Touch and Step Voltage Measurements on Field Installed Ground Grid and Concrete Pads

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Technical Update, December 2009

EPRI Project Manager

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PRODUCT DESCRIPTION

Concrete is commonly used as building material in substations (within the substation fence) and around substations (outside the fence) for driveways, foundations, walkways, oil containment, sidewalks, walls, and other structures. This project evaluates the effects of various types (reinforced, non-reinforced) and conditions (dry, wet) of concrete structures on step, touch, and transfer touch voltages in and around substations.

Results & Findings

The tops of test concrete pads dried much faster than the interiors. A thin and highly resistive layer seemed to form on the concrete surface that greatly reduced exposure current. This behavior was confirmed in the Thevenin's equivalent resistances.

Overall, touch voltages were somewhat higher on concrete pads (with no reinforcement) compared to those measured on soil. The difference in touch voltages increased as the concrete started drying. Exposure currents on soil reduced as the drying occurred but not as much as currents measured on pads. Open-circuit touch voltages increased as concrete dried, and they increased at a higher rate compared to those over soil areas. In wet conditions, ungrounded rebar and wire meshes tend to equalize voltages spatially (along the diagonal). In the process, touch voltages are reduced in comparison with the pad having no reinforcement. As concrete dries, ungrounded rebar become less effective, with characteristics similar to the pad having no reinforcement. Voltage equalizing characteristics of wire meshes remain the same. Open-circuit voltages reduce significantly when rebar or wire meshes are connected to the ground grid. Due to their close spacing, wire meshes are more efficient in reducing these voltages.

Unlike touch voltages, step voltages were not reduced when rebar or wire meshes were connected to the grounding grid. In wet conditions, rebar and wire meshes reduced these voltages compared to those on the pad with no reinforcement.

Challenges & Objective(s)

Institute of Electrical and Electronics Engineers (IEEE) Std. 80 and other references list the values of wet concrete resistivity in the range of 21 to 100 ohm-meters. Using such values for a ground grid design is not practical because the remaining areas where gravel is typically used become grossly overdesigned. The touch and step voltage characteristics of concrete pads under field conditions are not well known. The influence of various reinforcing materials is another parameter that also is unknown.

This report provides a step in filling this knowledge gap by providing measured values of concrete resistivity and touch and step voltages under various conditions.

Applications, Values & Use

This information will be useful to utility engineers who design and evaluate substation ground grids, and it can be used to improve existing industry specifications and regulatory standards.

EPRI plans to continue this research in future years and to evaluate various other types of substation surfaces.

EPRI Perspective

Safety impacts all segments of the electric power industry. Properly designed substation grounding systems must protect workers inside the substation, must provide proper grounding for substation electronic equipment, and must take full account of the environment outside the fence to minimize hazards to the utility personnel and the public. With the help of recognized industry experts, EPRI has led a number of research projects related to substation grounding systems, including the Substation Grounding Workstation and Guide and the Ground Grid Evaluator (commercialized under the name “Smart Ground Multimeter”). This project addresses a very important issue—the interaction between the substation grounding system and the safety of workers (within the substation) and the public outside the fence. This report provides useful and important data on characteristics of various types and conditions of concrete. This information is expected to be useful for improving industry standards and performance of substation ground grids and enhancing safety of workers within substations and the public outside the fence.

Approach

The project team’s goal was to measure surface potentials on soil and concrete pads with different reinforcement and in different environmental (dry and wet) conditions.

The project team constructed a 2 x 2 mesh grounding grid with four concrete pads, three inside the grid area and one outside. One pad had embedded rebar, another had an embedded wire mesh, while the third had no reinforcement. The pad installed outside the grid was selected for investigating the resistivity parameter. This pad also was without any reinforcement. To compare concrete results with those over native soil, one section of the grid was left without any surfacing material. However, this area was covered with a plastic sheet throughout the testing period to represent a controlled soil surface.

The voltage gradients in and around the ground grid were developed by injecting approximately 22 A from a 240/480-V isolation transformer. Measured variables included the injected current, ground potential rise (GPR), voltage between selected surface locations and a remote ground rod, and voltage across a 1000-Ω resistor representing a human body. Measurements were taken on six different days with varying moisture conditions. The touch and step voltages were calculated from the measured data. More detailed characterization of the concrete pads was obtained by determining the Thevenin’s equivalent resistance (R_{thev}) in series with the 1000-Ω resistor, or worker’s feet.

Keywords

Ground potential rise (GPR)
Reinforced concrete
Safety in substations
Substation grounding systems
Touch and step voltages

ACKNOWLEDGEMENTS

Southern Company is gratefully acknowledged for making available the results of a previous project, fully funded by Southern Company, as valuable input and starting point for this research.

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1
INTRODUCTION AND BACKGROUND

Introduction

Concrete is used as building material in substations (within the substation fence) and around substations (outside the fence) for driveways, foundations, walkways, oil containment, sidewalks, walls, etc. This project evaluates the effects of various types (reinforces, non-reinforced) and conditions (dry, wet) of concrete structures on step, touch and transfer touch voltages in and around substations.

Objective

The objective of this project is to measure surface potentials on soil and concrete pads with different reinforcement and in different environmental (dry and wet) conditions.

Background

There are several facts which can aid in the understanding of the electrical resistivity of concrete. A summary of information from a previous NEETRAC project is shown below:

- Concrete is an electrolytic conductor, making its resistivity strongly dependent on both the moisture content and the ion content of the concrete.
- Concrete is not homogeneous; it is composed of cement and aggregate. The conductivity of concrete is almost solely a function of the cement, as most aggregates are highly insulating in comparison to the cement.
- At power frequencies (for example, 60 Hz), the capacitance of concrete is negligible in comparison to its resistance. Thus, for electrical purposes, the ac impedance of concrete is essentially its dc resistance.
- The resistance of concrete can vary greatly as a function of its composition. By adding certain materials, concrete can be made highly resistive or highly conductive.

Several other facts are known [1, 2, 3, 4] about the electrical characteristics of concrete:

- The lower water/cement ratios of higher strength concretes correspond to higher electrical resistivities.
- Higher ion content (e.g., chloride ions from deicing salts) will decrease the resistivity of the concrete. This effect is more pronounced in concrete with a high water/cement ratio, and is low in high-strength concrete.
- The resistance of concrete can be varied greatly as a function of its composition. For instance:
    - "Ground granulated blast furnace slag" can increase resistivity by as much as an order of magnitude.

    - Alumina content will increase resistivity.
    - Silica fume will increase resistivity.
    - "Finely divided bituminous material, with subsequent heat treatment at 138 °C" will increase the resistivity.
    - Acetylene carbon black will decrease the resistivity.
    - Carbon fibers will decrease the resistivity.
    - Crystalline carbon can be used to make concrete highly conductive (<0.2 ohm-meters).
- Damage to concrete can also affect its electrical characteristics.

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TEST PROCEDURE

Field Installation of Ground Grid and Concrete Pads

Maintaining the symmetry, a 24’ x 24’, 4/0 copper ground grid with four 12’ x 12’ meshes was installed near the MTF Building in NEETRAC’s High Voltage Facility in Forest Park, Georgia. The grid conductors were buried approximately 18” deep. Following the installation of the ground grid, four 6’ x 6’ x 10” concrete pads were poured. Concrete was ordered with a strength rating of 4000 psi, comparable to that of concrete used in substations. When the concrete was delivered, extra time was taken to mix the concrete as consistently as possible. The aggregate was observed to be approximately 3/4" gravel.

Figure 2-1 shows the dimensions, locations and specifications of the grounding grid and four concrete pads. Figure 2-2 shows a photo of the pads during installation. The pad specifications are:

- Pad 1 does not contain reinforcement.
- Pad 2 contains rebars that can be connected to the ground grid, or not connected to the grid
- Pad 3 contains a wire mesh that can be connected to the ground grid, or not connected to the grid
- Pad 4 does not contain reinforcement.
- Soil 1 area does not contain any metal objects

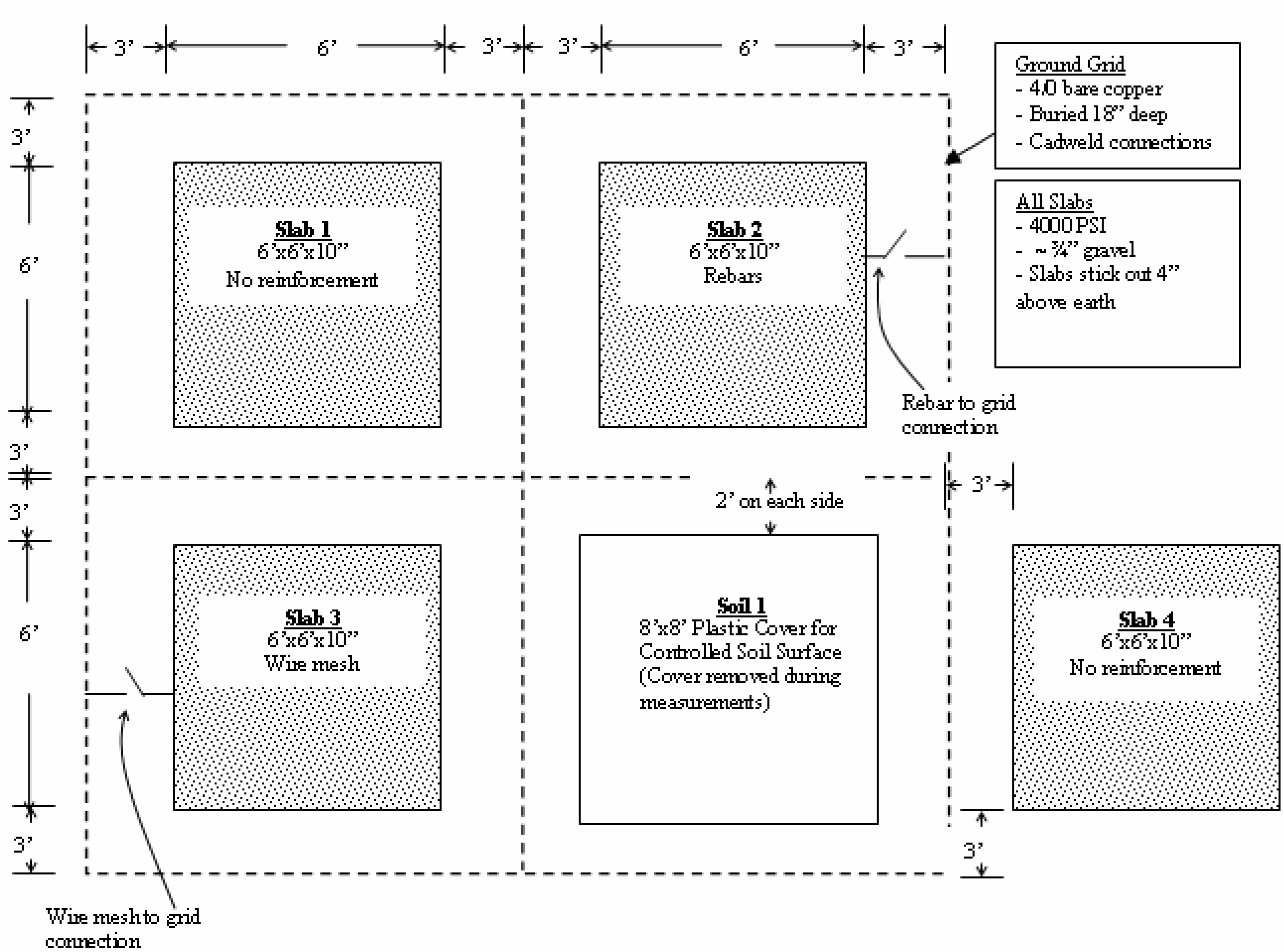

Figure 2-1
Ground Grid and Concrete Pad (Slab) Locations, Dimensions and Specifications

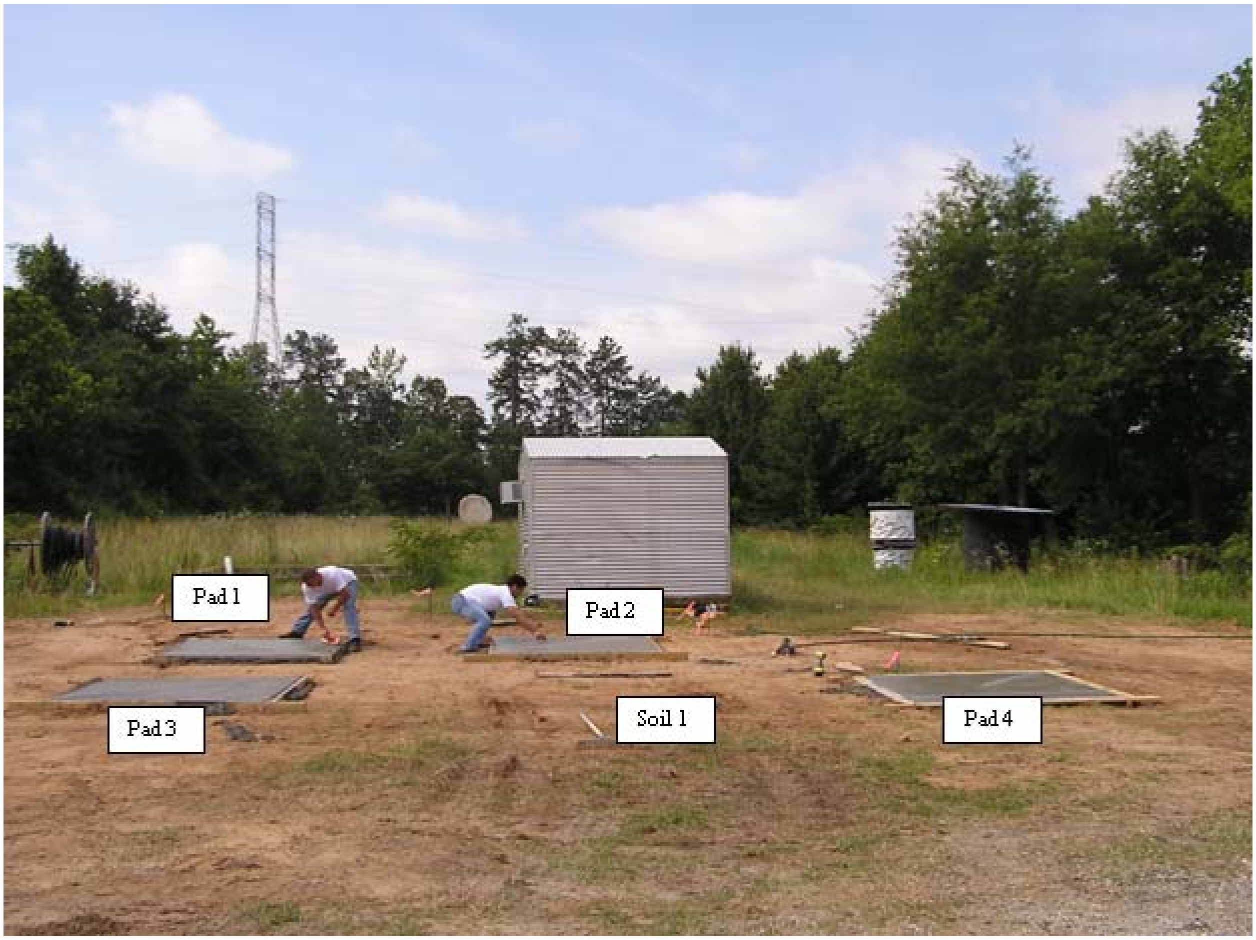

Figure 2-2
Pads during Installation

Timeline

The concrete pads were poured on June 15, 2009 and were allowed to cure for about five weeks before starting the measurements. Trial tests were performed on July 14 and again on July 22, 2009. The first series of tests was performed on July 24, 2009. Since dry and hot weather prevailed for weeks prior to this date, these data represent the "dry" data in this report.

Following the July 24 measurements, a sprinkler system was set up to wet the ground grid site. The "wet" data were obtained on August 3, 2009 between 10 AM and 11 AM. The site received approximately 4" of rain prior to these measurements as measured by the rain gauge. The following log shows the total moisture received by the site prior to these measurements:

- 7/24 (Friday) to 7/26 (Sunday) - ¼" with sprinkler running 8-10 AM on each day
- 7/27 (Monday) - 1" with sprinkler running 8 AM-1PM
- 7/28 (Tuesday) - ¼" with sprinkler running 10PM-12AM
- 7/29 (Wednesday) to 7/31 (Friday) - ¾" natural rain
- 7/31 (Friday) to 8/3 (Monday) - 1 ¾" natural rain

- 8/3 (Friday) - 1/8” with sprinkler running 9AM -9:45AM
- 8/3 (Friday) to 8/12/09 (Wednesday) – Little to no rain

The exposure currents are highly dependent on the wetness of the surface. For this reason, the exposure current measurements were obtained first. Figure 2-3 shows a photo of wet pads prior to these measurements.

Figure 2-3
Pads Prior to Wet Measurements

The next series of tests was performed on August 5, August 7, August 10 and August 12, 2009 as the pads continued to dry. During this period there was little to no rain recorded by the gauge.

Measurement Details

This project consisted of making several different measurements. A summary of these measurements is provided below:

- Injected current (I_g)
- Ground Potential Rise (GPR) with respect to a remote ground rod

- Voltages between the remote ground rod and metal pins embedded on the surfaces of concrete pads (V_{pin-R})
- Voltages between the remote ground rod and short pins driven in the soil (V_{pin-R})
- Exposure current (I_{ex}) measured as a voltage across a 1000   resistor representing a human body. (For this report, the voltage measured across the 1000   resistor is defined as a closed circuit touch voltage, V_{tcc})
- Resistivity of concrete using the four-pin method
- Resistivity of native soil using the four-pin method

Some of the variables as identified below were calculated from the measured data:

- Open circuit touch voltage (V_{toc})
- Open circuit step voltage (V_{stoc})
- Thevenin's equivalent resistance in series with feet (R_{thev})
- Two layer soil model for the native soil

Voltage gradients in and around the ground grid were created by injecting approximately 22 amperes into the ground grid. The current was supplied from a pole mounted distribution transformer via a 240/480 V isolation transformer as shown in Figure 2-4.

A summary of various measurements including their locations is shown in Figure 2-5.

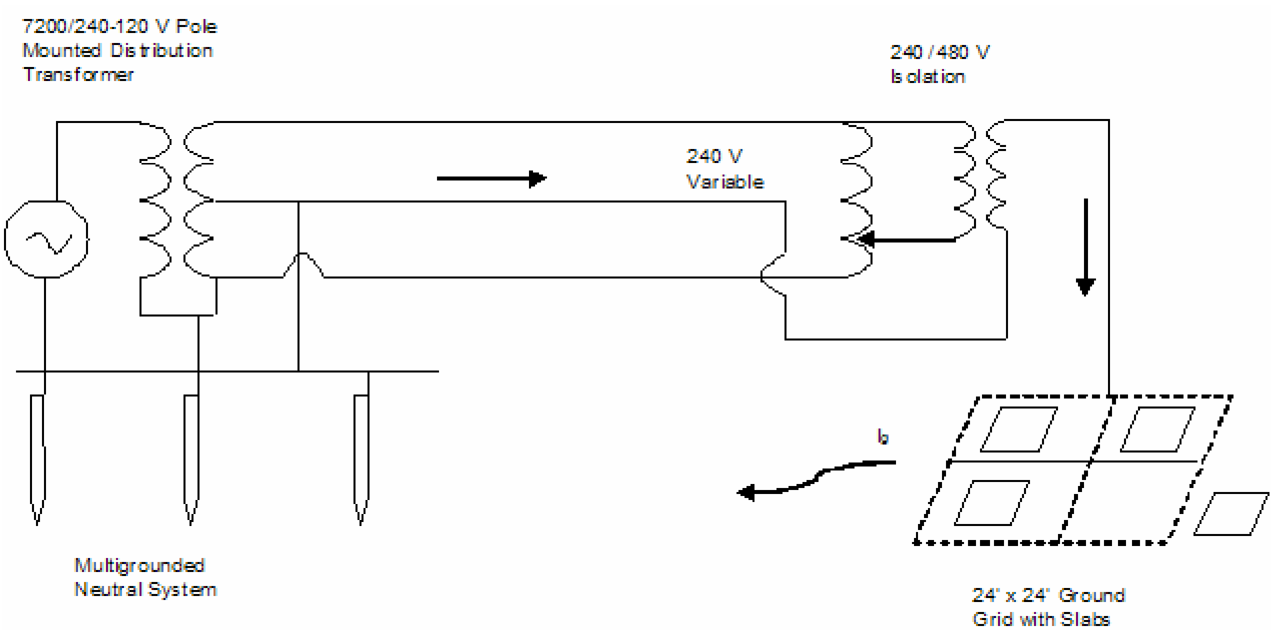

Figure 2-4
Current Injection Circuit

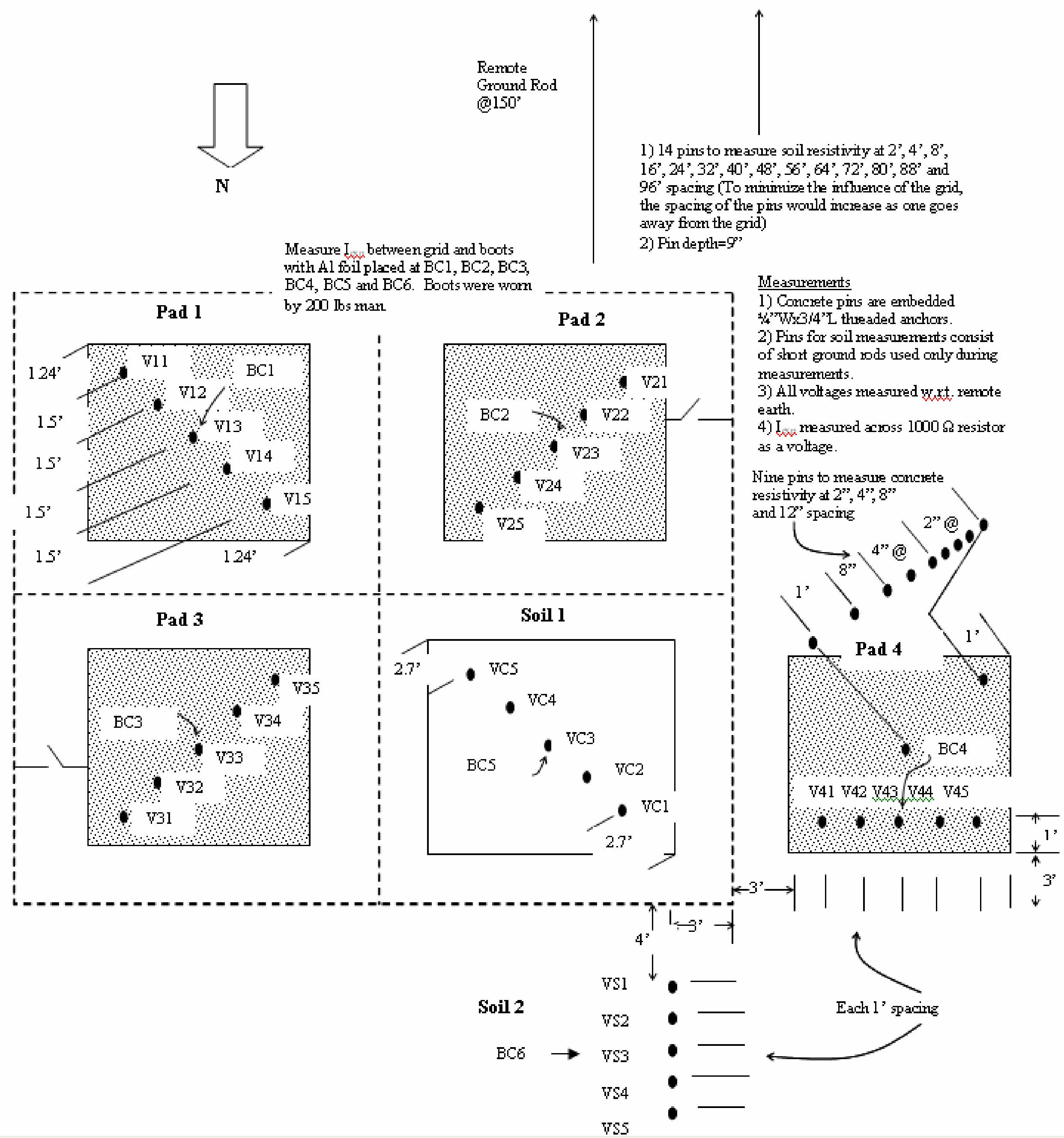

Figure 2-5
Measured Variables and their Locations

Apparent Resistivity Using the FOUR-PIN Measurement Method

The four-pin resistivity method was used to determine the electrical resistivity of the concrete and soil. The measurements were performed on Pad 4 for concrete resistivity. During preparation of the pad, multiple small pins were embedded in the pad. Each of these pins was hexagonal, approximately ¼" wide and ¾" long. Each pin had a threaded hole into which a small screw was placed. These screws were used as the contact points for the four-pin resistivity measurements. These pins were placed along a diagonal, flush with the surface. The pins were placed in locations to allow for four-pin resistivity measurements with spacings of 2, 4, 8, and 12 inches. Initially, the resistivity measurements were made with a battery operated four-pin resistivity meter (AEMC CQ-4026). During the trial tests, it was learned that the cracking around the pins due to drying was affecting the readings. The meter was then replaced by a 120 V source for injecting the current and a digital voltmeter to measure the resulting voltage as shown in Figure 2-6. Additionally, a zinc based conductive paint was applied around each pin to improve its contact with surrounding concrete.

Figure 2-6
Four-Pin Measurement of Pad Resistivity using Embedded Electrodes

The resistance values obtained from these measurements were converted to resistivity values by using the formula from IEEE Std. 80 as shown in Equation 2-1.

$$\rho = \frac{4\pi aR}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

Equation 2-1

where:

is the resistivity in ohm-meters,

a is the pin spacing either in meters or feet,

b is the pin depth with the same units as a,

R in ohms is the voltage between the inner pins divided by the current through the outer pins.

