN SIZE ANALYSIS (ASTM D422)

SAMPLE:Elmhurst-Touhy V 1

% + 3"	% Gravel	% Sand	% Silt	% Clay
0.0	0.4	22.2	37.4	40.0

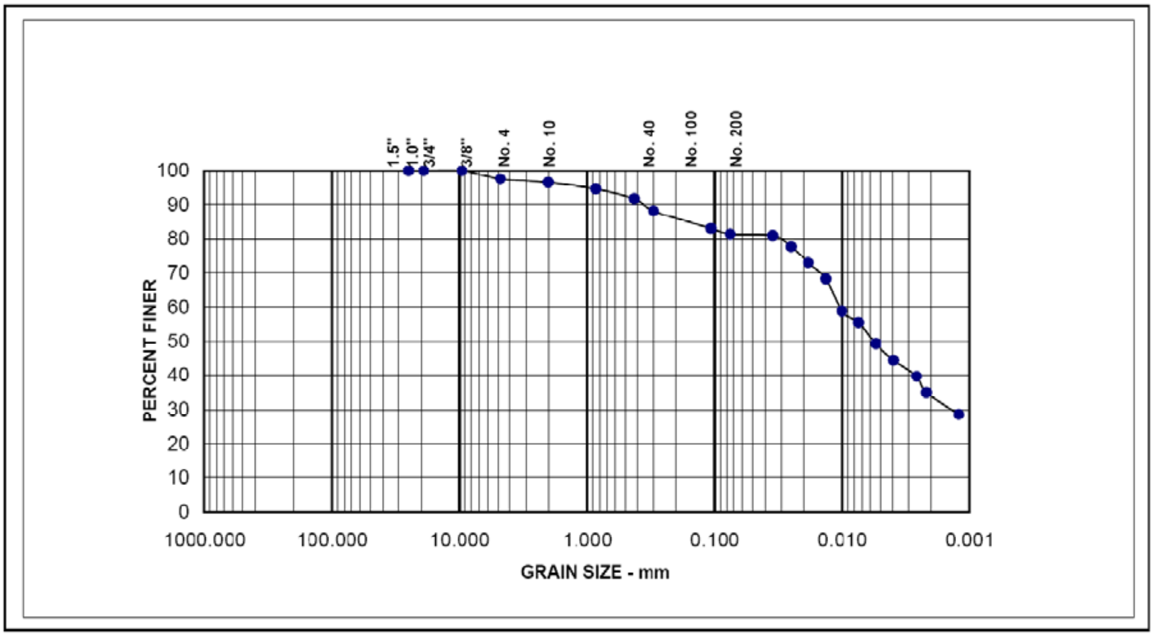
Sieve Size	Percent Passing
1"	100.0
3/4"	100.0
3/8"	100.0
#4	99.6
#10	97.7
#20	94.9
#40	91.6
#60	86.8
#140	79.5
#200	77.4

D60 (mm)	D30 (mm)	D10 (mm)	Cu	Cc
0.016	0.0025	-	-	-

Visual Soil Description:	Gray silty clay, some coarse to fine sand, trace fine gravel
Soil Classification:	CL
System:	USCS

Figure D - Physical properties of backfill of Utility-E Site-1

GRAIN SIZE ANALYSIS (ASTM D422)	SAMPLE:Elmhurst-Devon 3 1



% + 3"	% Gravel	% Sand	% Silt	% Clay
0.0	2.4	16.9	31.7	49.0

Sieve Size	Percent Passing
1"	100.0
3/4"	100.0
3/8"	100.0
#4	97.6
#10	96.6
#20	94.6
#40	91.8
#60	88.1
#140	82.9
#200	81.4

D60 (mm)	D30 (mm)	D10 (mm)	Cu	Cc
0.016	0.0025	-	-	-

Visual Soil Description:	Dark gray silty clay, little coarse to fine sand, trace fine gravel
Soil Classification:	CL
System:	USCS

Figure D4 - Physical properties of backfill of Utility-E Site-2

[END OF REPORT]