In the case of native soil, the number of pins and their spacing were significantly increased compared to measurements performed on concrete pad. The details of these measurements are provided in Figure 2-5.

Open Circuit Touch and Step Voltages

For the purpose of this report, the open circuit touch voltage (V_{toc}) is defined as the voltage measured between the ground grid conductor and a pin driven at a surface location. This surface location may or may not be one meter (approximately three feet) from the ground grid conductor as defined conventionally. In this project, each touch voltage was calculated by subtracting the pin-to-remote voltage (V_{pin}-R) from the ground potential rise (GPR). Both of these variables were measured using a Fluke 87 digital multimeter. The open circuit step voltages (V_{stoc}) were determined by taking a difference between two touch voltages located approximately three feet apart.

The description of the pins and the steps taken to make them suitable for voltage measurements is provided in the preceding section. Readers should refer to Figure 2-5 for identifying various surface locations and the location of the remote ground rod.

Exposure Currents or Closed Circuit Touch Voltages

Exposure current is defined as the current flowing through a 1000 resistor which connects to the ground grid conductor on one side and to a surface location via aluminum foils taped on the soles of two rubber boots on the other side. The exposure currents were measured as voltages across the 1000 resistor. With a 1000 resistor representing a human body, the voltage values read in “volts” directly represent the exposure current values in “mA”. Sometimes a 500 resistor is used to represent a human body. In such a case, the voltage read across the resistor must be doubled to represent the exposure current value in “mA”.

In the stray voltage field [5], the voltage measured across a resistor representing a human body is defined as a closed circuit touch voltage (V_{tcc}). In actuality, this is the voltage that appears across the body when a contact is made. Since a 1000 resistor represents a human body in this project, it is convenient to define the “exposure current” in mA as the “Closed Circuit Touch Voltage” in

Volts. Additional details on the significance of this voltage are provided in the following section.

A 200 pound man wore the rubber boots throughout the exposure current measurements as shown in Figure 2-7.

The exposure current measurements were performed only at six locations, one location on each pad and one location on each soil area. These locations are marked as “BC” in Figure 2-5.

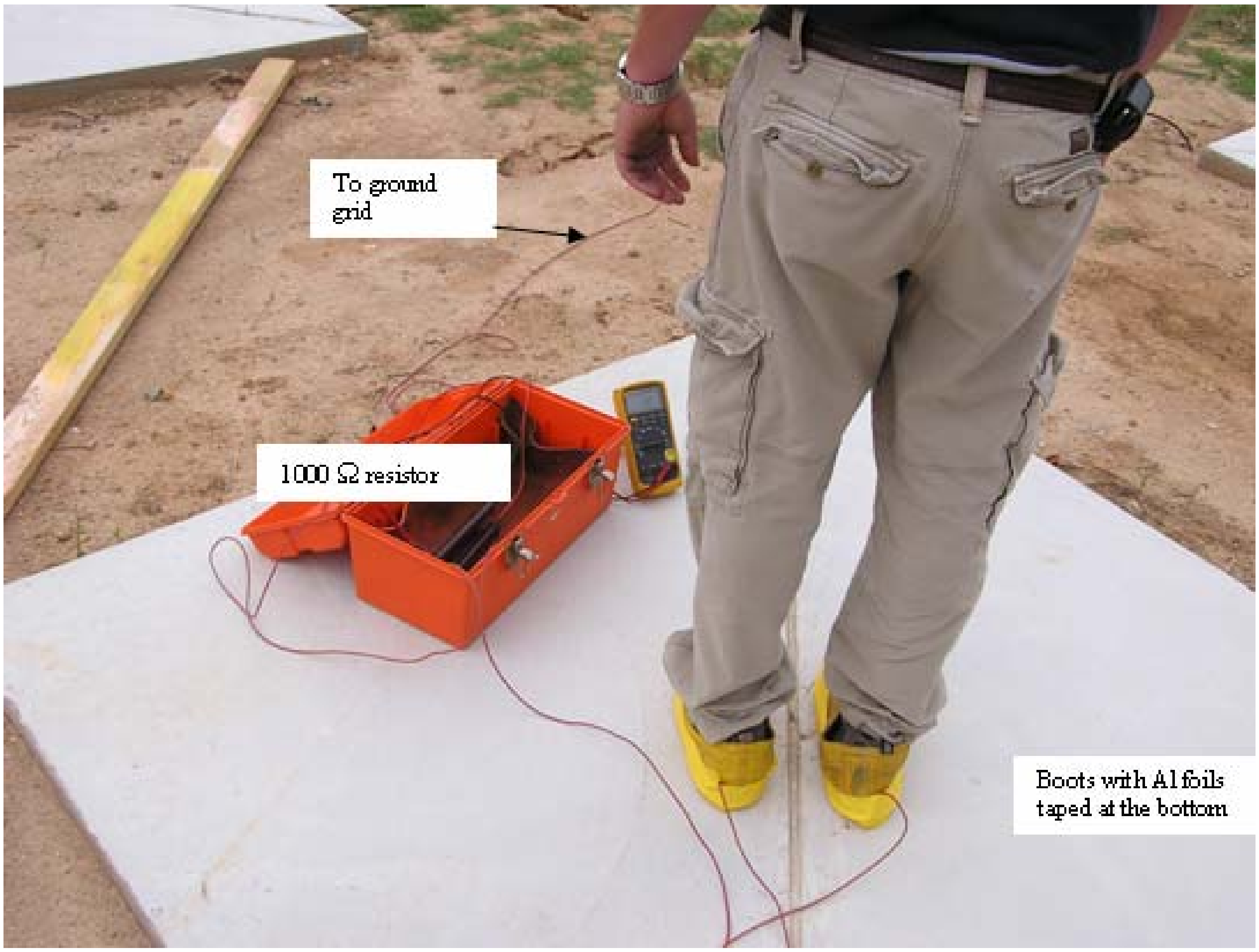

Figure 2-7
Measurement of Exposure Current

Thevenin’s Equivalent Resistance in Series with Feet

To characterize a surfacing material such as concrete, gravel or soil; it is necessary to determine the Thevenin’s Equivalent Resistance (R_{thev}) that appears in series with the feet when a contact is made. Since this resistance appears in series with the feet, it plays a major role in determining the exposure current in a given environment.

The Thevenin's equivalent resistance can be computed by a number of methods as published in several technical articles [6, 7, 8]. The IEEE Std. 80 provides a conservative but simple relationship for this resistance as shown in Equation 2-2.

$$R_{thev} = 1.5\rho_s \quad \text{Ohms} \qquad \textbf{Equation 2-2}$$

where:

$_s$ is resistivity of the surfacing material in ohm-meters

The circuit of Figure 2-8 describes the various electrical parameters and their interactions with each other in determining the exposure (body) current. However, this complex network is far from providing a simplified approach to solve for the current. One approach, which provides considerable insight, is to reduce the entire circuit of Figure 2-8 into a two-port network, typically known as Thevenin's equivalent circuit. The circuit looking from the two contact points C_1 and C_2/C_3 (i.e., the person's feet together and in parallel) is shown in Figure 2-9. Note that a two-port network can be similarly established between contact points C_2 and C_3 to represent a step voltage that may exist between two feet.

Referring to Figure 2-9, Thevenin's principle replaces the entire circuit of Figure 2-8 by an equivalent circuit consisting of an equivalent voltage source, V_{toc}, in series with an equivalent impedance, R_{thev}, behind the two points contacted by the person (the hand, [point C_1 and the feet, point C_2/C_3). When these two points are contacted, the current I_{exp} would flow through the body developing voltage V_{tcc} across the body.

From Figure 2-9, two equations can be easily established:

$$V_{toc} = I_{\exp}\left(R_{thev} + 1000\right) \ \text{Volts} \qquad \textbf{Equation 2-3}$$

$$V_{tcc} = I_{\exp} \times 1000 \ \text{Volts} \qquad \textbf{Equation 2-4}$$

Combining equations 2-3 and 2-4, an important relationship evolves.

$$R_{thev} = 1000\left(\frac{V_{toc} - V_{tcc}}{V_{tcc}}\right) \quad \text{Ohms} \qquad \textbf{Equation 2-5}$$

Equation 2-5 suggests that $V_{toc} \geq V_{tcc}$, i.e., the open circuit touch voltage (the voltage measured between the ground grid conductor and a pin driven at a surface location, V_{toc}) is **greater** that the closed circuit touch voltage (the voltage measured across a resistor representing a human body, used in the stray voltage field, V_{tcc}). It also suggests that the difference in two touch voltages would be larger with higher value of R_{thev}.

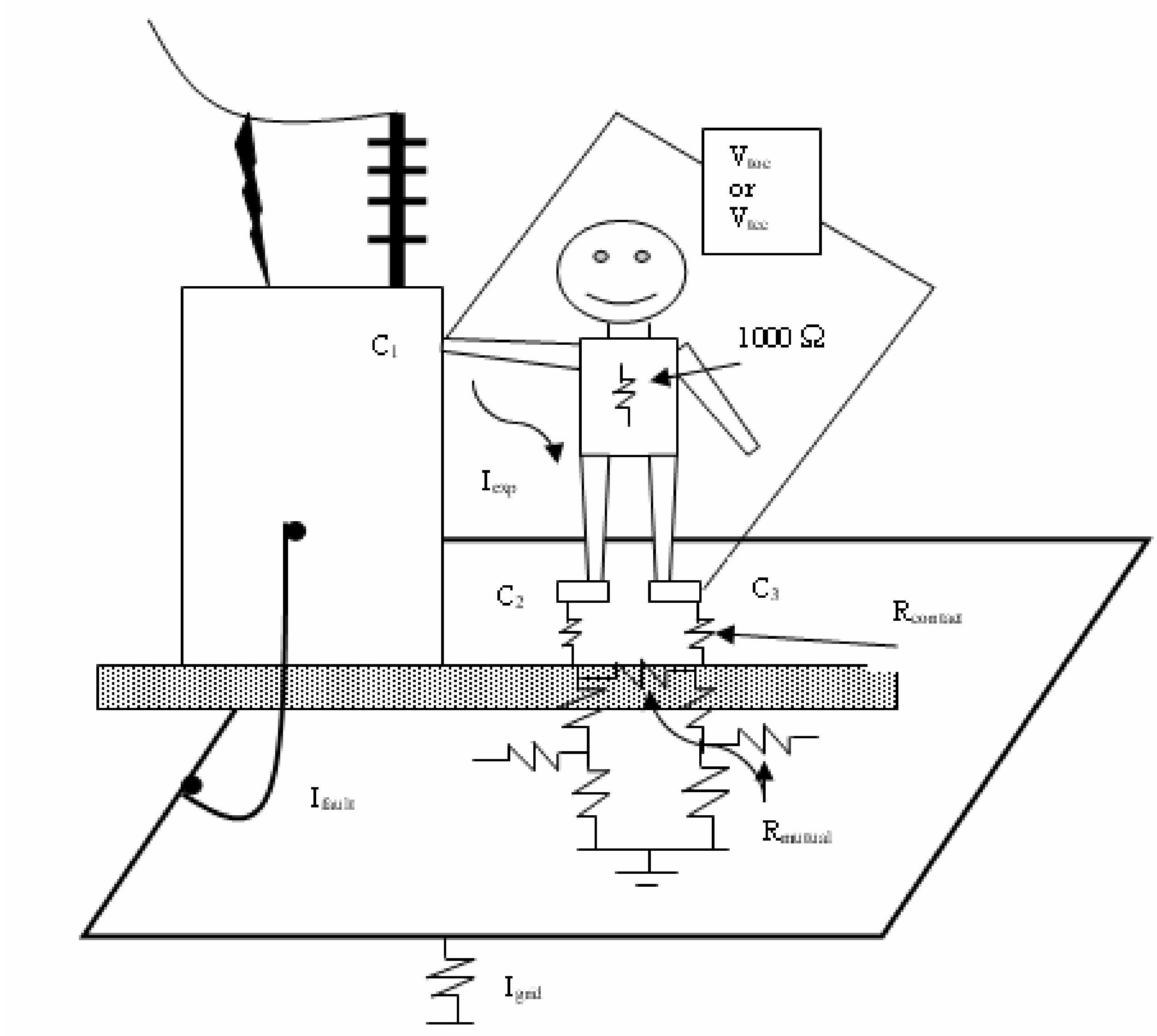

Figure 2-8
Resistance Network in Series with Feet

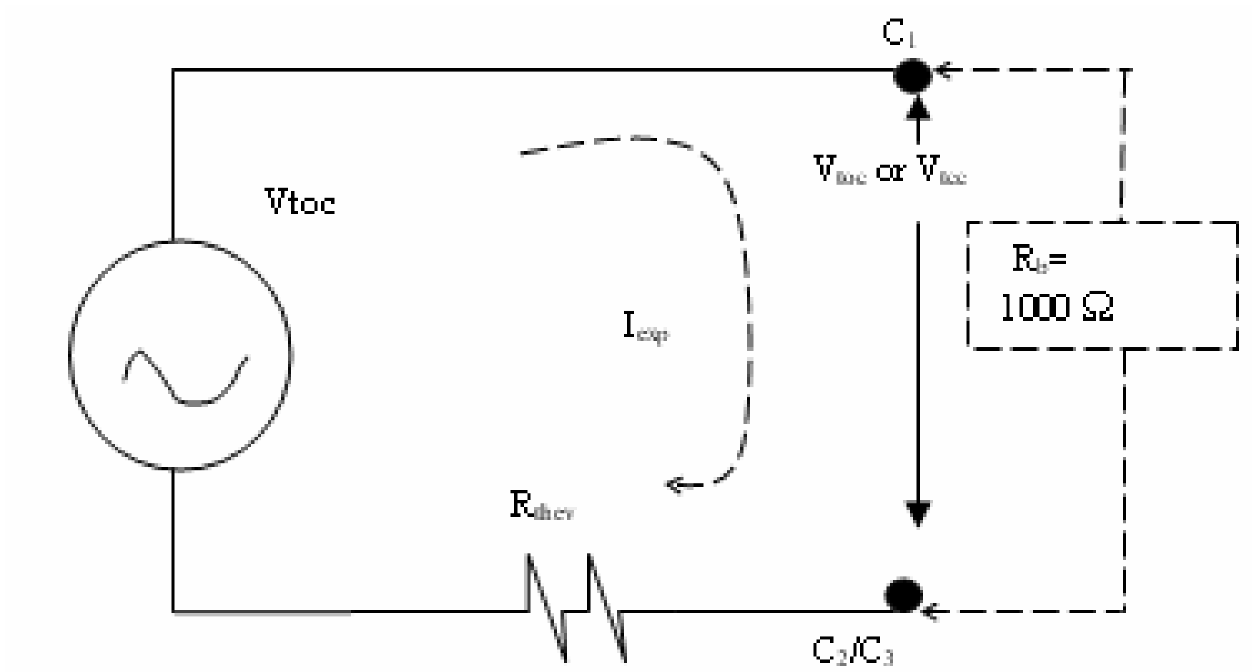

Figure 2-9
Thevenin's Equivalent Circuit to Represent Touch Voltage and Exposure Current for Human

3
TEST RESULTS AND ANALYSIS

General

Appendix A provides a complete set of measured and calculated test data in tabular format.

Apparent Resistivity Measurements of Concrete and Soil by Four-Pin Method

Concrete and soil resistivity were measured using the four-pin method as described in the previous sections.

Concrete Resistivity

The concrete resistivities measured on Pad 4 are shown in Figure 3-1.

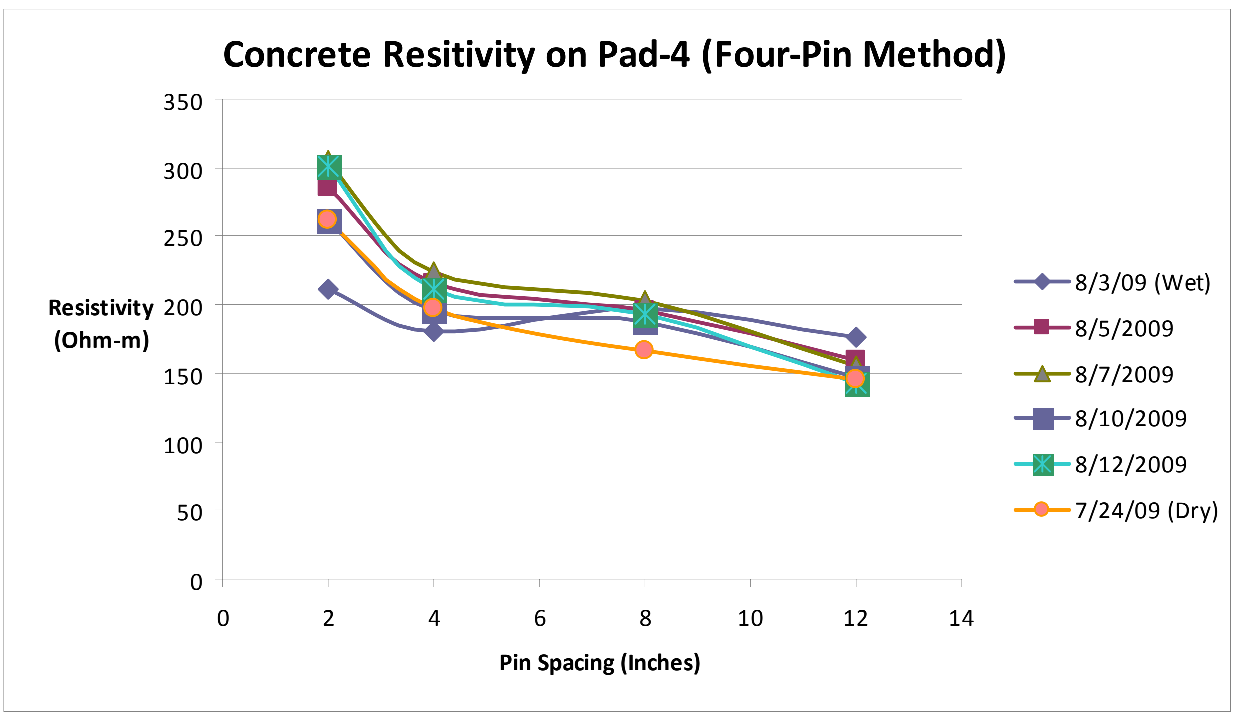

Figure 3-1
Pad 4 Concrete Resistivity vs. Pin Spacing for Different Moisture Conditions

Overall, the resistivity values declined with the increase in the pin spacing. The environmental changes seem to influence the surface layer (2" spacing) the most where the spread between the highest and lowest resistivity is almost 45%. This spread is about 23% at 12” pin spacing, mostly due to the influence of the soil below Pad 4.

Based on the pad dimensions, it seems reasonable to estimate the concrete resistivity from the values measured at 2” and 4” spacing. The validity of this assumption can also be found in a previous project at NEETRAC (sponsored by Southern Company). That project performed four-pin measurements on 3’ x 3’ x 9.5” concrete blocks by placing them on conductive and insulating bottoms. The results showed that the differences in resistivity measured at 2” and 4” spacing were not significant regardless of the resistivities at the bottom.

With the above assumption, the concrete resistivity is estimated to be 196 ohm-meters during wet and 264 ohm-meters during dry conditions.

Soil Resistivity

The soil investigation consisted of measuring the resistivity from 2’ pin spacing to a maximum of 96’ spacing, as described in Figure 2-5 (upper right-hand corner). Figure 3-2 shows the measured data along with an equivalent two layer soil model. The soil model was determined by using the WinIGS™ program.

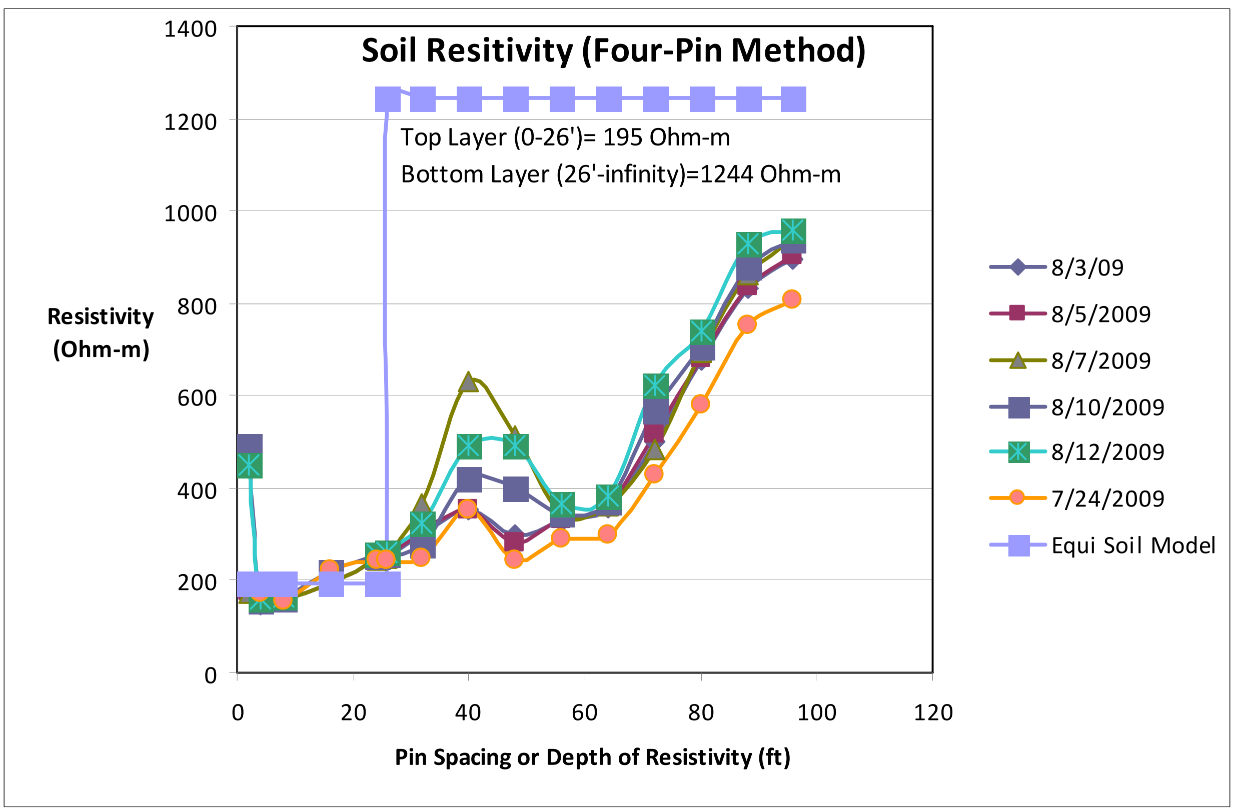

Figure 3-2
Soil Resistivity vs. Pin Spacing

Overall, the soil resistivity increased with increasing spacing or soil depth. The two layer model, as a result, consisted of a bottom layer having the resistivity of 1,244 ohm-meters in comparison with 195 ohm-meters for the top layer. It is interesting to note that the wet resistivity value of the concrete is nearly the same as that of the top soil layer (195 ohm-meters).

Depending on the moisture content in the surface layer, the resistivity of the soil corresponding to 2' spacing showed some significant changes. At this spacing, the resistivities measured on 8/10/2009 and 8/12/2009 were significantly higher compared to those measured on other days. The spread in resistivity again increased at about 40' spacing for no obvious reasons.

Open Circuit Touch and Step Voltages

Safety analysis of a ground grid almost always includes computing or measuring open circuit touch and step voltages. The safety goals for the grounding grid are accomplished when these voltages are within the tolerable limits that are typically determined from the characteristics of surfacing materials. Due to numerous applications of concrete in substations, it is important to know its characteristics not only in regard to the voltages on the surface but also its ability to provide an effective resistance in series with the feet when a contact is made. The open circuit touch and step voltage data are presented in this section. The exposure current and Thevenin's resistance data are presented next.

Open Circuit Touch Voltages

Figures 3-3 through 3-5 show the open circuit touch voltages measured on 8/3/09 (wet), 8/12/09 (semi dry) and 7/24/09 (dry) respectively. Each figure contains six graphs, five for three concrete pads inside the ground grid area and one for controlled soil area, Soil 1. The graphs are:

- Pad 1: one graph since this pad does not include reinforcement
- Pad 2: one graph with the rebars ungrounded (i.e., not connected to the ground grid), and one graph with the rebars grounded (i.e., connected to the ground grid)
- Pad 3: one graph with the wire mesh ungrounded (i.e., not connected to the ground grid), and one graph with the wire mesh grounded (i.e., connected to the ground grid)

Figure 3-6 shows six graphs, three for Pad 4 (no reinforcing, located outside the grid) and three for the outside soil area, Soil 2.

To gain additional insight, Figures 3-7 through 3-10 display the same data but in different ways.

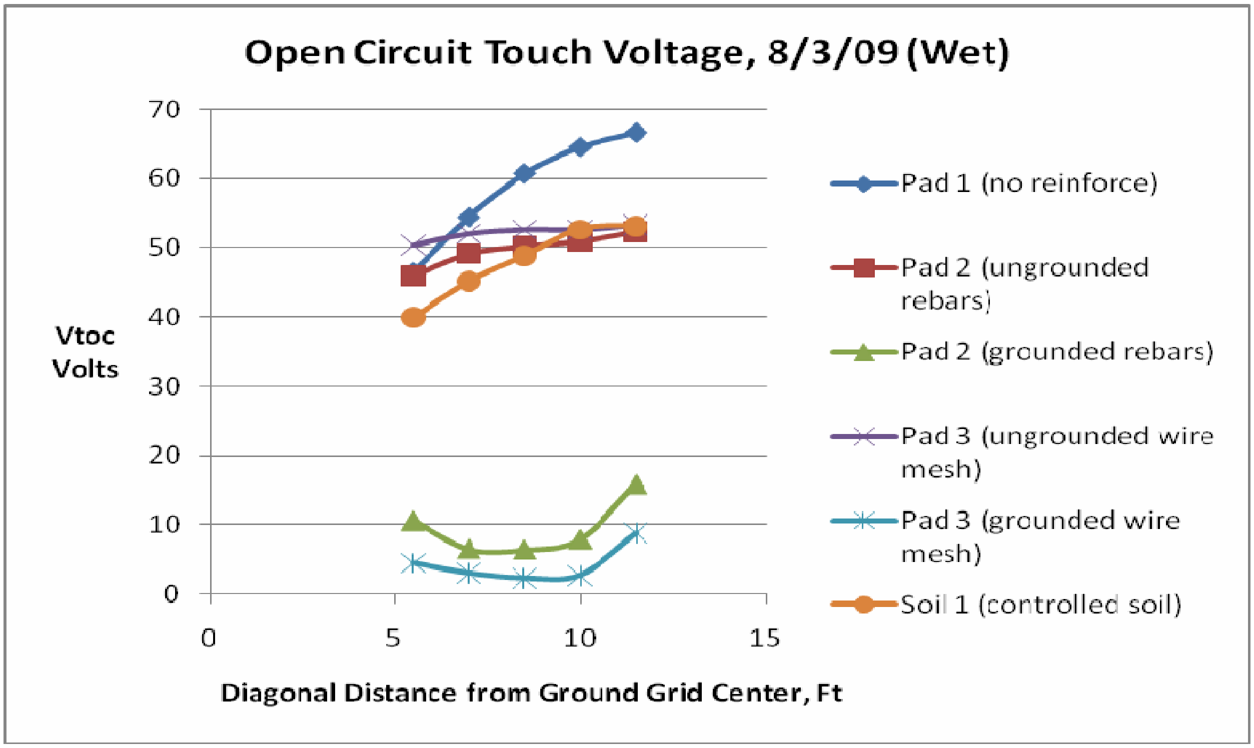

Figure 3-3
V_{toc} Measured on 8/3/09 (Wet)

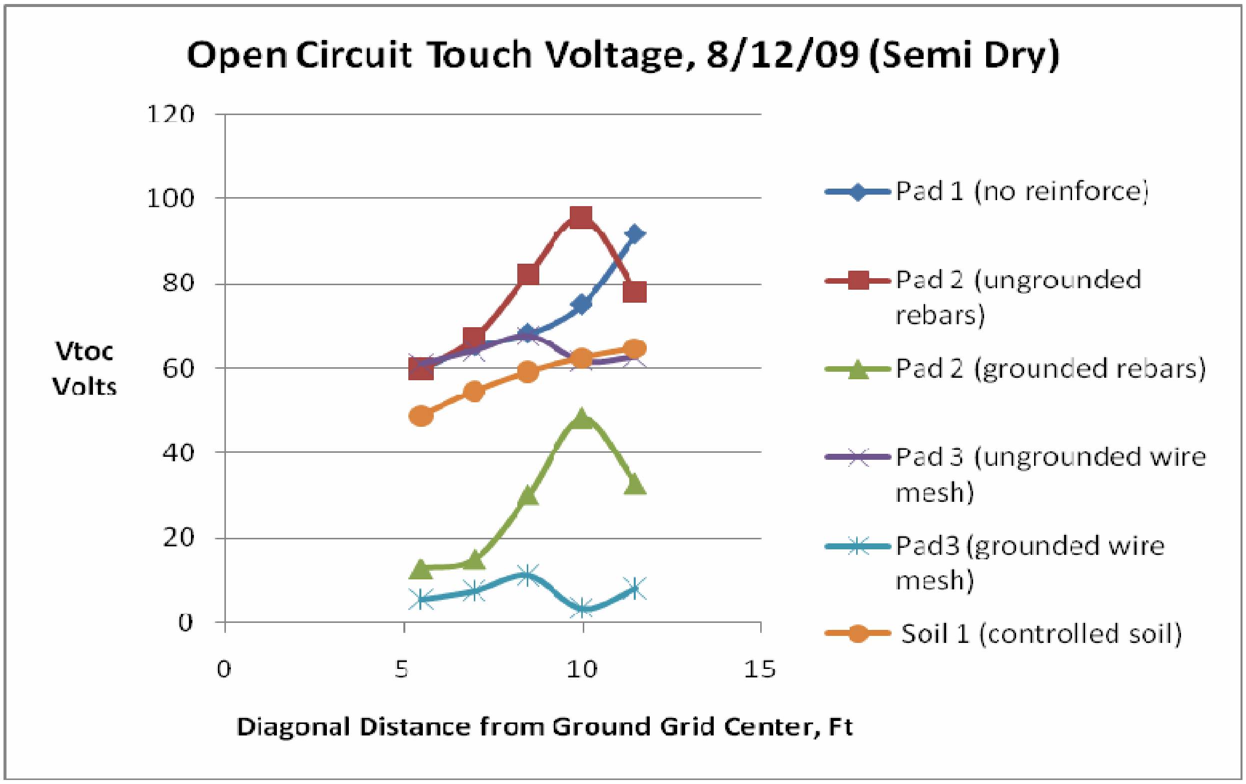

Figure 3-4
V_{toc} Measured on 8/12/09 (Semi Dry)

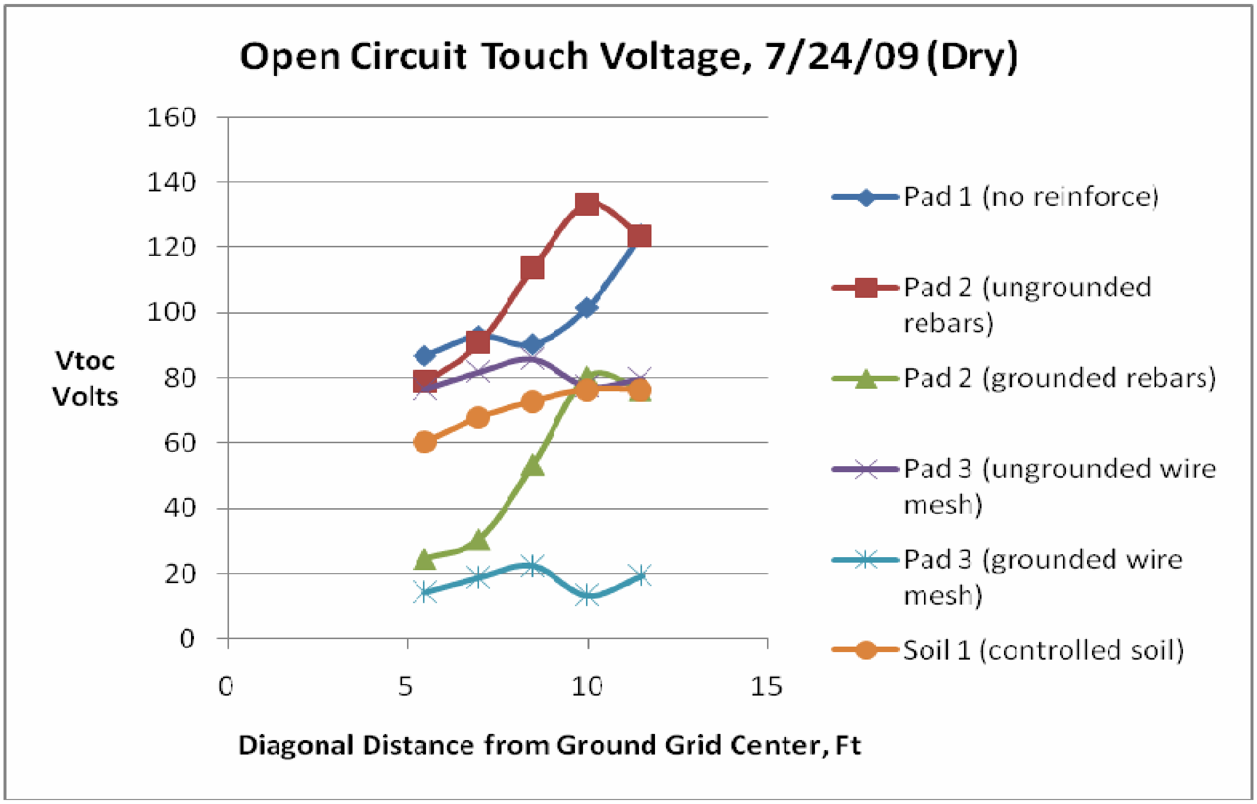

Figure 3-5
V_{toc} Measured on 7/24/09 (Dry)

Figure 3-6 shows six graphs, three for Pad 4 (no reinforcing, located outside the grid) and three for the outside soil area, Soil 2.

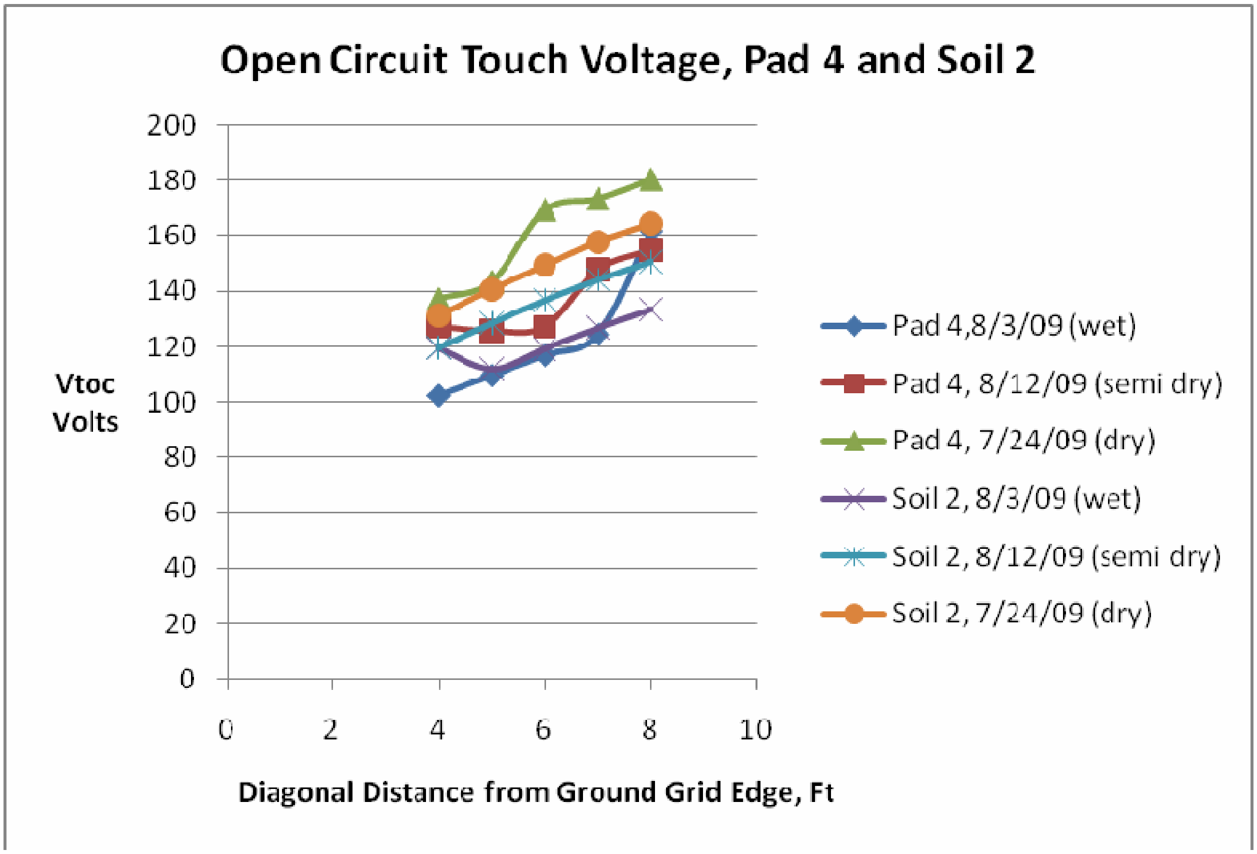

Figure 3-6
V_{toc} Measured on Pad 4 and Soil 2

To gain additional insight, Figures 3-7 through 3-10 display the same data but in different ways.

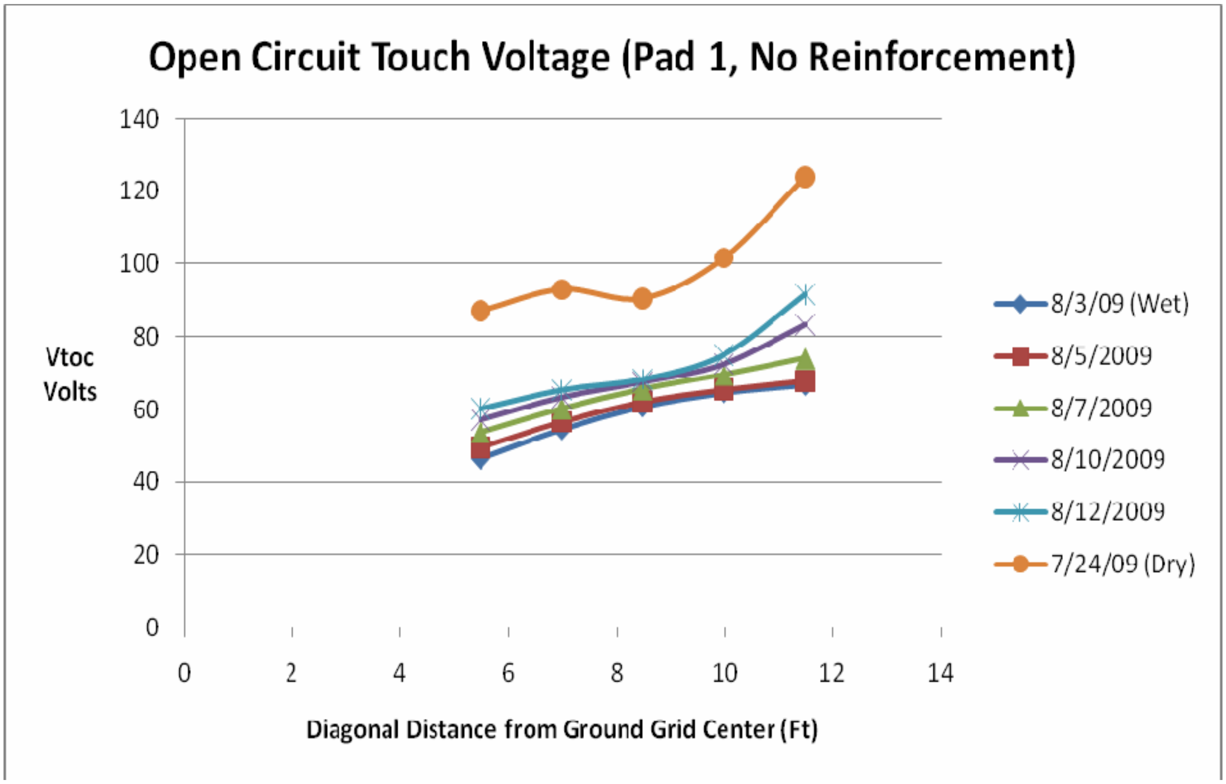

Figure 3-7
V_{toc} Measured on Pad 1 (No Reinforcement)

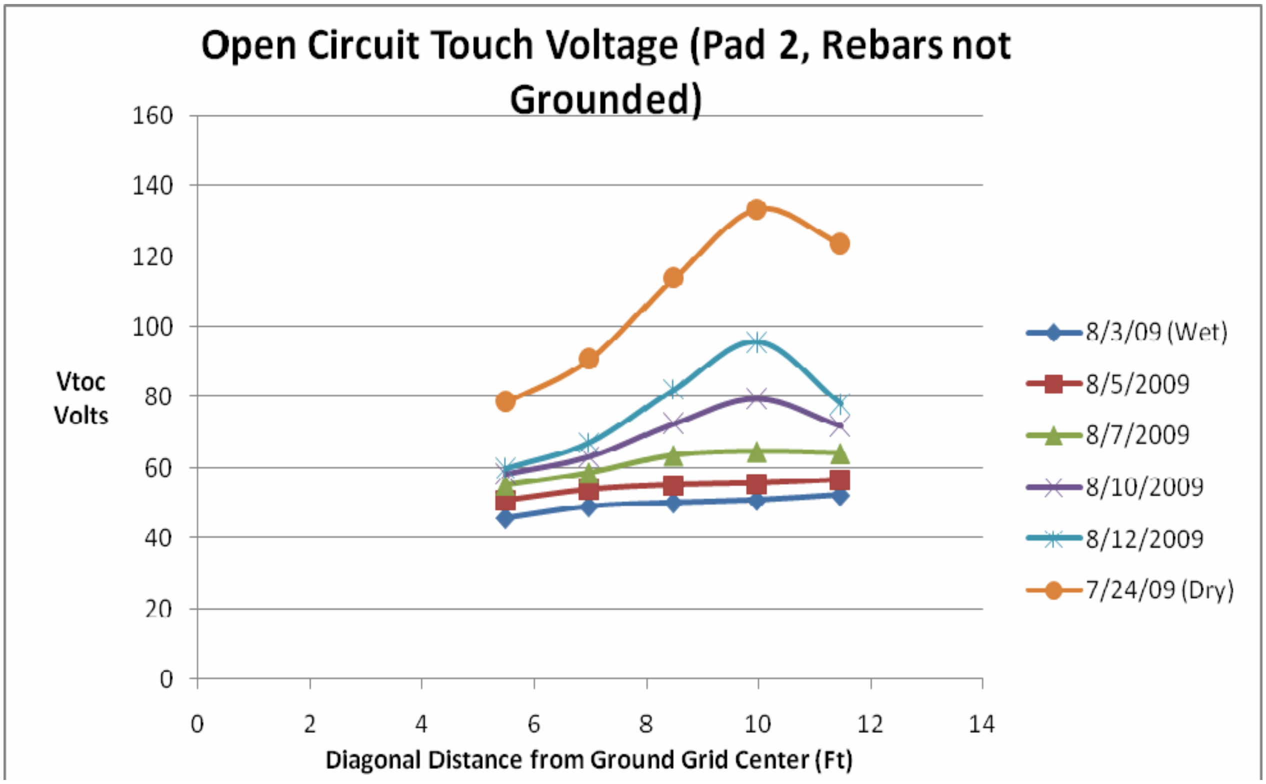

Figure 3-8
V_{toc} Measured on Pad 2 (Ungrounded rebars)

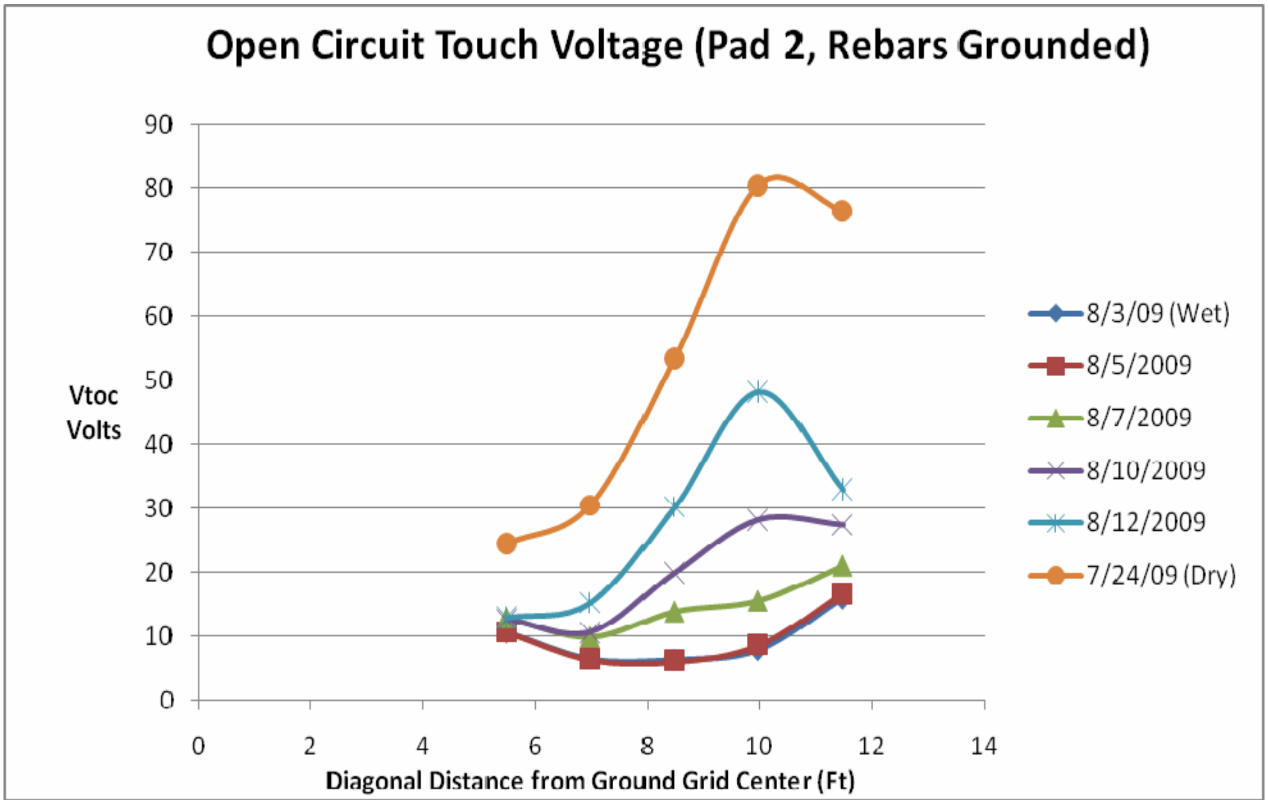

Figure 3-9
V_{toc} Measured on Pad 2 (Grounded rebars)

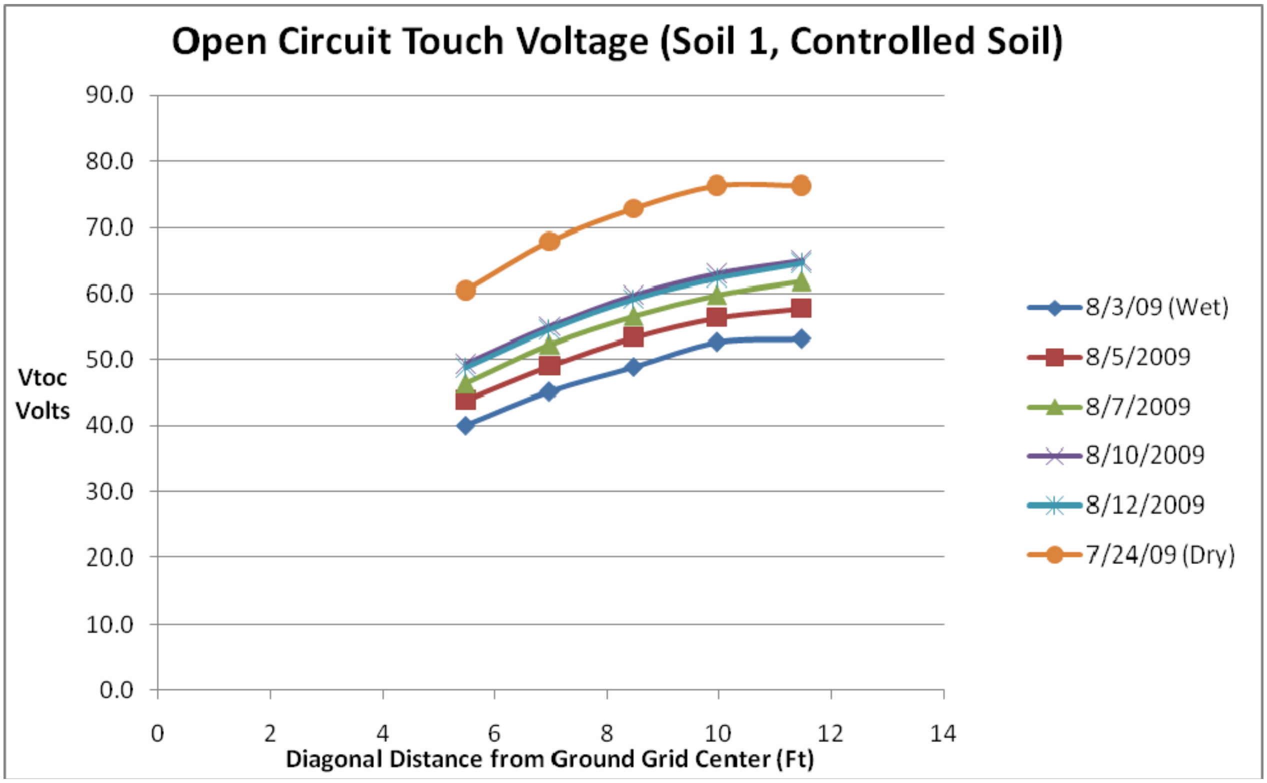

Figure 3-10
V_{toc} Measured on Soil 1 (Controlled Soil)

The following are some notable characterisitics of the pads and native soils in regard to open circuit touch voltages:

- For a given environmental condition, the highest voltages were measured on Pad 4 (no reinforcing, outside the grid) among the concrete pads and on Soil 2 among the two soil areas. This is due to their locations outside the ground grid area.
- The voltages increase as drying of pads and soils occur. The voltages on the concrete pads increase at a higher rate compared to those over the soil areas.
- For a given environmental condition, the voltages on Pad 1 (no reinforcing) and Pad 2 (rebars not grounded) are mostly higher compared to those on Soil 1 (controlled soil). The voltages on Pad 3 (ungrounded wire mesh) are close to those on Soil 1.
- In wet conditions, ungrounded rebars and wire meshes tend to equalize the voltages spatially (along the diagonal). In the process, the touch voltages are reduced in comparison with the pad having no reinforcement (Pad 1). As the concrete dries, the ungrounded rebars become less effective with the characterisitics similar to Pad 1. The voltage equalizing characterisitics of wire meshes remian the same.
- The voltages reduce significantly when the rebars or wire meshes are connected to the ground grid. Due to their close spacing, the wire meshes are more efficient in reducing these voltages. As an example, in wet conditions, the rebars reduced the voltages by 70% while the wire meshes reduced the voltages by 83%. As the concrete dries, the grounded rebars

become less effective and behave more like the pad without any reinforcement while grounded wire meshes continue their efficiency.

- Regardless of environmental conditions or grounding connection, the wire meshes due to their close spacing are much more effective in reducing and spatially equalizing the voltages compared to rebars. As the drying progresses, the ungrounded rebars behave the same way as the concrete with no reinforcement (Pad 1).

Open Circuit Step Voltages

Step voltages were calculated by taking a difference between the two touch voltages each three feet apart. Similar to touch voltage characteristics, the characteristics of open circuit step voltages over four concrete pads and two soil areas are shown in Figures 3-11 through 3-18. Figures 3-11 through 3-13 show the open circuit step voltages measured on 8/3/09 (wet), 8/12/09 (semi dry) and 7/24/09 (dry) respectively. Each figure contains six graphs, five for three concrete pads inside the ground grid area and one for controlled soil area, Soil 1. The graphs are:

- Pad 1: one graph since this pad does not include reinforcement
- Pad 2: one graph with the rebars ungrounded (i.e., not connected to the ground grid), and one graph with the rebars grounded (i.e., connected to the ground grid)
- Pad 3: one graph with the wire mesh ungrounded (i.e., not connected to the ground grid), and one graph with the wire mesh grounded (i.e., connected to the ground grid)

Figure 3-14 shows six graphs, three for Pad (no reinforcing, located outside the grid) 4 and three for the outside soil area, Soil 2.

To gain additional insight, the same data are presented differently in Figures 3-15 through 3-18.

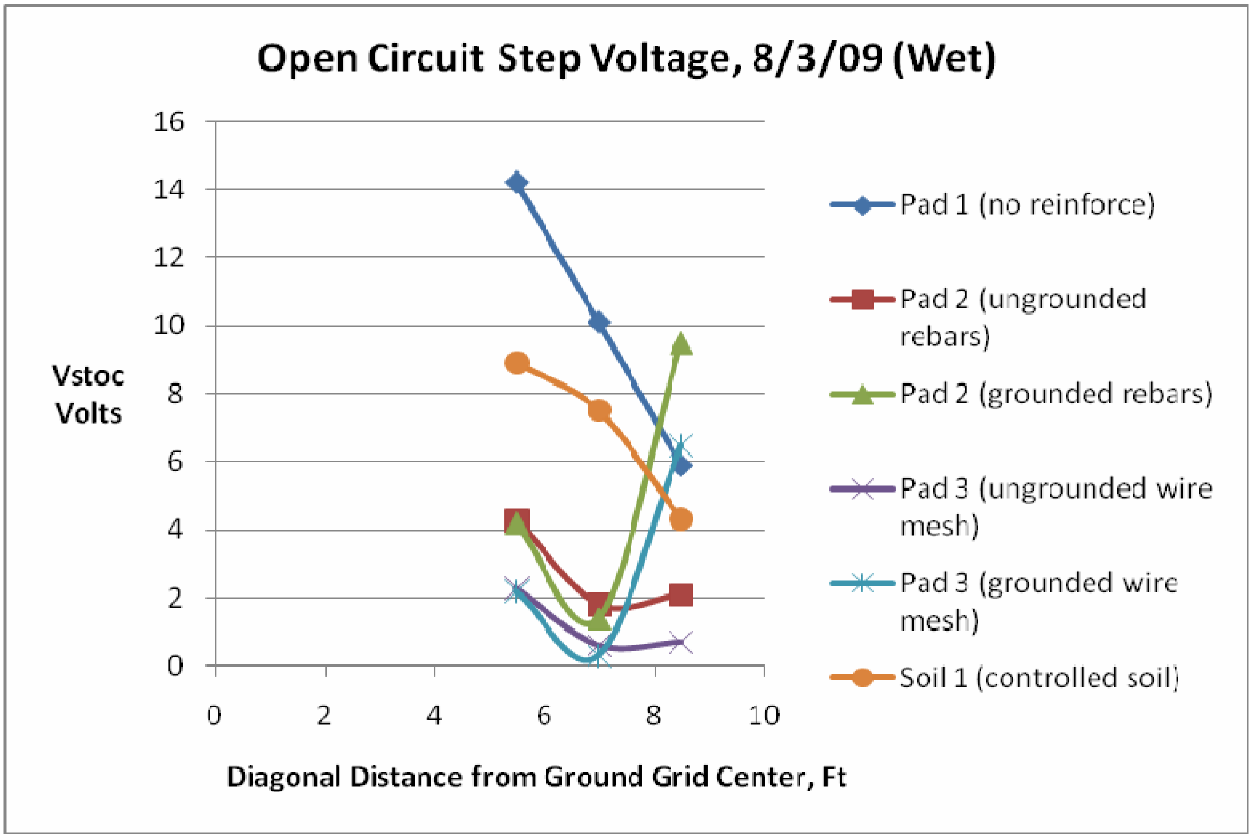

Figure 3-11
V_{stoc} Measured on 8/3/09 (Wet)

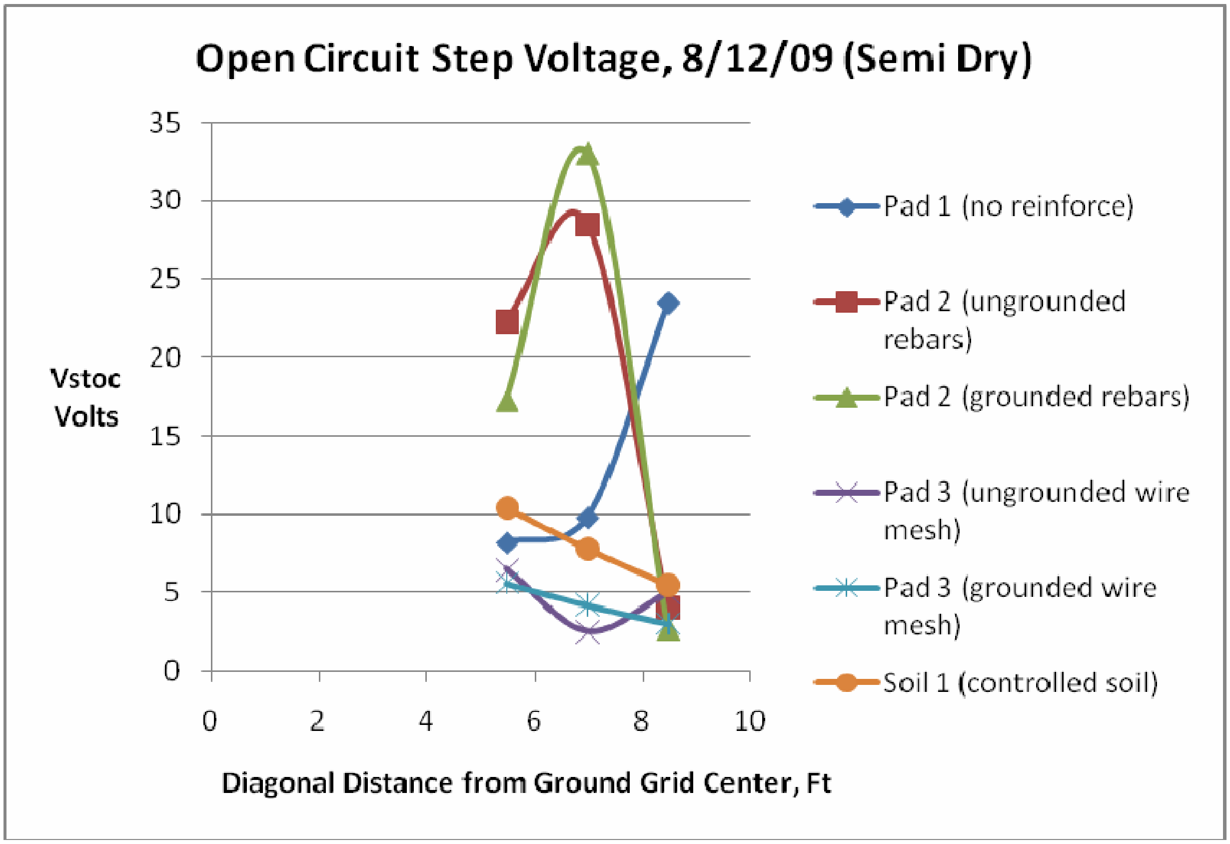

Figure 3-12
V_{stoc} Measured on 8/12/09 (Semi Dry)

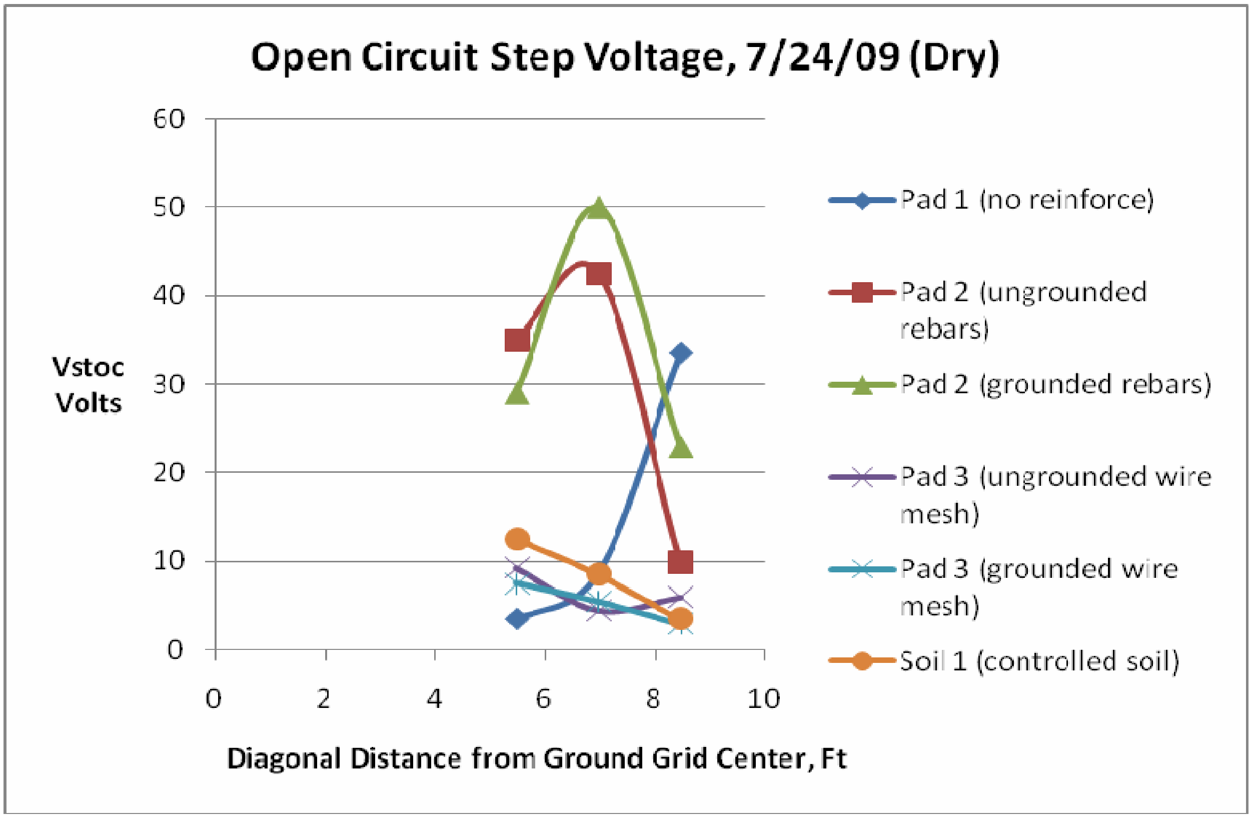

Figure 3-13
V_{stoc} Measured on 8/3/09 (Dry)

Figure 3-14 shows six graphs, three for Pad (no reinforcing, located outside the grid) 4 and three for the outside soil area, Soil 2.

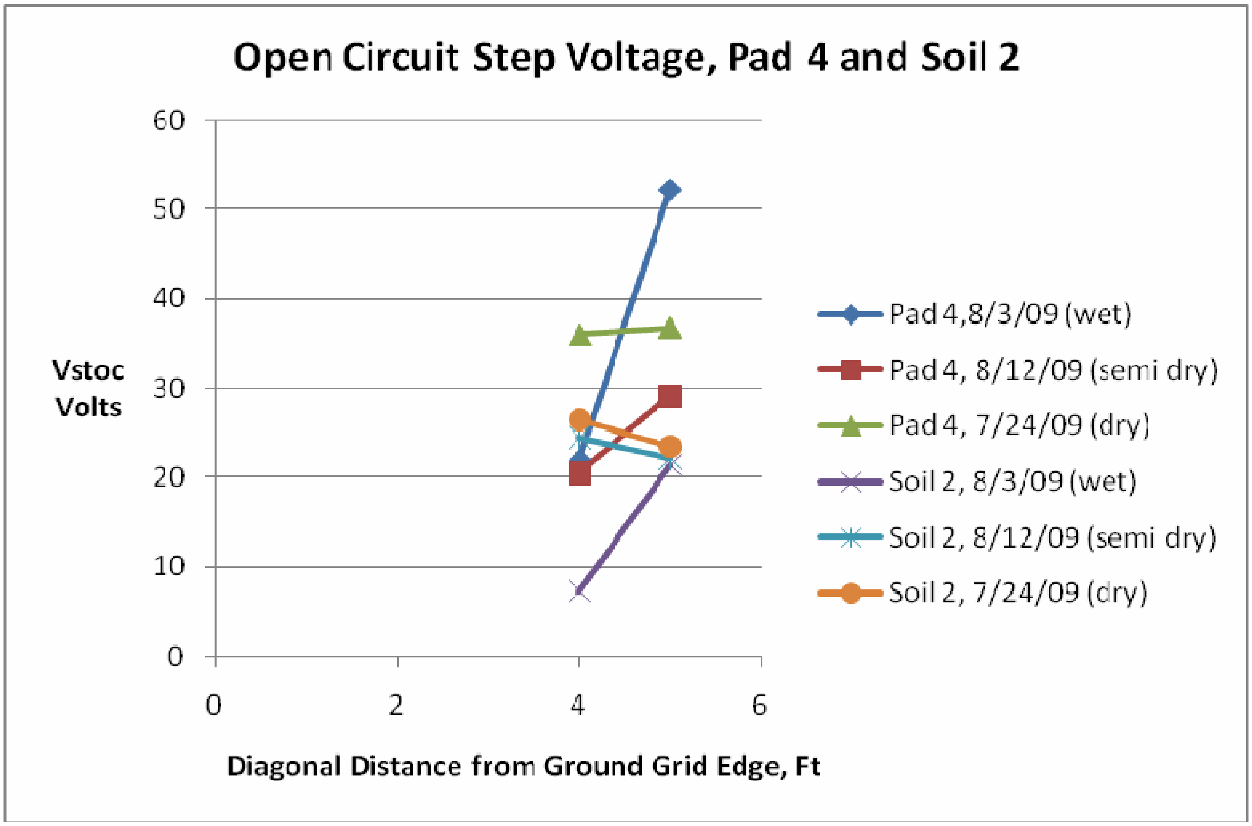

Figure 3-14
V_{stoc} Measured on Pad 4 & Soil 2

To gain additional insight, the same data are presented differently in Figures 3-15 through 3-18.

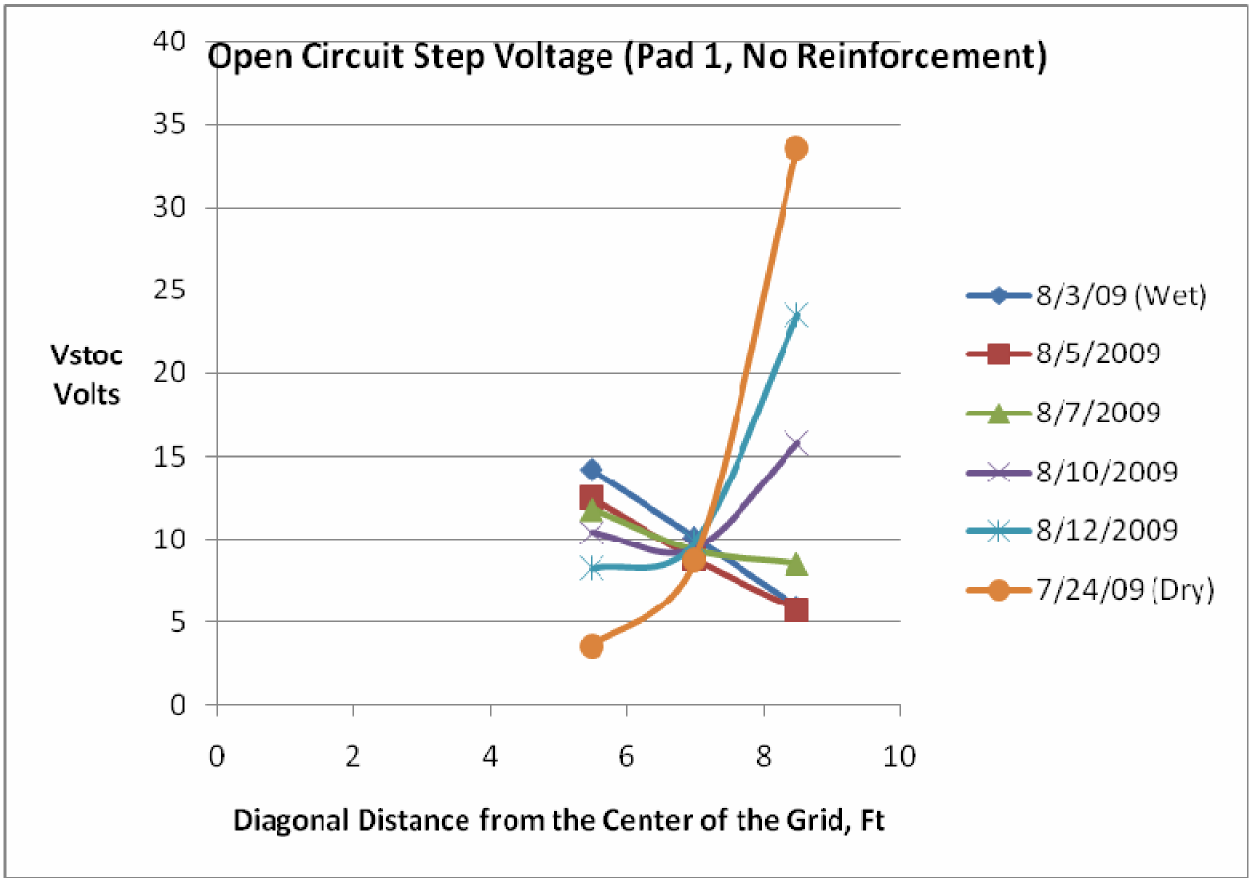

Figure 3-15
V_{stoc} Measured on Pad 1 (No Reinforcement)

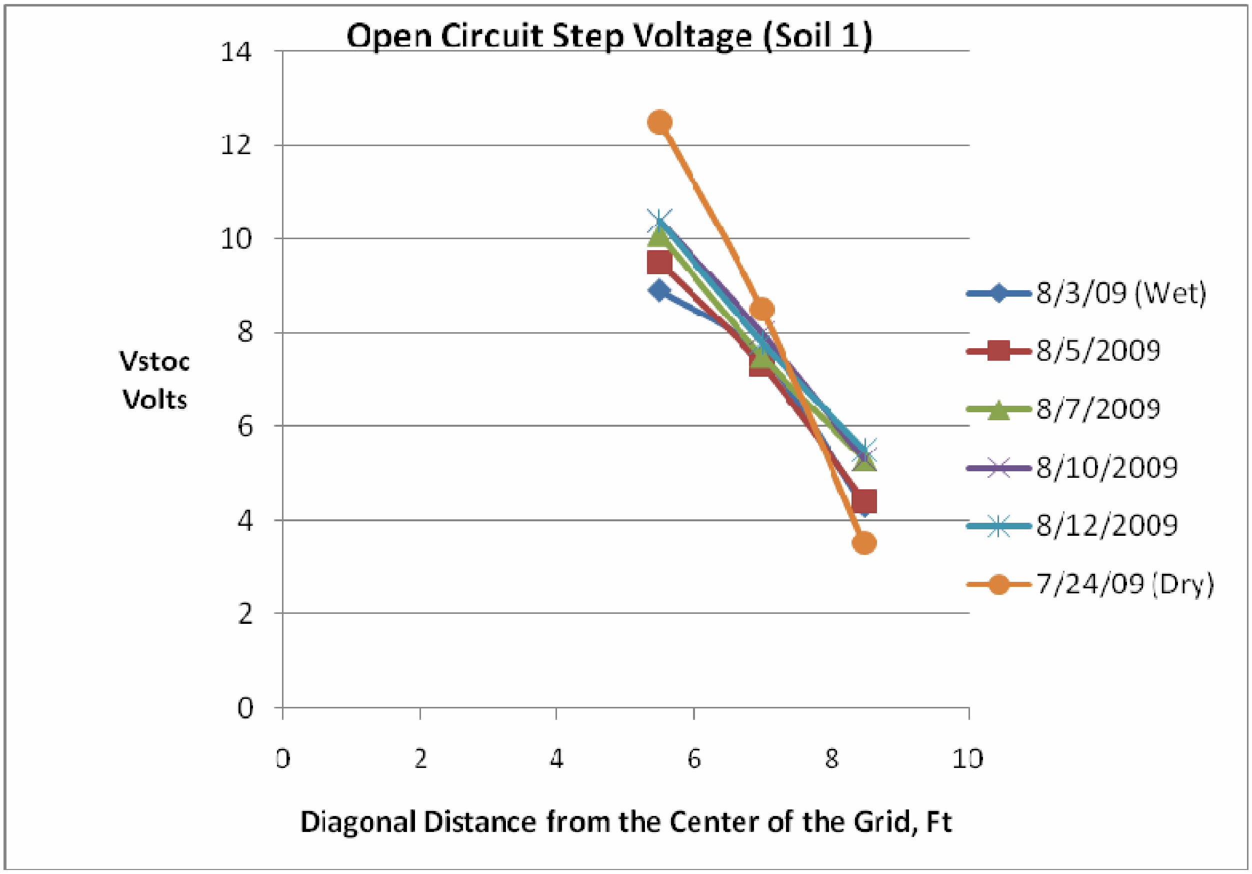

Figure 3-16
V_{stoc} Measured on Soil 1 (Controlled Soil)

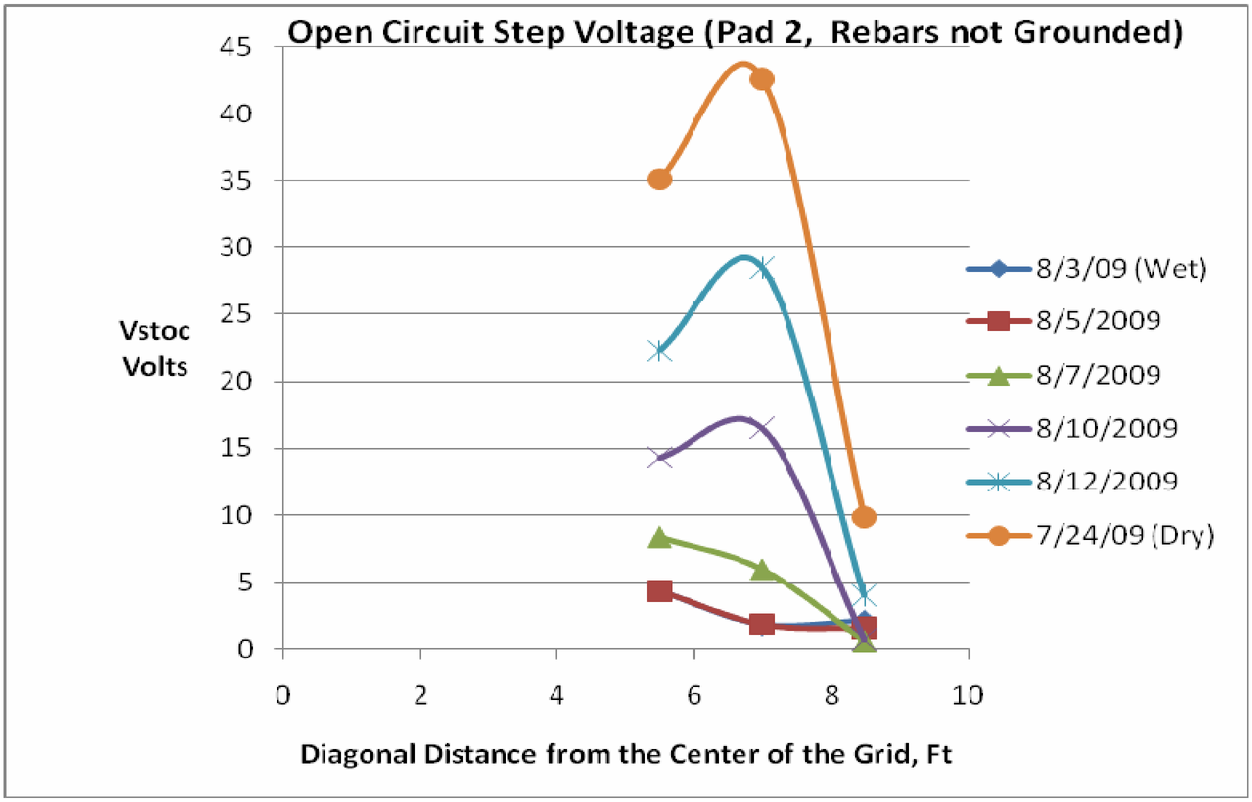

Figure 3-17
V_{stoc} Measured on Pad 2 (Ungrounded Rears)

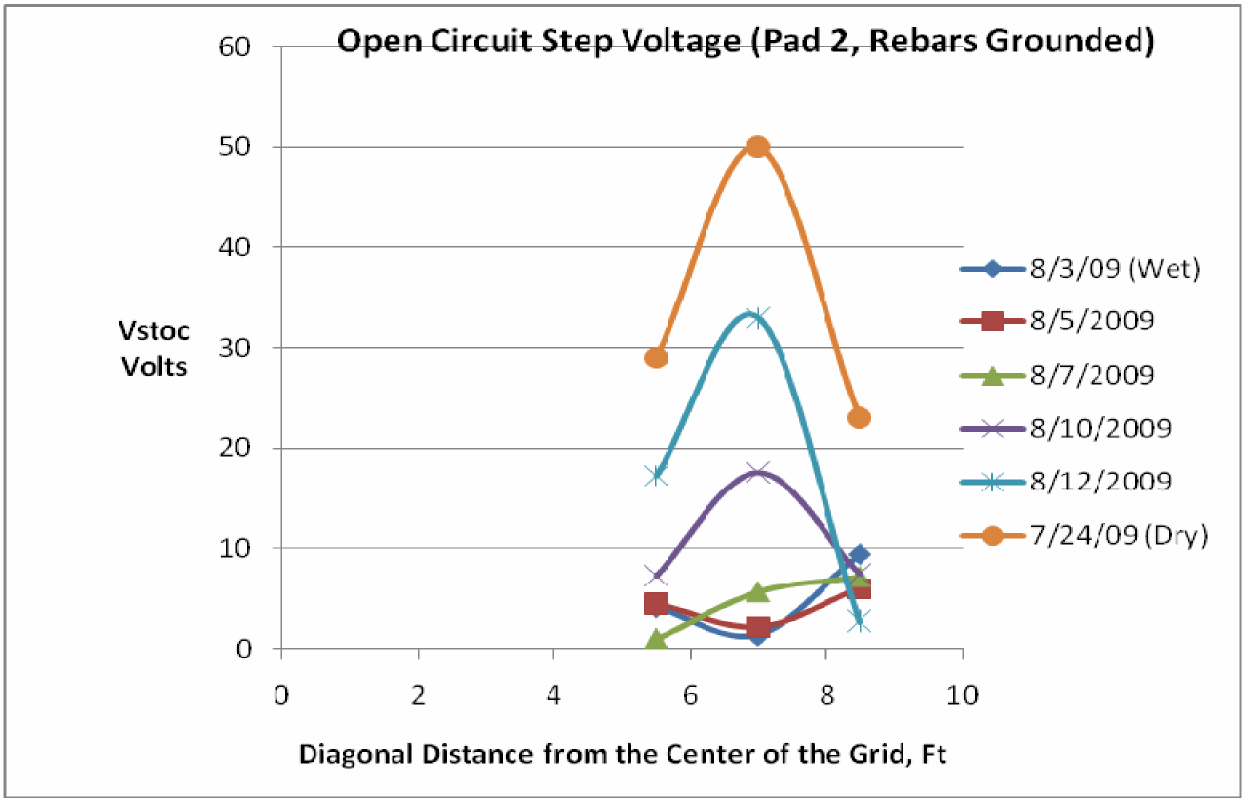

Figure 3-18
V_{stoc} Measured on Pad 2 (Grounded Rebars)

A summary of step voltage characteristics for pads and soils is provided below:

- The step voltages at all measured locations are lower than corresponding touch voltages.
- Similar to touch voltages, the step voltages increase as the concrete pads and soils continue to dry. However, this trend was not observed in the case of Pad 4.
- Unlike touch voltages, the step voltages are not reduced when rebars or wire meshes are connected to the grounding grid.
- In wet conditions, rebars and wire meshes reduce the voltages compared to those on the pad with no reinforcement (Pad 1). As the concrete dries, the rebars become less and less effective compared to wire meshes.

Exposure Currents or Closed Circuit Touch Voltages

Since the voltage value measured across the 1000 resistor (Volts) can represent the exposure current (I_{exp}) in mA units, it is convenient to assign two titles to the same value. Each exposure current value presented in this section is also titled "closed circuit touch voltage, V_{tcc}". The significance of a closed circuit touch voltage in determining the Thevenin's equivalent resistance has been explained in a earlier (Equation 2-5).

The bar charts in Figures 3-19 through 3-26 present the exposure current data for Pad 1 (no reinforcing), Soil 1, Pad 2 (ungrounded rebars), Pad 2 (grounded rebars), Pad 3 (ungrounded wire mesh), Pad 3 (grounded wire mesh), Pad 4 (no reinforcing, outside the grid) and Soil 2 respectively.

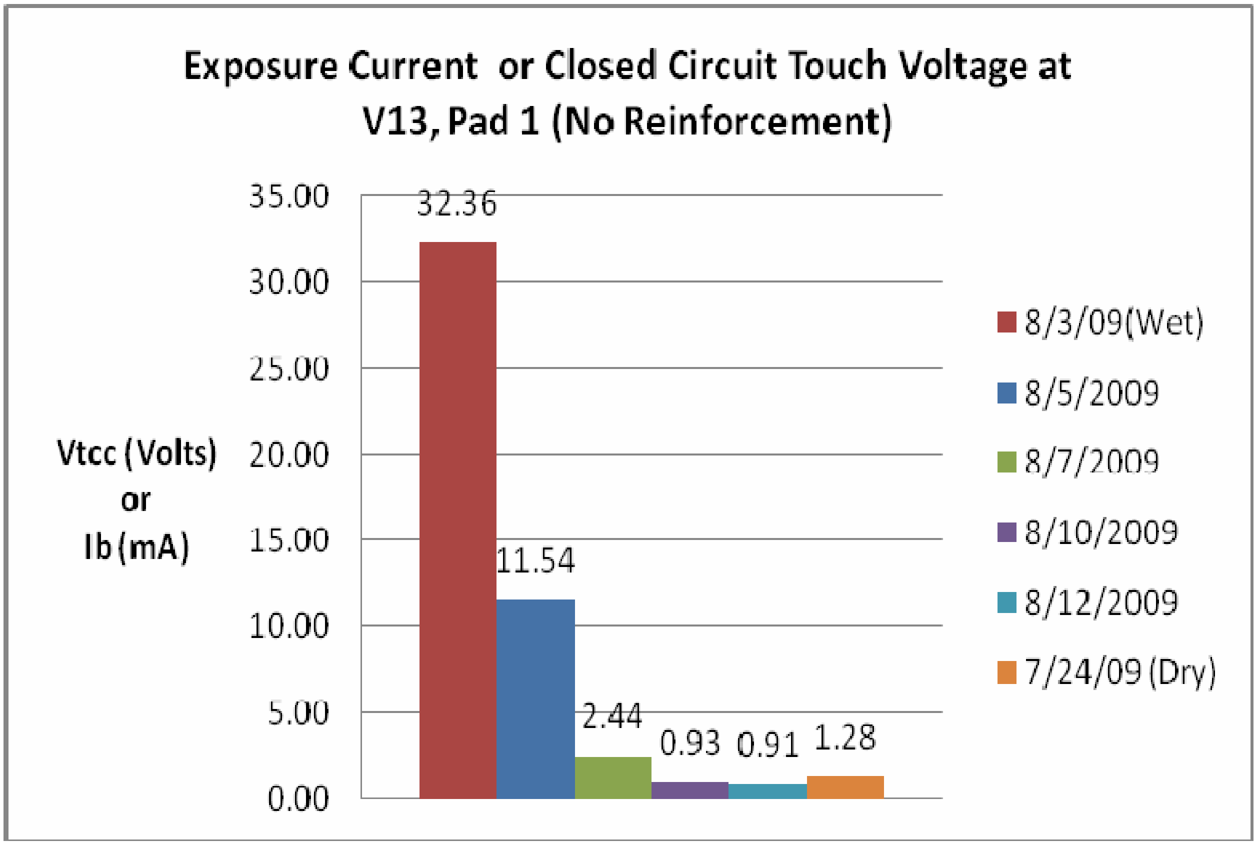

Figure 3-19
I_{exp} on Pad 1 (No Reinforcing)

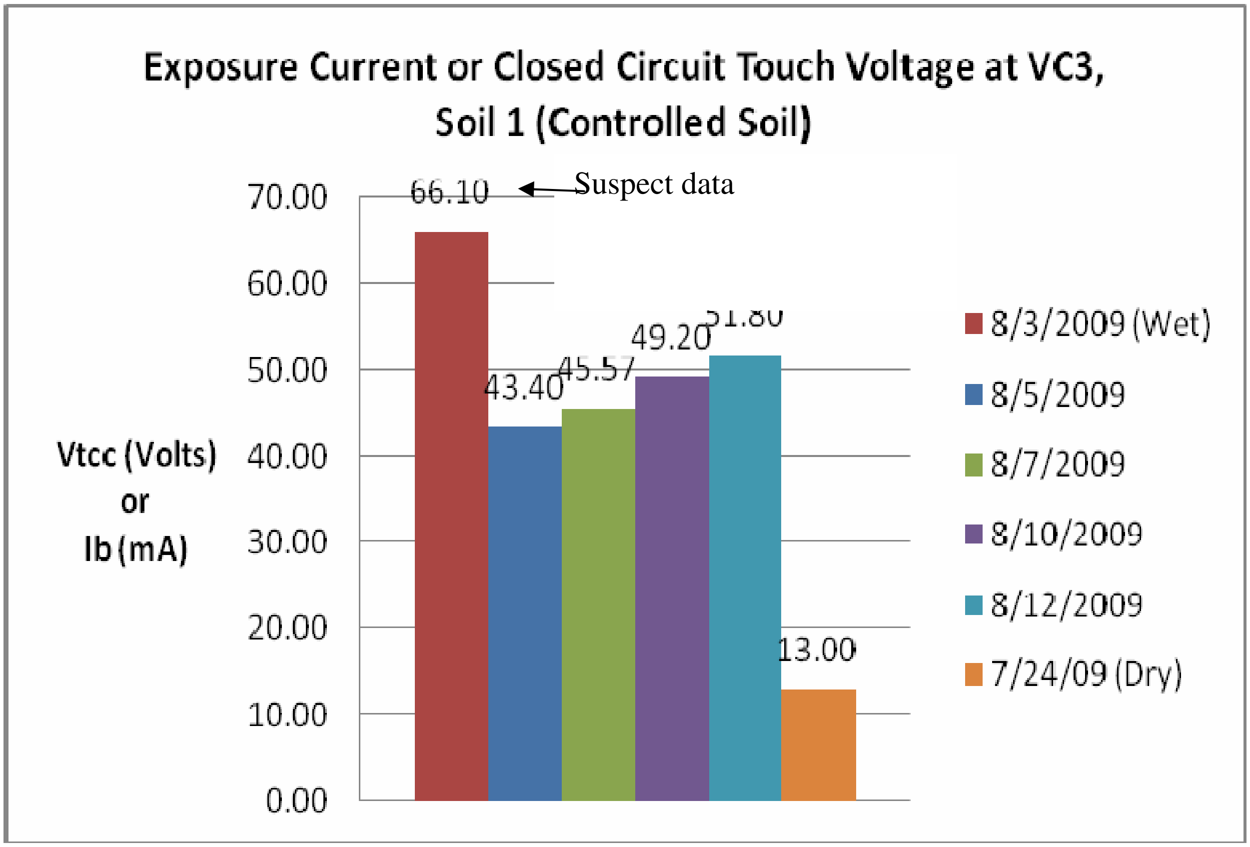

Figure 3-20
I_{exp} on Soil 1 (Controlled soil)

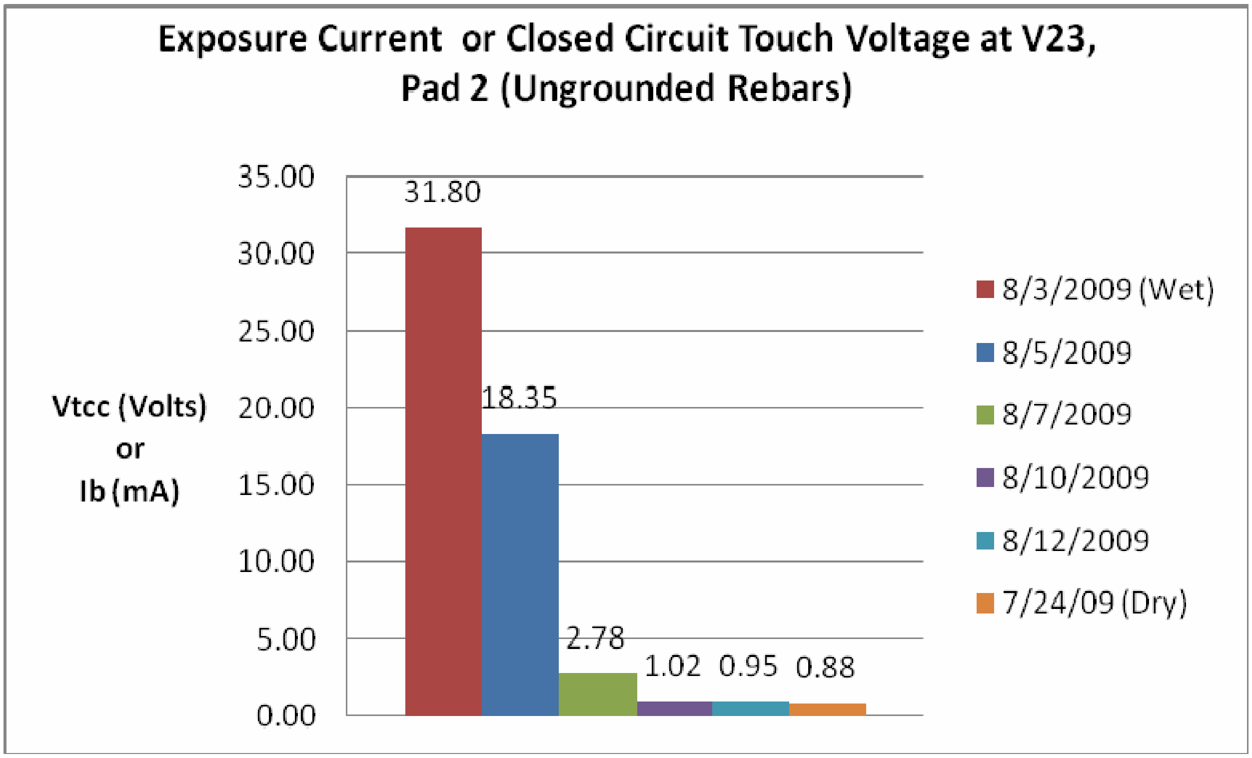

Figure 3-21
I_{exp} on Pad 2 (Ungrounded Rebars)

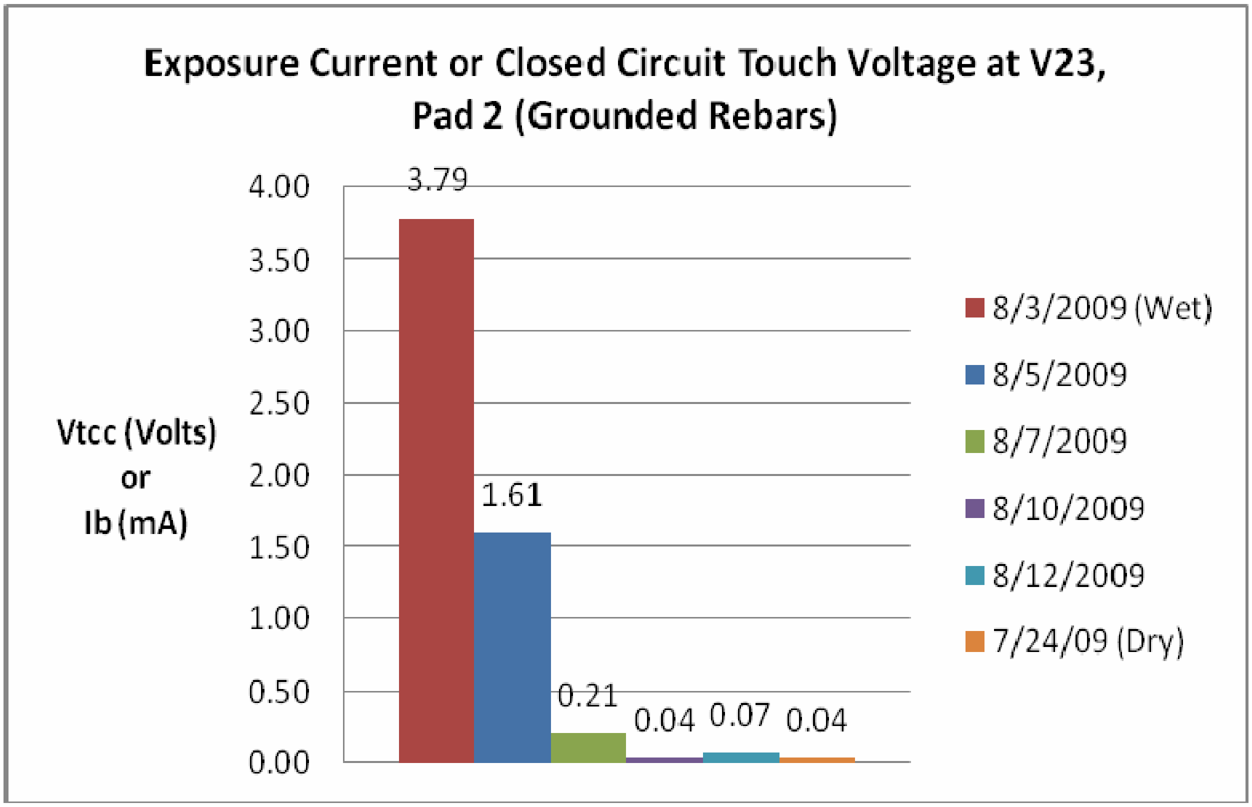

Figure 3-22
I_{exp} on Pad 2 (Grounded Rebars)

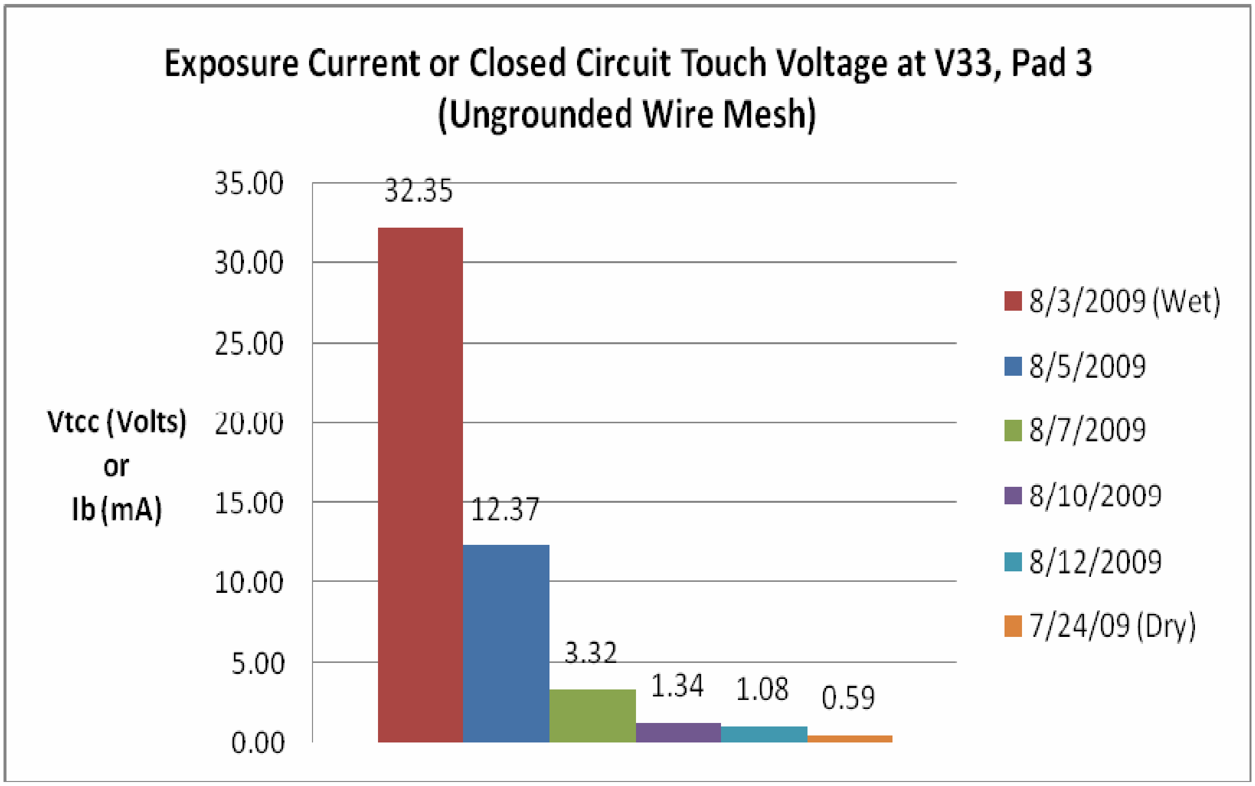

Figure 3-23
I_{exp} on Pad 3 (Ungrounded Wire Mesh)

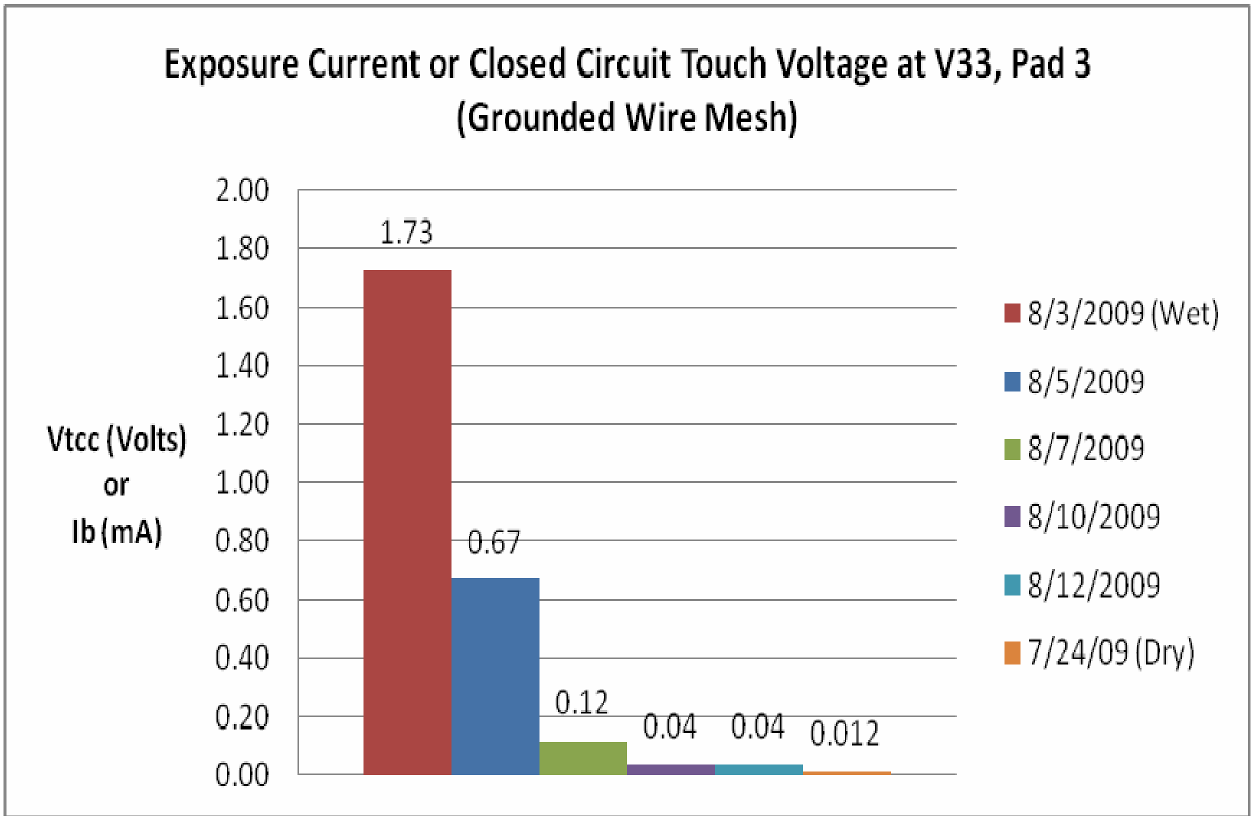

Figure 3-24
I_{exp} on Pad 3 (Grounded Wire Mesh)

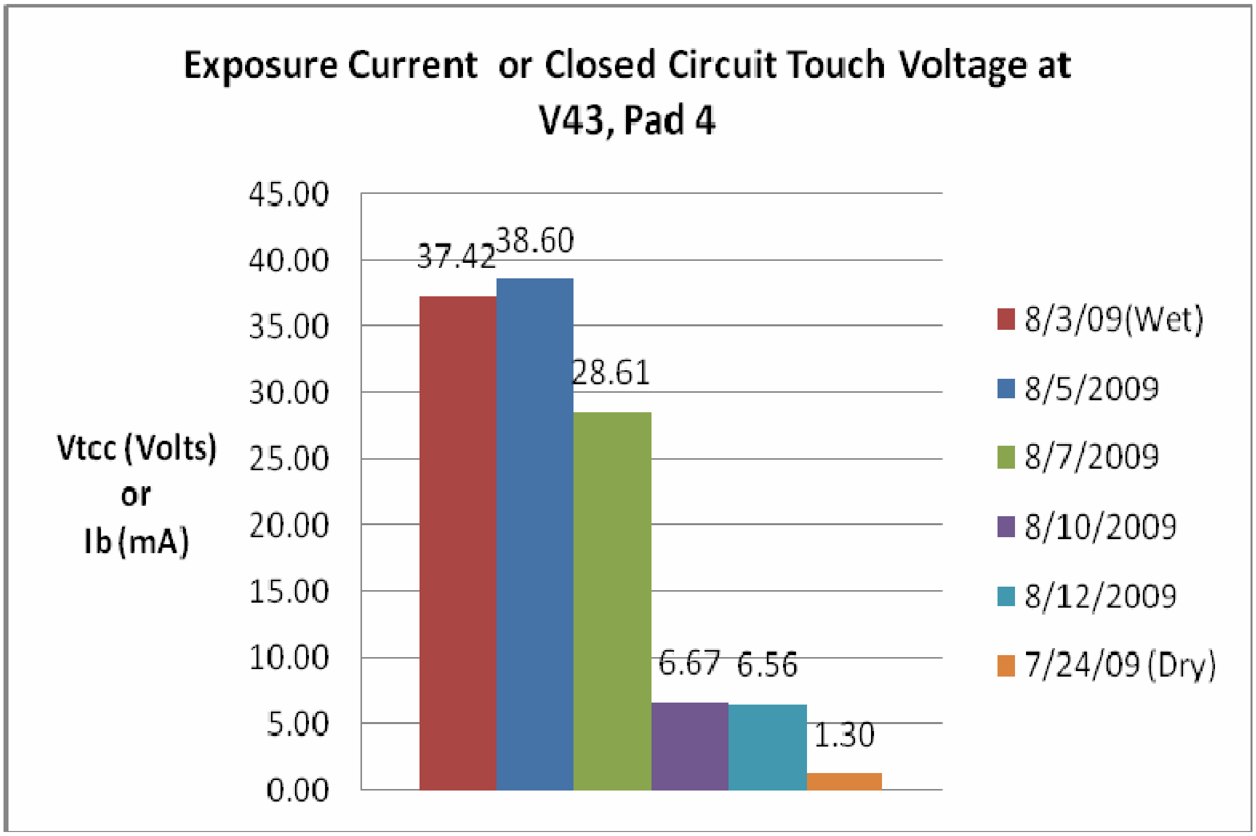

Figure 3-25
I_{exp} on Pad 4 (No reinforcing, Outside the Grid)

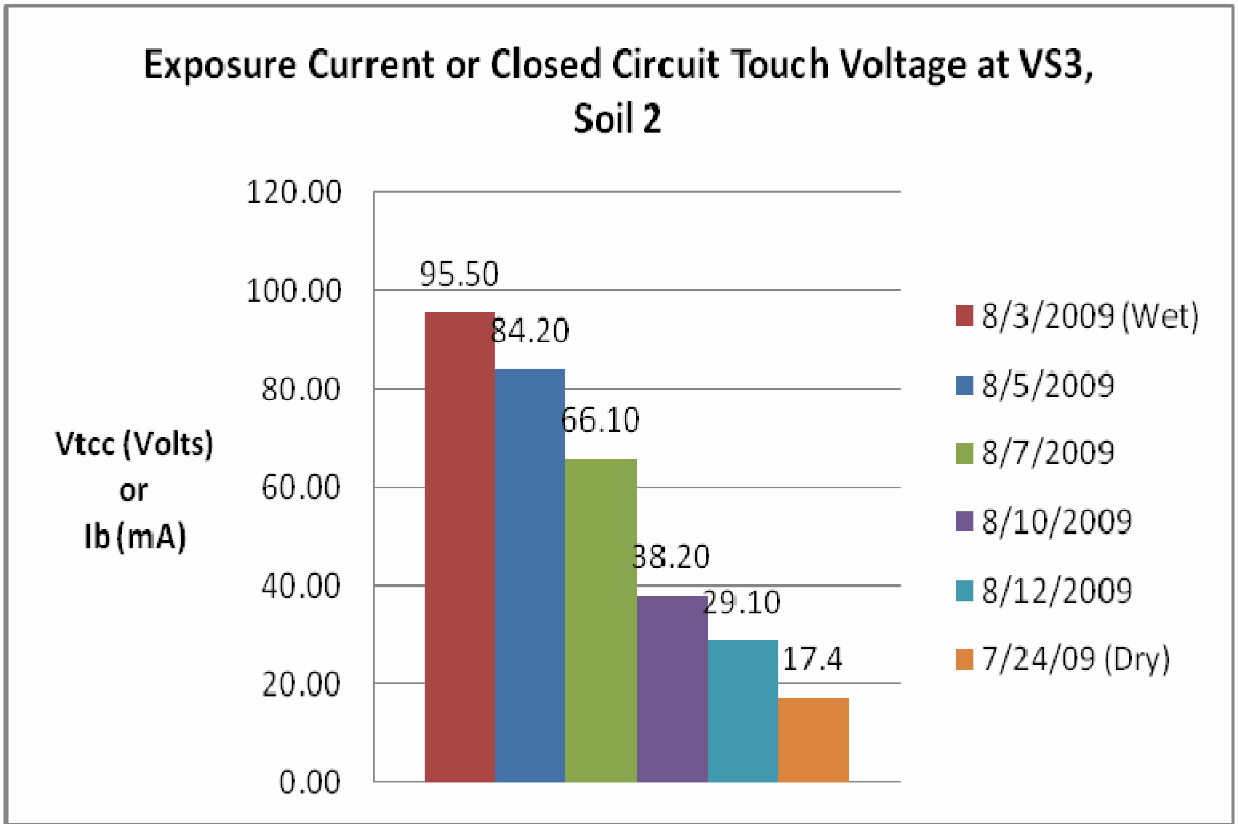

Figure 3-26
I_{exp} on Soil 2

The following observations are made from the exposure current data presented in Figures 3-19 through 3-26:

- Caution should be exercised in interpreting the data for Soil 1 (Figure 3-20). A plastic cover was placed over the Soil 1 area on 7/24/09 prior to wetting. From that time on, the plastic cover was removed only during the measurements. During each measurement period, significant condensation was observed as a result of placing the plastic cover over the Soil 1 area. This condensation on the surface seems to be responsible for relatively constant exposure current data measured between 8/3/09 and 8/12/09. However, the exposure current measured prior to covering showed a significant reduction (7/24/09, dry). On another note, a comparison between the open and closed circuit touch voltage values measured on 8/3/09 (49 V vs. 66 V) indicated that the closed circuit touch voltage data (66 V) might have been an error.
- Between wet and dry conditions, the wet condition (8/3/09) causes the maximum exposure current at each location. However, in the case of Pad 4 (no reinforcing, outside the grid), the current measured on 8/5/09 slightly exceeded the current measured on 8/3/09 (Figure 3-25).
- The exposure currents reduce at a dramatic rate as the concrete continues to dry. For example, in the case of Pad 1 (no reinforcement), Pad 2 (rebars grounded or ungrounded) and

Pad 3 (wire mesh grounded or ungrounded), the currents reduced almost by a couple orders of magnitudes between 8/3/09 (wet) and 7/24/09 (dry).

- Ungrounded rebars or wire meshes have little influence on exposure currents. However, grounding of rebars and wire meshes reduces the exposure current significantly. For example, in wet condition, grounding of rebars reduced the exposure current from 31.8 mA to 3.8 mA. The wire meshes being more efficient, the current reduced from 32.4 mA to 1.7 mA.
- Overall, the exposure currents are higher on soil areas compared to concrete locations. Also, as drying occurs, the exposure currents reduce at a much slower rate compared to concrete areas.

Thevenin's Equivalent Resistance

Measuring resistivity in different environmental conditions may not be sufficient to characterize a surfacing material such as concrete. For example, the four-pin data did not show any significant change in resistivity as the concrete dried and yet there were substantial reductions in exposure currents due to drying. As concrete dries, a highly resistive layer is quickly formed on the surface. To account for this layer, a concrete block must be tested using the "Volume Resistivity Method". Another way to characterize concrete including any surface stratification is to determine the Thevenin's equivalent resistance by measuring open and closed circuit touch voltages as presented in earlier (Equation 2-5)

The bar charts in Figures 3-27 through 3-34 show the Thevenin's equivalent resistances for Pad 1 (no reinforcing), Soil 1, Pad 2 (ungrounded rebars), Pad 2 (grounded rebars), Pad 3 (ungrounded rebars), Pad 3 (grounded rebars), Pad 4 (no reinforcing, outside the grid) and Soil 2 respectively.

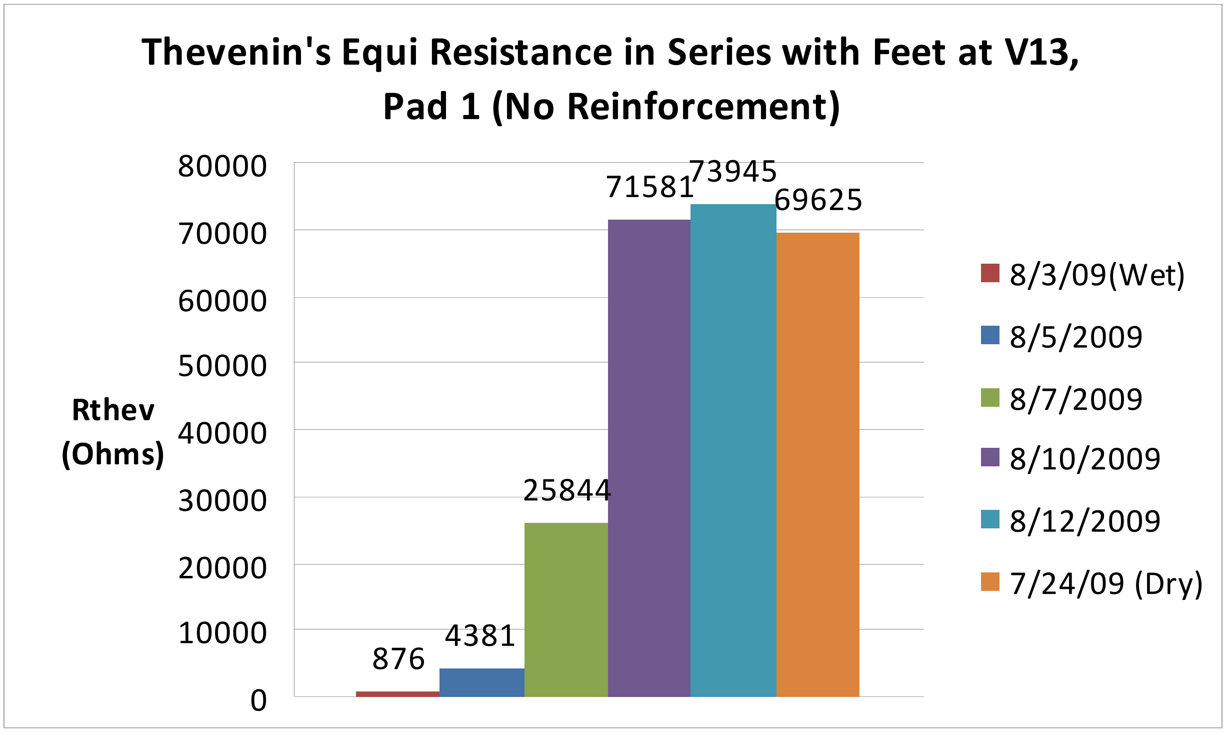

Figure 3-27
R_{thev} on Pad 1 (No Reinforcing)

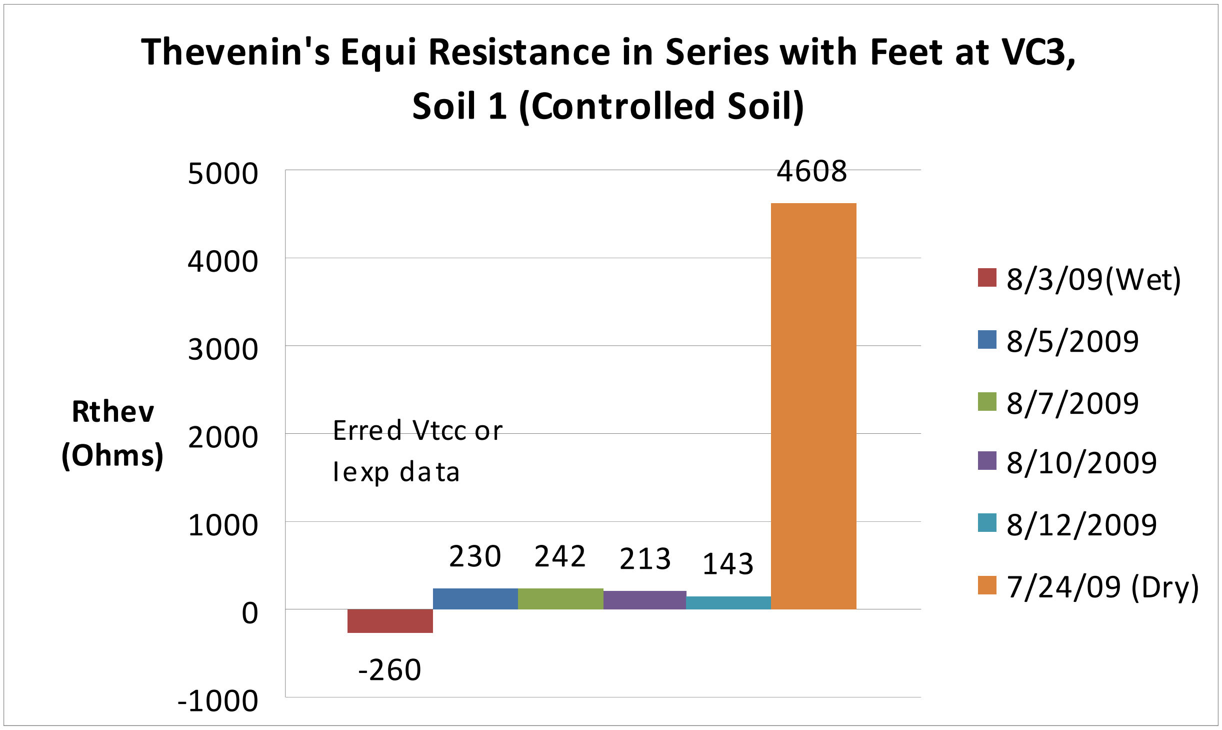

Figure 3-28
I_{exp} on Soil 1 (Controlled Soil)

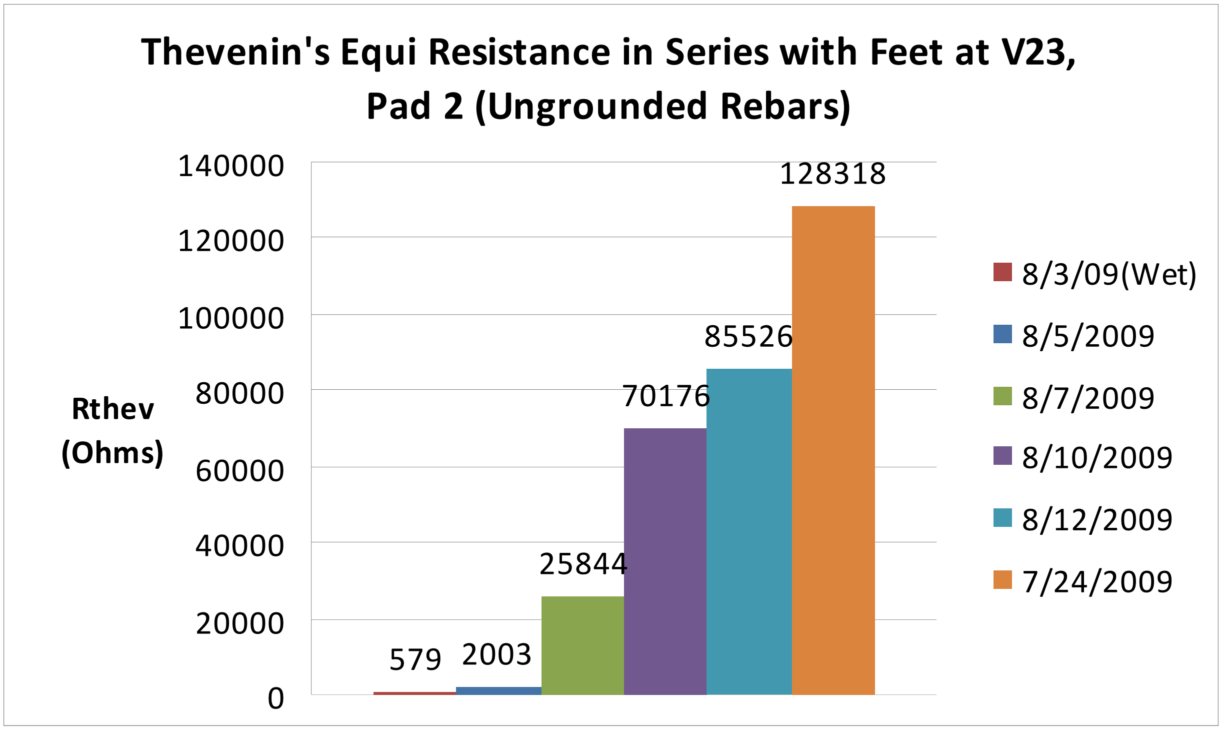

Figure 3-29
R_{thev} on Pad 2 (Ungrounded Rebars)

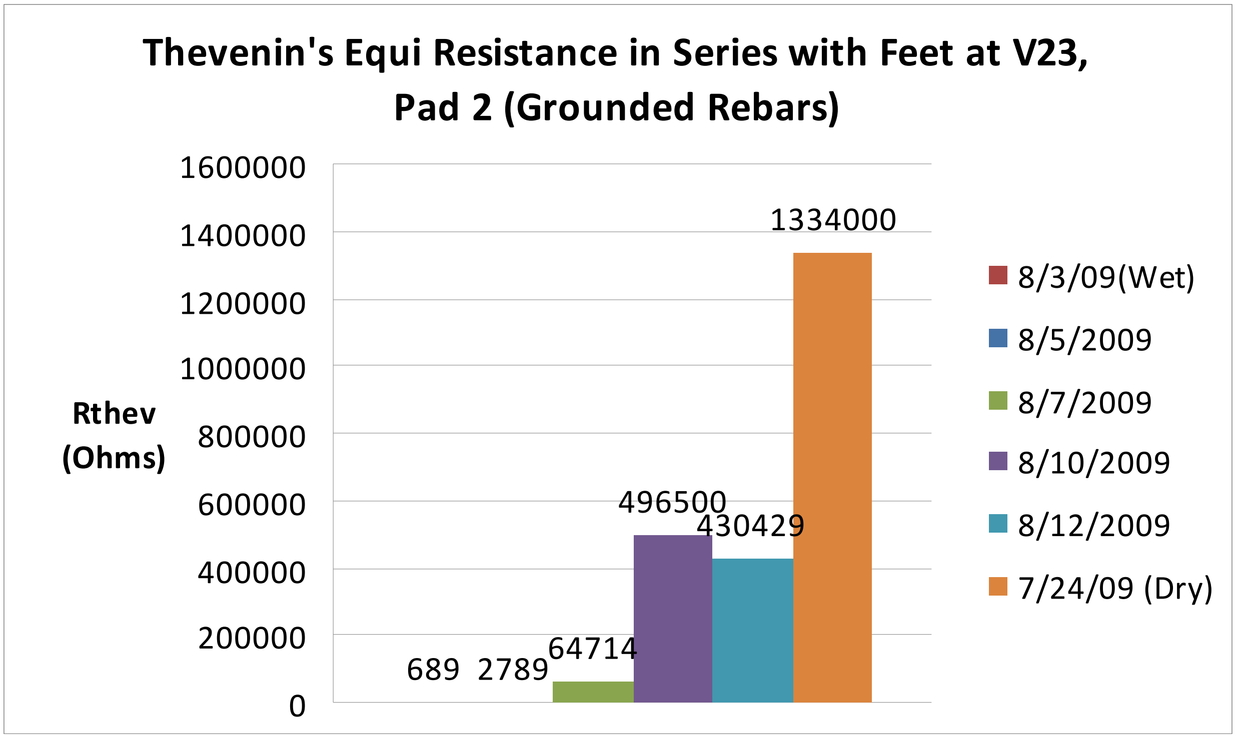

Figure 3-30
R_{thev} on Pad 2 (Grounded Rebars)

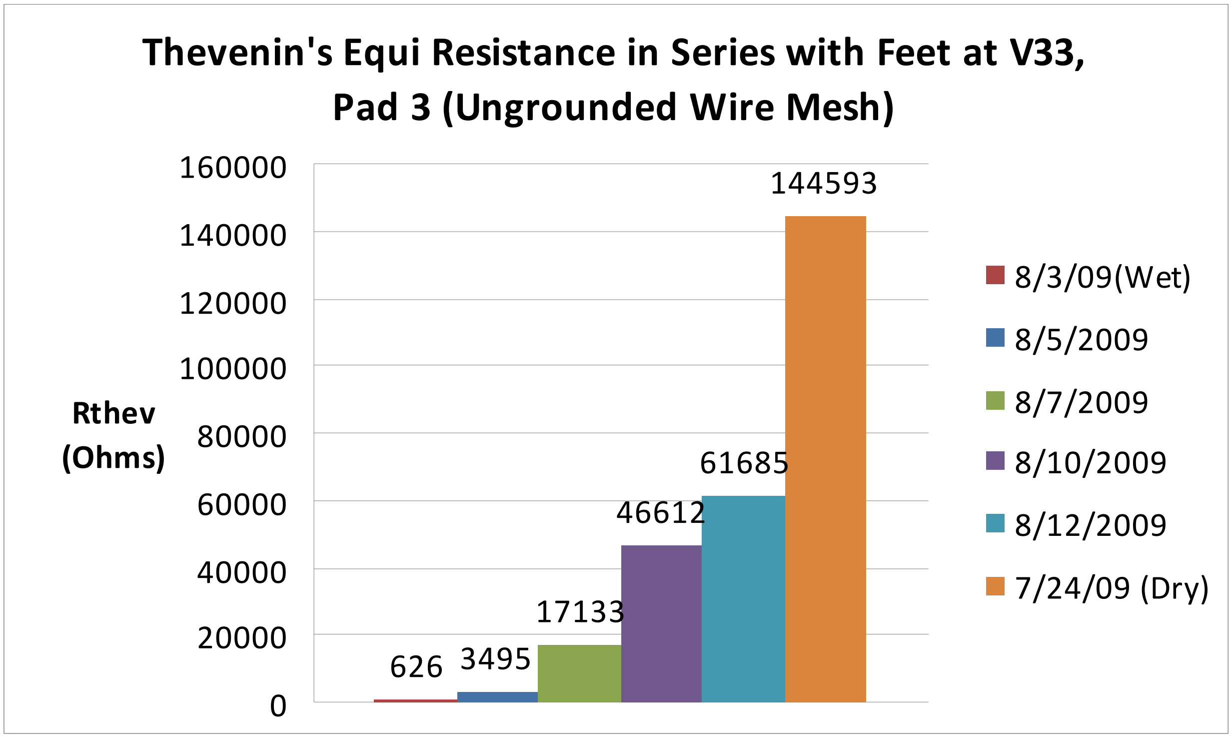

Figure 3-31
R_{thev} on Pad 3 (Ungrounded Wire Mesh)

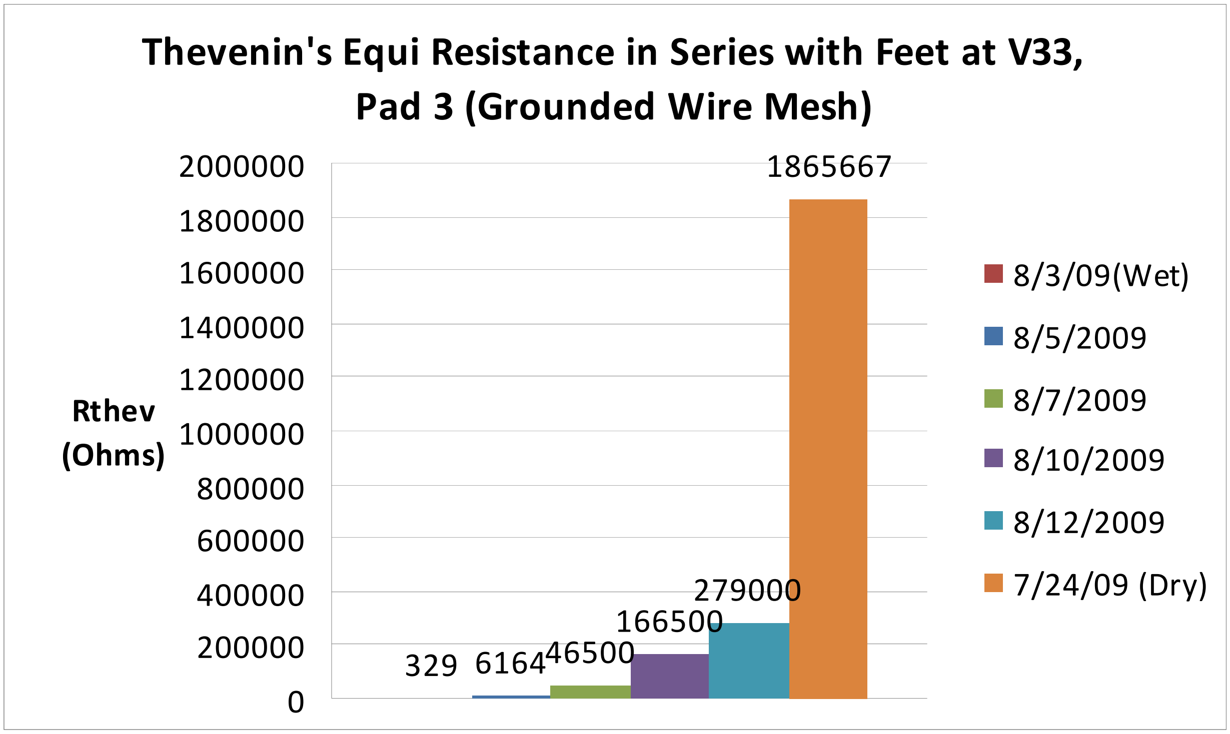

Figure 3-32
R_{thev} on Pad 3 (Grounded Wire Mesh)

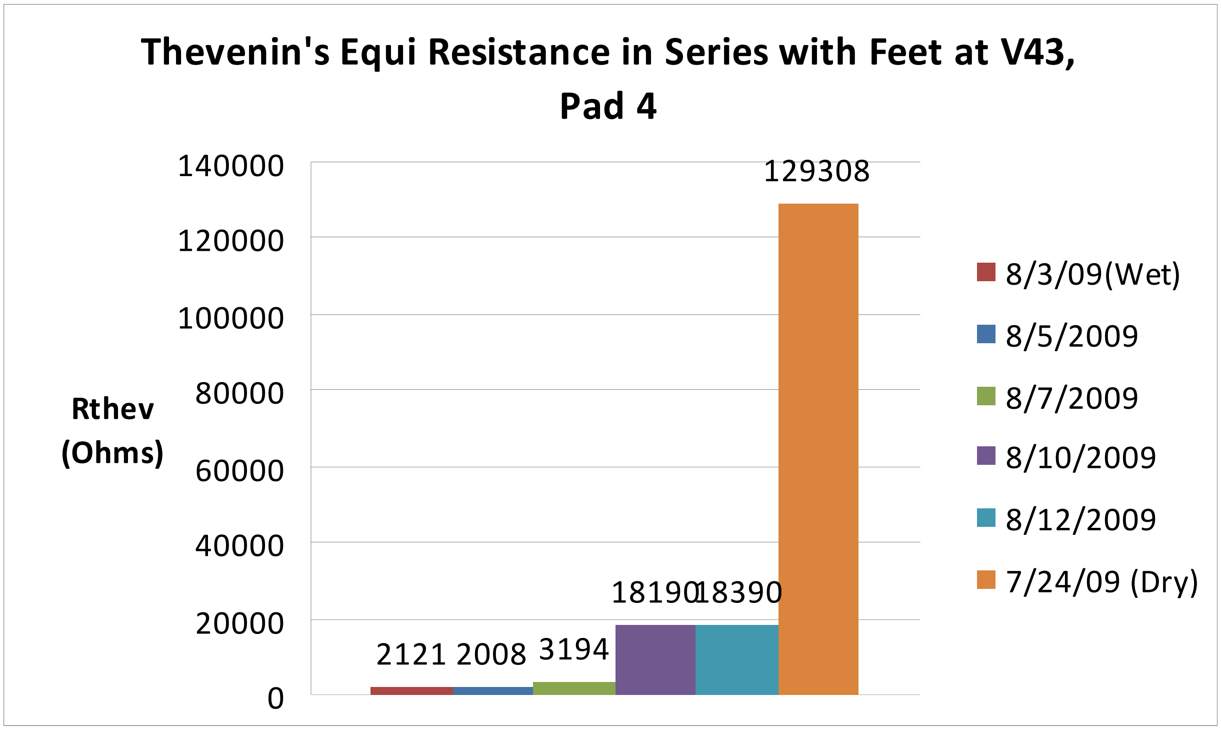

Figure 3-33
R_{thev} on Pad 4 (No Reinforcing, Outside the Grid)

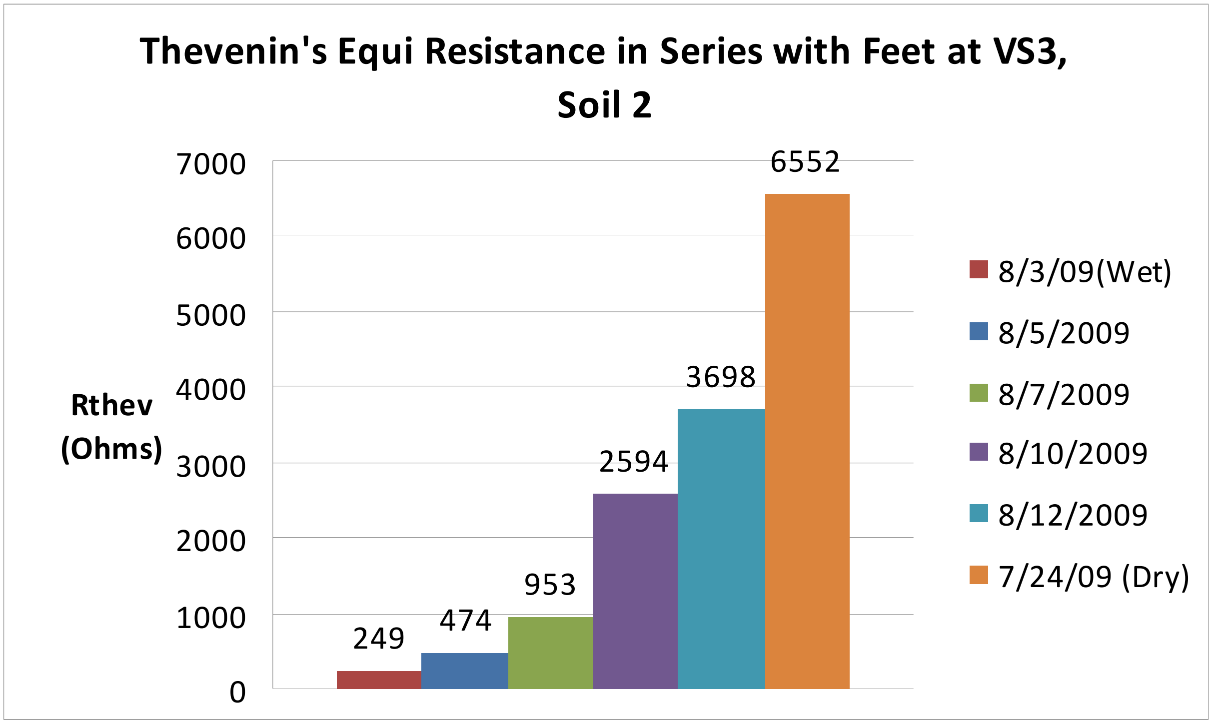

Figure 3-34
R_{thev} on Soil 2

The following observations are made from Thevenin's equivalent resistance data presented in Figures 3-27 through 3-43:

- The same caution as mentioned for exposure currents should be exercised in interpreting the data for Soil 1 (Figure 3-28). A plastic cover was placed over the Soil 1 area on 7/24/09 prior to wetting. From that time on, the plastic cover was removed only during the measurements. During each measurement period, significant condensation was observed as a result. This condensation on the surface seems to be responsible for relatively constant resistance data measured between 8/3/09 and 8/12/09. On another note, the negative value shown for the date 8/3/09 is due to the erroneous closed circuit touch voltage data shown in Figure 3-20.
- Except for Pad 4 (no reinforcing, outside the grid), the wet condition of 8/3/09 caused the minimum resistances in series with the feet. In the case of Pad 4 (Figure 3-33), the resistance calculated for 8/5/09 was slightly less than that during wet conditon (8/3/09).
- The Thevenin's resistances increase at a dramatic rate as the concrete dries. For example, in the case of Pad 1 (no reinforcement), the resistance increased from 876 (wet) to 69,625 (dry).
- Pads with ungrounded rebars or wire meshes do not show a definite advantage over the pad with no reinforcement. However, the influence of grounded rebars and wire meshes is mostly to increase the resistances in series with the feet.

- Overall, the Thevenin's resistances are lower for the soil areas compared to concrete locations. Also, as drying occurs, the resistances increase at a much slower rate compared to concrete areas.

4

CONCLUSIONS

The following can be concluded from this project:

General

- The conductivity of concrete is highly dependent upon the water content of the concrete and can vary significantly over time.
- The resistivity values of different regions of the same concrete pad vary widely. Exposed regions of concrete dry quickly with high values of resistivity while interior regions may have much lower values.
- During the course of six sets of measurements, the ground potential rise (GPR) varied from 318.3 V to 357.5 V. The ground grid current varied from 21.87 A to 22.77 A.

Concrete and Soil Resistivity

- Overall, the resistivity values for the concrete pad declined with the increase in the pin spacing. The environmental changes seem to influence the surface layer (2" spacing) the most where the spread between the highest and lowest resistivity is almost 45%. This spread is about 23 % at 12" pin spacing mostly due to the influence of the soil below Pad 4 (no reinforcing, outside the grid).
- During the drying process, a thin layer of high resistivity is quickly formed on top of the concrete pad. The four-pin method with anchored pins (3/4" deep) is inefficient in accounting for this layer except in highly wet conditions. This is of practical significance because the presence or absence of the insulating layer, due to dry or wet concrete, will dramatically affect the available exposure current during a fault. As an example, the concrete resistivity as measured with the four-pin method changed from 196 ohm-meters wet to 264 ohm-meters dry. At the same time, the measured exposure current changed from 32.4 mA wet to 1.3 mA dry.
- Overall, the soil resistivity increased with increasing spacing or soil depth. An equivalent two layer model consists of a bottom layer having a resistivity of 1,244 ohm-meters in comparison with 195 ohm-meters for the top layer. It is interesting to note that the wet resistivity value of the concrete is nearly the same as that of the top layer.

Open Circuit Touch Voltage

- The open circuit touch voltages increase as drying of pads and soils occurs. The voltages on the concrete pads increase at a higher rate compared to those over the soil areas. For example, the voltage increases from 66.6 V (wet) to 124 V (dry) in the case of Pad 1 (no reinforcement) and from 53.2 V (wet) to 76.4 V (dry) in the case of Soil 1 (controlled soil).
- In wet conditions, ungrounded rebars and wire meshes tend to equalize the voltages spatially (along the diagonal). In the process, touch voltages are reduced in comparison with the pad having no reinforcement. As the concrete dries, the ungrounded rebars become less effective

with the characterisitics similar to the pad having no reinforncement. The voltage equalizing characterisitics of wire meshes remain the same.

- The open circuit voltages reduce significantly when the rebars or wire meshes are connected to the ground grid. Due to their close spacing, wire meshes are more efficient in reducing these voltages. As an example in wet conditions, the rebars reduced the voltages by 70% while the wire meshes reduced the voltages by 83%. As the concrete dries, the grounded rebars become less effective and behave more like the pad without any reinforcement while grounded wire meshes continue their effectiveness.

Open Circuit Step Voltage

- The step voltages at all measured locations were lower than corresponding touch voltages. Their magnitudes also increase as the concrete pads and soils continue to dry.
- Unlike touch voltages, step voltages are not reduced when rebars or wire meshes are connected to the grounding grid.
- In wet conditions, rebars and wire meshes reduce the voltages compared to those on the pad with no reinforcement (Pad 1). As the concrete dries, rebars become less and less effective compared to wire meshes.

Exposure Current or Closed Circuit Voltage

- The wet condition causes the maximum exposure current for both concrete and soil.
- The exposure currents reduce at a dramatic rate as the concrete dries. For example, in the case of Pad 1 (no reinforcement), the current reduced from 32.4 mA (wet) to 1.3 mA (dry).
- Ungrounded rebars or wire meshes have little influence on exposure currents. However, grounding of rebars and wire meshes reduces the exposure current significantly. For example, grounding of rebars reduced the exposure current from 31.8 mA to 3.8 mA for the wet condition. The wire meshes being more effective, reduced the current from 32.4 mA to 1.7 mA.
- Overall, the exposure currents are higher for the soil areas compared to concrete locations. Also, as drying occurs, the exposure currents reduce at a much slower rate compared to concrete areas.

Thevenin's Equivalent Resistance

- The wet condition causes the minimum Thevenin's resistance in series with the feet for both concrete and soil.
- The Thevenin's resistances increase at a dramatic rate as the concrete dries. For example, in the case of Pad 1 (no reinforcement), the resistance increased from 876 (wet) to 69,625 (dry).
- Pads with ungrounded rebars or wire meshes do not show a definite advantage over the pad with no reinforcement. However, grounding of rebars and wire meshes mostly increases the resistances in series with the feet.
- Overall, the Thevenin's resistances are lower for the soil areas compared to concrete locations. Also, as drying occurs, the resistances increase at a much slower rate compared to concrete areas.

- The Thevenin's resistance values determined in this project may be used for determining tolerable touch voltages for concrete applications in substations. For example, if a conservative design is desired, an average value may be determined from wet (8/3/09) Pad 1 (no reinforcement) , Pad 2 (ungrounded rebars) and Pad 3 (ungrounded wire meshes) resistance values and equated to the resistivity of the concrete as shown in Equation 4-1[9].

  $$R_{thev\ (av)} = 1.5 \quad _{concrete}$$ **Equation 4-1**

  For less conservative designs, the values from the 8/5/09 charts may be selected.

5
EQUIPMENT USED

Volt-ohmmeter: Fluke 87, CQ4020

Fluke Amprobe 3000, CQ-4021

Soil Resistivity: AEMC CQ-4026

6
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A

MEASURED AND CALCULATED DATA SHEETS

Figure A-1 shows the measured variable and their locations.

Table A-1 contains the raw measured data (see Figure A-1 for location IDs).

Table A-2 contains the values of the Open Circuit Touch (V_{toc}) and Step (V_{stoc}) Voltages.

Table A-3 summarizes the Open Circuit Touch Voltage (V_{toc}), Closed Circuit Touch Voltage (V_{tcc}) values, and the Thevenin's equivalent resistance in series with the person's feet.

The remaining pages are data sheets from the Wenner four-pin measurement method.

Figure A-2 shows an example of the four-pin soil measurement process on pad 4.

Figure A-3 shows an example of measurement of I_{exp} and V_{tcc} on Pad 1.

Figure A-4 shows the concrete pads prior to wet measurements.

Figure A-5 shows the rubber boots with Al foil used for I_{exp} measurements.

Figure A-6 shows the rebars at pad 2.

Figure A-7 shows the wire meshes at pad 3.

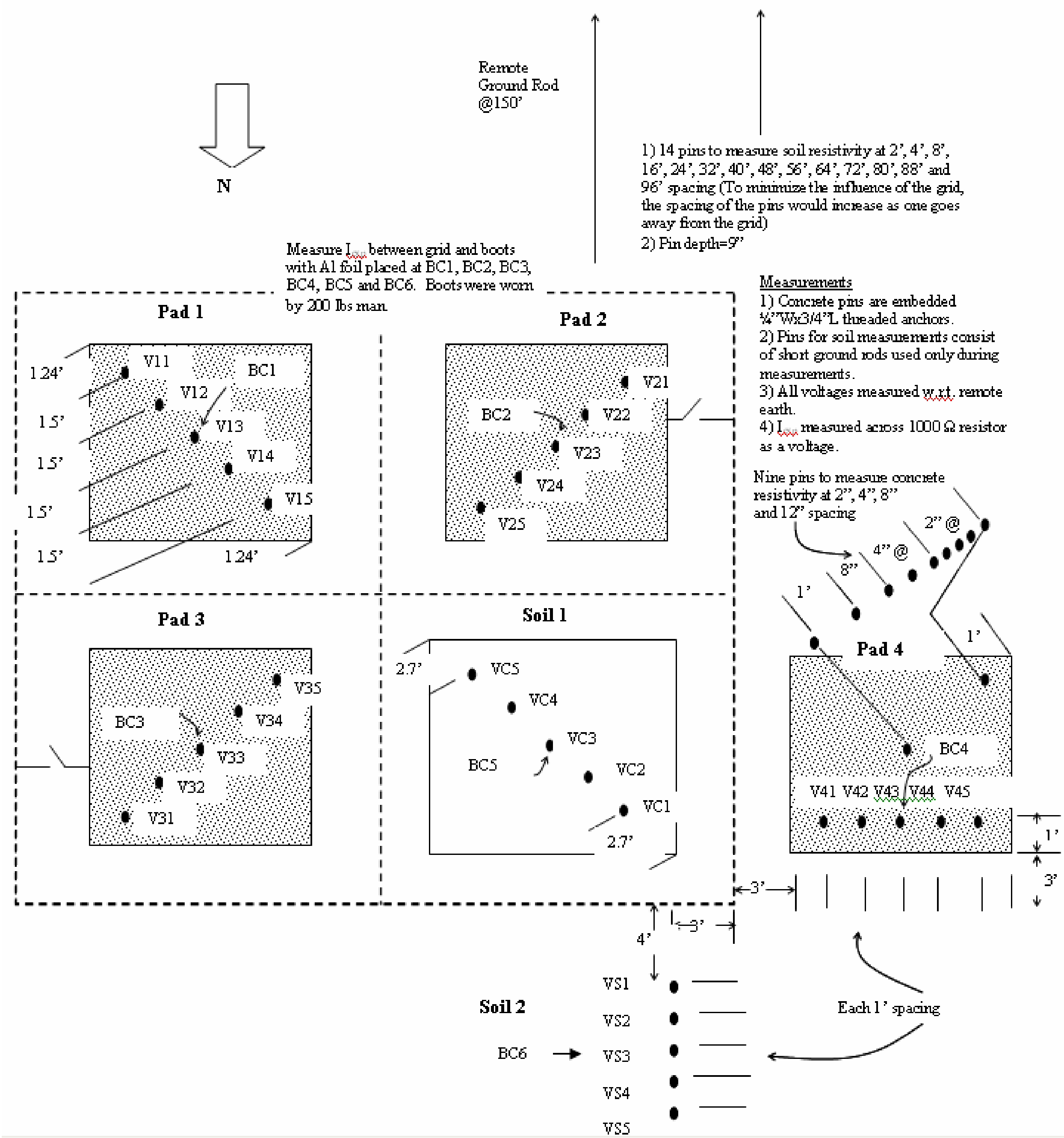

Figure A-1
Measured Variables and their Locations

Table A-1
Measured Data (See Figure A-1 for Location IDs)

Date	7/24/09 (dry)	8/3/09(wet)	8/5/09	8/7/09	8/10/09	8/12/09		7/24/09(dr y)	8/3/09(w et)	8/5/09	8/7/09	8/10/09	8/12/09
GPR	357.5V	318.3V	317.6V	323.2V	340.7V	341.2V	VC1	281.0	265.1	259.8V	261.3V	275.7V	276.5V
I (grid)	21.97A	22.77A	21.87A	22.09A	22.02A	22.5A	VC2	281.0	265.6	261.2V	263.4V	277.7V	278.8V
Pin to Remote Voltages (V_{pin} - R)							VC3	284.5	269.4	264.2V	266.6V	281.0V	282.0V
V21	233.8	266.0	261.0V	259.0V	268.8V	263.0V	VC4	289.5	273.1	268.5V	270.9V	285.7V	286.6V
V22	224.0	267.4	262.0V	258.5V	261.0V	245.5V	VC5	297.0	278.3	273.7V	276.8V	291.4V	292.4V
V23	243.6	268.1	262.5V	259.6V	268.1V	259.0V	VS1	226.0	198.9	210.0V	203.4V	221.0V	221.6V
V24	266.6	269.2	263.8V	264.5V	277.5V	274.0V	VS2	216.5	206.3	201.5V	202.2V	211.8V	212.8V
V25	278.7	272.4	266.8V	268.0V	282.4V	281.3V	VS3	208.0	199.0	193.5V	194.1V	203.4V	204.5V
V21G	281.0	302.4	301.0V	302.2V	313.3V	308.3V	VS4	199.5	191.6	186.5V	185.6V	196.0V	197.1V
V22G	277.0	310.4	309.0V	307.7V	312.5V	293.0V	VS5	193.0	184.9	179.9V	180.6V	189.5V	190.7V
V23G	304.0	311.9	311.5V	309.4V	320.8V	311.0V	**Closed Circuit Touch Voltage ($V_{t(cc),}$ V) or Body Current (I_b, mA)**						
V24G	327.0	311.8	311.2V	313.4V	330.1V	326.0V	BC1	1.28V	32.36V	11.54V	2.44V	0.93V	0.91V
V25G	333.0	307.7	307.0V	310.4V	328.1V	328.3V	BC2	0.88V	31.80V	18.35V	2.78V	1.02V	0.95V
V31	277.5	265.0	262.0V	263.8V	279.4v	278.5V	BC2G	0.04V	3.79V	1.61V	0.21V	0.04V	0.07V
V32	280.0	265.7	262.5V	264.4V	280.0V	279.5V	BC3	0.59V	32.35V	12.37V	3.32V	1.34V	1.08V
V33	271.5	265.7	262.0V	263.0V	276.9V	273.5V	BC3G	0.012V	1.73V	0.67V	0.12V	0.04V	0.04V
V34	275.5	266.3	262.2V	263.2V	278.5V	277.0V	BC4	1.30V	37.42V	38.6V	28.61V	6.67V	6.56V
V35	280.8	268.0	263.8V	265.2V	280.9V	280.0V	BC5	13.0V	66.1V	43.5V	45.57V	49.2V	51.8V
V31G	338.0	309.5	308.0V	314.5V	333.9V	333.0V	BC6	0.0004V	95.5V	84.2V	66.10V	38.2V	29.1V
V32G	344.0	315.6	313.0V	318.7V	335.0V	337.8V	**Concrete Resistivity on Pad 4 (4-Pin Method)**						
V33G	335.0	316.0	312.8V	317.5V	334.0V	330.0V	2” depth	262Ω-m	211Ω-m	285Ω-m	305Ω-m	262Ω-m	301Ω-m
V34G	338.5	315.3	312.2V	317.1V	335.1V	333.6V	4”depth	197Ω-m	180Ω-m	216Ω-m	224Ω-m	196Ω-m	211Ω-m

V35G	342.5	313.8	311.5V	317.7V	336.4V	335.6V	8"depth	166Ω-m	198Ω-m	196Ω-m	203Ω-m	188Ω-m	193Ω-m
V11	233.4	251.7	249.8V	249.2V	257.4V	249.5V	12"depth	145Ω-m	177Ω-m	160Ω-m	156Ω-m	147Ω-m	143Ω-m
V12	255.8	253.8	252.2V	253.7V	268.0V	266.2V							
V13	267.0	257.6	255.5V	257.7V	273.2V	273.0V							
V14	264.5	263.9	261.0V	263.0V	277.4V	276.0V							
V15	270.5	271.8	268.0V	269.5V	283.6V	281.2V							
V41	220.0	223.4	216.0V	215.0V	219.0V	214.0V							
V42	213.8	215.0	208.8V	209.4V	217.7V	215.5V							
V43	188.0	207.1	201.5V	203.2V	212.7V	214.0V							
V44	184.0	198.5	194.0V	194.3V	199.5V	193.5V							
V45	177.0	190.7	156.6V	188.1V	193.2V	186.3V							

V measurements = Fluke 87 CQ 4020, I measurements Amprobe 3000 CQ-4021

Table A-1 Notes:

1. Concrete resistivity readings on Pad 4 could not be obtained with the Biddle Instrument due to high pin resistances. We switched over to supplying 120 volts between the current pins and measuring the voltage between the inner pins for all concrete resistivity measurements.
2. 7/24/09 readings represent dry readings. There was no rain for a week prior to measurement.
3. 8/3/09 readings represent the wet readings. There was a significant prior rain in addition to intentional wetting (2 hours a day for three days) with the sprayer. The readings were taken 10 to 15 minutes after stopping the spraying.
4. There was no prior spraying or rain for readings obtained on 8/5/09, 8/7/09, 8/10/09 and 8/12/09.
5. Suffix "G" indicates the readings with ground grid connected to the rebars or wire mesh.

Table A-2
Open Circuit Touch (V_{toc}) and Step (V_{stoc}) Voltages

Loc ID (Diagonal Dist from Center)	[1]V_{toc} Volts	[2]V_{stoc} Volts	Loc ID (Diagonal Dist from Center)	V_{toc} Volts	V_{stoc} Volts
8/3/09 (Wet)			**8/5/09**		
PAD 1			**PAD 1**		
V15 (5.48’)	46.5	14.2	V15 (5.48’)	49.6	12.5
V14 (6.98’)	54.4	10.1	V14 (6.98’)	56.6	8.8
V13 (8.48’)	60.7	5.9	V13 (8.48’)	62.1	5.7
V12 (9.98’)	64.5		V12 (9.98’)	65.4	
V11 (11.48’)	66.6		V11 (11.48’)	67.8	
PAD 2 (Rebars Disconnected)			**PAD 2 (Rebars Disconnected)**		
V25 (5.48’)	45.9	4.3	V25 (5.48’)	50.8	4.3
V24 (6.98’)	49.1	1.8	V24 (6.98’)	53.8	1.8
V23 (8.48’)	50.2	2.1	V23 (8.48’)	55.1	1.5
V22 (9.98’)	50.9		V22 (9.98’)	55.6	
V21 (11.48’)	52.3		V21 (11.48’)	56.6	
PAD 2 (Rebars Connected)			**PAD 2 (Rebars Connected)**		
V25G (5.48’)	10.6	4.2	V25G (5.48’)	10.6	4.5
V24G (6.98’)	6.5	1.4	V24G (6.98’)	6.4	2.2
V23G (8.48’)	6.4	9.5	V23G (8.48’)	6.1	6.0
V22G (9.98’)	7.9		V22G (9.98’)	8.6	
V21G (11.48’)	15.9		V21G (11.48’)	16.6	
PAD 3 (Wire Mesh Disconnected)			**PAD 3 (Wire Mesh Disconnected)**		
V35 (5.48’)	50.3	2.3	V35 (5.48’)	53.8	1.8
V34 (6.98’)	52.0	0.6	V34 (6.98’)	55.4	0.3
V33 (8.48’)	52.6	0.7	V33 (8.48’)	55.6	0.0
V32 (9.98’)	52.6		V32 (9.98’)	55.1	
V31 (11.48’)	53.3		V31 (11.48’)	55.6	
PAD 3 (Wire Mesh Connected)			**PAD 3 (Wire Mesh Connected)**		
V35G (5.48’)	4.5	2.2	V35G (5.48’)	6.1	1.3
V34G (6.98’)	3.0	0.3	V34G (6.98’)	5.4	0.8
V33G (8.48’)	2.3	6.5	V33G (8.48’)	4.8	4.8
V32G (9.98’)	2.7		V32G (9.98’)	4.6	
V31G (11.48’)	8.8		V31G (11.48’)	9.6	

Soil 1			**Soil 1**		
VC5 (5.48’)	40.0	8.9	VC5 (5.48’)	43.9	9.5
VC4 (6.98’)	45.2	7.5	VC4 (6.98’)	49.1	7.3
VC3 (8.48’)	48.9	4.3	VC3 (8.48’)	53.4	4.4
VC2 (9.98’)	52.7		VC2 (9.98’)	56.4	
VC1 (11.48’)	53.2		VC1 (11.48’)	57.8	
PAD 4			**PAD 4**		
3V41 (4’)	102.3	22.0	3V41 (4’)	101.6	22.0
V42 (5’)	109.5	52.2	V42 (5’)	108.8	52.2
V43 (6’)	116.8		V43 (6’)	116.1	
V44 (7’)	124.3		V44 (7’)	123.6	
V45 (8’)	161.7		V45 (8’)	161.0	
Soil 2			**Soil 2**		
3VS1 (4’)	119.4	7.3	3VS1 (4’)	107.6	23.5
VS2 (5’)	112.0	21.4	VS2 (5’)	116.6	21.1
VS3 (6’)	119.3		VS3 (6’)	124.1	
VS4 (7’)	126.7		VS4 (7’)	131.1	
VS5 (8’)	133.4		VS5 (8’)	137.7	
8/7/09			**8/10/09**		
PAD 1			**PAD 1**		
V15 (5.48’)	53.7	11.8	V15 (5.48’)	57.1	10.1
V14 (6.98’)	60.2	9.3	V14 (6.98’)	63.3	9.4
V13 (8.48’)	65.5	8.5	V13 (8.48’)	67.5	15.8
V12 (9.98’)	69.5		V12 (9.98’)	72.7	
V11 (11.48’)	74.0		V11 (11.48’)	83.3	
PAD 2 (Rebars Disconnected)			**PAD 2 (Rebars Disconnected)**		
V25 (5.48’)	55.2	8.4	V25 (5.48’)	58.3	14.3
V24 (6.98’)	58.7	6.0	V24 (6.98’)	63.2	16.5
V23 (8.48’)	63.6	0.6	V23 (8.48’)	72.6	0.7
V22 (9.98’)	64.7		V22 (9.98’)	79.7	
V21 (11.48’)	64.2		V21 (11.48’)	71.9	
PAD 2 (Rebars Connected)			**PAD 2 (Rebars Connected)**		
V25G (5.48’)	12.8	1.0	V25G (5.48’)	12.6	7.3
V24G (6.98’)	9.8	5.7	V24G (6.98’)	10.6	17.6
V23G (8.48’)	13.8	7.2	V23G (8.48’)	19.9	7.5
V22G (9.98’)	15.5		V22G (9.98’)	28.2	

V21G (11.48’)	21.0		V21G (11.48’)	27.4	
PAD 3 (Wire Mesh Disconnected)			**PAD 3 (Wire Mesh Disconnected)**		
V35 (5.48’)	58.0	2.2	V35 (5.48’)	59.8	4.0
V34 (6.98’)	60.0	1.2	V34 (6.98’)	62.2	1.5
V33 (8.48’)	60.2	0.8	V33 (8.48’)	63.8	2.5
V32 (9.98’)	58.8		V32 (9.98’)	60.7	
V31 (11.48’)	59.4		V31 (11.48’)	61.3	
PAD 3 (Wire Mesh Connected)			**PAD 3 (Wire Mesh Connected)**		
V35G (5.48’)	5.5	0.2	V35G (5.48’)	4.3	2.4
V34G (6.98’)	6.1	1.6	V34G (6.98’)	5.6	0.1
V33G (8.48’)	5.7	3.0	V33G (8.48’)	6.7	0.1
V32G (9.98’)	4.5		V32G (9.98’)	5.7	
V31G (11.48’)	8.7		V31G (11.48’)	6.8	
Soil 1			**Soil 1**		
VC5 (5.48’)	46.4	10.2	VC5 (5.48’)	49.3	10.4
VC4 (6.98’)	52.3	7.5	VC4 (6.98’)	55.0	8.0
VC3 (8.48’)	56.6	5.3	VC3 (8.48’)	59.7	5.3
VC2 (9.98’)	59.8		VC2 (9.98’)	63.0	
VC1 (11.48’)	61.9		VC1 (11.48’)	65.0	
PAD 4			**PAD 4**		
3V41 (4’)	108.2	20.7	3V41 (4’)	121.7	19.6
V42 (5’)	113.8	21.3	V42 (5’)	123.0	24.5
V43 (6’)	120.0		V43 (6’)	128.0	
V44 (7’)	128.9		V44 (7’)	141.3	
V45 (8’)	135.1		V45 (8’)	147.5	
Soil 2			**Soil 2**		
3VS1 (4’)	119.8	17.8	3VS1 (4’)	119.7	2.5
VS2 (5’)	121.0	21.6	VS2 (5’)	128.9	22.3
VS3 (6’)	129.1		VS3 (6’)	137.3	
VS4 (7’)	137.6		VS4 (7’)	144.7	
VS5 (8’)	142.6		VS5 (8’)	151.2	
8/12/09			**7/24/09 (Dry)**		
PAD 1			**PAD 1**		
V15 (5.48’)	60.0	8.2	V15 (5.48’)	86.9	3.5
V14 (6.98’)	65.2	9.8	V14 (6.98’)	92.9	8.7
V13 (8.48’)	68.2	23.5	V13 (8.48’)	90.4	33.6

V12 (9.98’)	75.0		V12 (9.98’)	101.6	
V11 (11.48’)	91.7		V11 (11.48’)	124.0	
PAD 2 (Rebars Disconnected)			**PAD 2 (Rebars Disconnected)**		
V25 (5.48’)	59.9	22.3	V25 (5.48’)	78.7	35.1
V24 (6.98’)	67.2	28.5	V24 (6.98’)	90.8	42.6
V23 (8.48’)	82.2	4.0	V23 (8.48’)	113.8	9.8
V22 (9.98’)	95.7		V22 (9.98’)	133.4	
V21 (11.48’)	78.2		V21 (11.48’)	123.6	
PAD 2 (Rebars Connected)			**PAD 2 (Rebars Connected)**		
V25G (5.48’)	12.9	17.3	V25G (5.48’)	24.4	29.0
V24G (6.98’)	15.2	33.0	V24G (6.98’)	30.4	50.0
V23G (8.48’)	30.2	2.7	V23G (8.48’)	53.4	23.0
V22G (9.98’)	48.2		V22G (9.98’)	80.4	
V21G (11.48’)	32.9		V21G (11.48’)	76.4	
PAD 3 (Wire Mesh Disconnected)			**PAD 3 (Wire Mesh Disconnected)**		
V35 (5.48’)	61.2	6.5	V35 (5.48’)	76.6	9.3
V34 (6.98’)	64.2	2.5	V34 (6.98’)	81.9	4.5
V33 (8.48’)	67.7	5.0	V33 (8.48’)	85.9	6.0
V32 (9.98’)	61.7		V32 (9.98’)	77.4	
V31 (11.48’)	62.7		V31 (11.48’)	79.9	
PAD 3 (Wire Mesh Connected)			**PAD 3 (Wire Mesh Connected)**		
V35G (5.48’)	5.6	5.6	V35G (5.48’)	14.9	7.5
V34G (6.98’)	7.6	4.2	V34G (6.98’)	18.9	5.5
V33G (8.48’)	11.2	3.0	V33G (8.48’)	22.4	3.0
V32G (9.98’)	3.4		V32G (9.98’)	13.4	
V31G (11.48’)	8.2		V31G (11.48’)	19.4	
Soil 1			**Soil 1**		
VC5 (5.48’)	48.8	10.4	VC5 (5.48’)	60.4	12.5
VC4 (6.98’)	54.6	7.8	VC4 (6.98’)	67.9	8.5
VC3 (8.48’)	59.2	5.5	VC3 (8.48’)	72.9	3.5
VC2 (9.98’)	62.4		VC2 (9.98’)	76.4	
VC1 (11.48’)	64.7		VC1 (11.48’)	76.4	
PAD 4			**PAD 4**		
3V41 (4’)	127.2	20.5	3V41 (4’)	137.4	36.0
V42 (5’)	125.7	29.2	V42 (5’)	143.6	36.8
V43 (6’)	127.2		V43 (6’)	169.4	

V44 (7’)	147.7		V44 (7’)	173.4	
V45 (8’)	154.9		V45 (8’)	180.4	
Soil 2			**Soil 2**		
3VS1 (4’)	119.6	24.5	3VS1 (4’)	131.4	26.5
VS2 (5’)	128.4	22.1	VS2 (5’)	140.9	23.5
VS3 (6’)	136.7		VS3 (6’)	149.4	
VS4 (7’)	144.1		VS4 (7’)	157.9	
VS5 (8’)	150.5		VS5 (8’)	164.4	

[1] V_{toc}= GPR-V_{pin}-R,

[2] Difference between two V_{toc} each 3’ apart,

[3]The distances are from the edge of the ground grid.

Table A-3
Open Circuit Touch Voltage (V_{toc}), Closed Circuit Touch Voltage (V_{tcc}) and Thevenin's Equivalent Resistance in Series with Feet

Loc ID (Figure 1)	V_{toc} Volts	V_{tcc} Volts	[1]R_{thev} k•	Loc ID (Figure 1)	V_{toc} Volts	V_{tcc} Volts	[1]R_{thev} k•
8/3/09 (Wet)				**8/10/09**			
BC1 (Pad 1)	60.7	32.4	0.876	BC1 (Pad 1)	67.5	0.93	71.6
BC2 (Pad 2, Rebars Disconnected)	50.2	31.8	0.579	BC2 (Pad 2, Rebars Disconnected)	72.6	1.02	70.1
BC2G (Pad 2, Rebars Connected)	6.4	3.8	0.689	BC2G (Pad 2, Rebars Connected)	19.9	0.04	496.5
BC3 (Pad 3, Wire Mesh Disconnected)	52.6	32.4	0.626	BC3 (Pad 3, Wire Mesh Disconnected)	63.8	1.3	46.6
BC3G (Pad 3, Wire Mesh Connected)	2.3	1.7	0.329	BC3G (Pad 3, Wire Mesh Connected)	6.7	0.04	166.5
BC4 (Pad 4)	116.8	37.42	2.12	BC4 (Pad 4)	128.0	6.67	18.2
BC5 (Soil 1)	48.9	66.1 (?)	N/A	BC5 (Soil 1)	59.7	49.2	0.213
BC6 (Soil 2)	119.3	95.5	0.249	BC6 (Soil 2)	137.3	38.2	2.59
8/5/09				**8/12/09**			
BC1 (Pad 1)	62.1	11.54	4.38	BC1 (Pad 1)	68.2	0.91	73.9
BC2 (Pad 2, Rebars Disconnected)	55.1	18.35	2.00	BC2 (Pad 2, Rebars Disconnected)	82.2	0.95	85.5
BC2G (Pad 2, Rebars Connected)	6.1	1.6	2.79	BC2G (Pad 2, Rebars Connected)	30.2	0.07	430.4
BC3 (Pad 3, Wire Mesh Disconnected)	55.6	12.4	3.49	BC3 (Pad 3, Wire Mesh Disconnected)	67.7	1.08	61.7
BC3G (Pad 3, Wire Mesh Connected)	4.8	0.67	6.16	BC3G (Pad 3, Wire Mesh Connected)	11.2	0.04	279.0
BC4 (Pad 4)	116.1	38.6	2.0	BC4 (Pad 4)	127.2	6.56	18.4
BC5 (Soil 1)	53.4	43.4	0.230	BC5 (Soil 1)	59.2	51.8	0.143

BC6 (Soil 2)	124.1	84.2	0.474	BC6 (Soil 2)	136.7	29.1	3.7
8/7/09				**7/24/09 (Dry)**			
BC1 (Pad 1)	65.5	2.44	25.8	BC1 (Pad 1)	90.4	1.28	69.6
BC2 (Pad 2, Rebars Disconnected)	63.6	2.78	21.9	BC2 (Pad 2, Rebars Disconnected)	113.8	0.88	128.3
BC2G (Pad 2, Rebars Connected)	13.8	0.21	64.7	BC2G (Pad 2, Rebars Connected)	53.4	0.04	1334.0
BC3 (Pad 3, Wire Mesh Disconnected)	60.2	3.32	17.1	BC3 (Pad 3, Wire Mesh Disconnected)	85.9	0.59	144.6
BC3G (Pad 3, Wire Mesh Connected)	5.7	0.12	46.5	BC3G (Pad 3, Wire Mesh Connected)	22.4	0.012	1865.7
BC4 (Pad 4)	120.0	28.6	3.19	BC4 (Pad 4)	169.4	1.3	129.3
BC5 (Soil 1)	56.6	45.6	0.242	BC5 (Soil 1)	72.9	13.0	4.6
BC6 (Soil 2)	129.0	66.1	0.953	BC6 (Soil 2)	131.4	17.4	6.6

[1] $R_{thev} = 1000\left[(V_{toc} - V_{tcc}) / V_{tcc}\right]$ Ohms

WENNER FOUR-PIN GROUNDING DATA SHEET FOR PROJECT NO. 09-075

SITE: 09075 Test pads

Location: MTF

Soil Condition: Clay w/ some rocks - DRY

Date: 7/24/09

TESTERS: B.F., B.d., S.P.

Approved:

EQUIPMENT USED: AEMC 4500 CQ-4026

CALIBRATION DUE: 8/22/09

DISTANCE BETWEEN PINS ("a" IN FEET)	**RESISTANCE ("R" IN OHMS)**	**[1]K**	**ρ =KR OHM-METERS**
2	269	5	1345
4	21.3	8	170.4
8	9.7	16	155.2
16	7.24	31	224.44
24	5.26	46	241.96
32	3.99	62	247.38
40	4.55	78	354.9
48	2.61	93	242.73
56	2.67	108	288.36
64	2.44	123	300.12
72	3.1	138	427.8
80	3.78	154	582.12
88	4.46	169	753.74
96	4.38	184	805.92

[1] $K = \dfrac{1.22\pi a}{1 + \left[\dfrac{2a}{\sqrt{a^2 + 4b^2}}\right] - \left[\dfrac{a}{\sqrt{a^2 + b^2}}\right]}$ where: b=0.75' (Pin Depth)

WENNER FOUR-PIN GROUNDING DATA SHEET FOR PROJECT NO. 09-075

SITE: 09075 Test pads

Location: MTF

Soil Condition: Clay w/ some rocks AFTER WETTING

Date: 8/3/09

TESTERS: B.F., B.d., S.P.

Approved:

EQUIPMENT USED: AEMC 4500 CQ-4026

CALIBRATION DUE: 8/22/09

DISTANCE BETWEEN PINS (“a”), Feet	**RESISTANCE (“R”), OHMS**	**1K**	**ρ =KR OHM-METERS**
2	34.4	5	172
4	18.4	8	147.20
8	10.0	16	160
16	6.2	31	192.2
24	5.3	46	243.8
32	4.82	62	298.84
40	4.52	78	352.56
48	3.22	93	299.46
56	3.02	108	326.16
64	2.89	123	355.47
72	3.64	138	502.32
80	4.39	154	676.06
88	4.93	169	833.17
96	4.87	184	896.08

[1] $$K = \frac{1.22\pi a}{1 + \left[\frac{2a}{\sqrt{a^2 + 4b^2}}\right] - \left[\frac{a}{\sqrt{a^2 + b^2}}\right]}$$ where: b=0.75’ (Pin Depth)

WENNER FOUR-PIN GROUNDING DATA SHEET FOR PROJECT NO. 09-075

SITE: 09075 Test pads

Location: MTF

Soil Condition: Clay w/ some rocks – no rain since 8/3

Date: 8/5/09

TESTERS: B.F., B.d.,

Approved:

EQUIPMENT USED: AEMC 4500 CQ-4026

CALIBRATION DUE: 8/22/09

DISTANCE BETWEEN PINS ("a"), Feet	RESISTANCE ("R"), OHMS	[1]K	ρ =KR OHM-METERS
2	35.5	5	177.5
4	18.59	8	148.720
8	9.93	16	158.88
16	6.22	31	192.82
24	5.33	46	245.18
32	4.94	62	306.28
40	4.54	78	354.12
48	3.04	93	282.72
56	3.08	108	332.64
64	2.93	123	360.39
72	3.75	138	517.5
80	4.42	154	680.68
88	4.94	169	834.86
96	4.91	184	903.44

[1] $$K = \frac{1.22\pi a}{1+\left[\frac{2a}{\sqrt{a^2+4b^2}}\right]-\left[\frac{a}{\sqrt{a^2+b^2}}\right]}$$ where: b=0.75' (Pin Depth)

WENNER FOUR-PIN GROUNDING DATA SHEET FOR PROJECT NO. 09-075

SITE: 09075 Test pads

Location: MTF

Soil Condition: Clay w/ some rocks

Date: 8/7/09

TESTERS: B.F., B.d.,

Approved:

EQUIPMENT USED: AEMC 4500 CQ-4026

CALIBRATION DUE: 8/22/09

DISTANCE BETWEEN PINS ("a"), Feet	RESISTANCE ("R"), OHMS	[1]K	ρ =KR OHM-METERS
2	34.3	5	171.5
4	19.1	8	153
8	10.0	16	160
16	6.19	31	192
24	5.33	46	245
32	5.89	62	365
40	8.1	78	632
48	5.5	93	512
56	3.2	108	346
64	2.95	123	363
72	3.5	138	483
80	4.5	154	693
88	5.1	169	862
96	5.1	184	938

[1] $K = \dfrac{1.22\pi a}{1 + \left[\dfrac{2a}{\sqrt{a^2+4b^2}}\right] - \left[\dfrac{a}{\sqrt{a^2+b^2}}\right]}$ where: b=0.75' (Pin Depth)

WENNER FOUR-PIN GROUNDING DATA SHEET FOR PROJECT NO. 09-075

SITE: 09075 Test pads

Location: MTF

Soil Condition: Clay w/ some rocks

Date: 8/10/09

TESTERS: B.F., B.d.,

Approved:

EQUIPMENT USED: AEMC 4500 CQ-4026

CALIBRATION DUE: 8/22/09

DISTANCE BETWEEN PINS ("a"), Feet	RESISTANCE ("R"), OHMS	[1]K	ρ =KR OHM-METERS
2	98.0	5	490
4	19.5	8	156
8	10.0	16	160
16	7.1	31	220
24	5.5	46	253
32	4.5	62	279
40	5.4	78	421
48	4.3	93	400
56	3.2	108	346
64	3.0	123	369
72	4.1	138	566
80	4.6	154	708
88	5.2	169	879
96	5.1	184	938

[1] $$K = \frac{1.22\pi a}{1 + \left[\frac{2a}{\sqrt{a^2 + 4b^2}}\right] - \left[\frac{a}{\sqrt{a^2 + b^2}}\right]}$$ where: b=0.75' (Pin Depth)

WENNER FOUR-PIN GROUNDING DATA SHEET FOR PROJECT NO. 09-075

SITE: 09075 Test pads

Location: MTF

Soil Condition: Clay w/ some rocks

Date: 8/12/09

TESTERS: B.F., B.d.,

Approved:

EQUIPMENT USED: AEMC 4500 CQ-4026

CALIBRATION DUE: 8/22/09

DISTANCE BETWEEN PINS ("a"), Feet	RESISTANCE ("R"), OHMS	[1]K	ρ =KR OHM-METERS
2	90.2	5	451
4	19.7	8	158
8	10.2	16	163
16	125.2 (?)	31	3881 (?)
24	5.6	46	258
32	5.2	62	322
40	6.3	78	491
48	5.3	93	493
56	3.4	108	367
64	3.1	123	381
72	4.5	138	621
80	4.8	154	739
88	5.5	169	930
96	5.2	184	957

[1] $K = \dfrac{1.22\pi a}{1 + \left[\dfrac{2a}{\sqrt{a^2 + 4b^2}}\right] - \left[\dfrac{a}{\sqrt{a^2 + b^2}}\right]}$ where: b=0.75' (Pin Depth)

Figure A-2
4-pin Soil Measurement on Pad 4

Figure A-3
I_{exp} and V_{tcc} Measurement on Pad 1

Figure A-4
Concrete Pads Prior to Wet Measurements

Figure A-5
Rubber Boots with Al Foil for I_{exp} Measurements

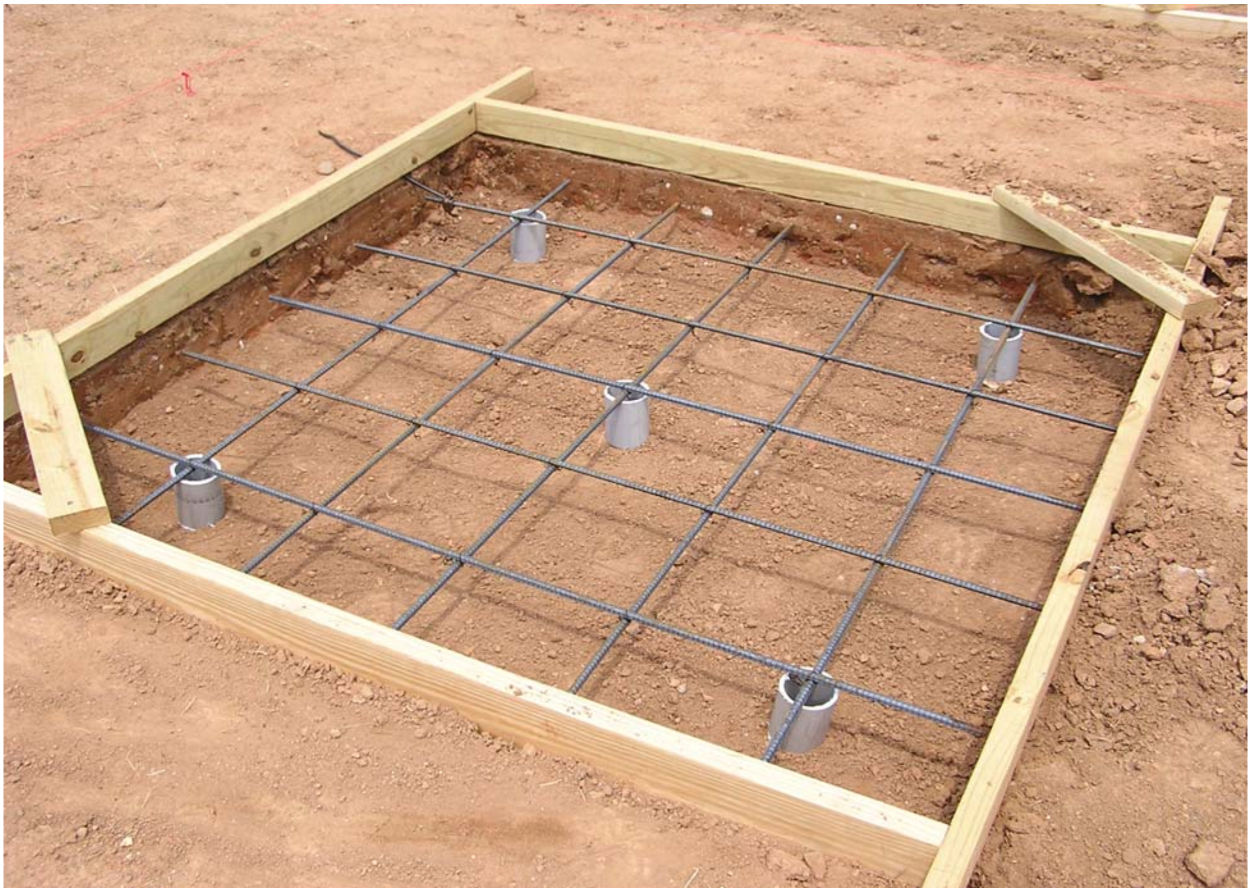

Figure A-6
Rebars at Pad 2

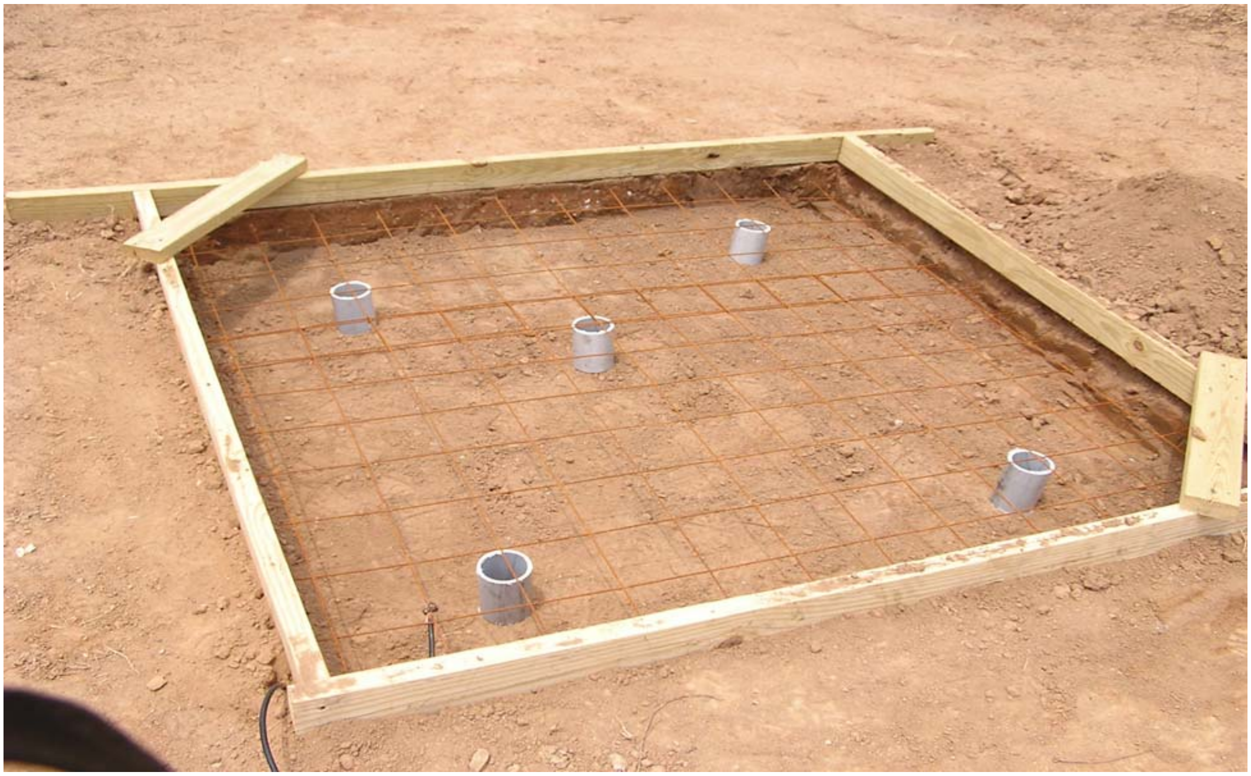

Figure A-7
Wire Meshes at Pad 3

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