Touch and Step Voltage Measurements on Field Installed Ground Grid Overlaid with Gravel and Asphalt Beds

EPRI WHITE PAPER

3002008836

Presented by Lane Garrett at the Annual Substations Committee Meeting
Atlanta, GA
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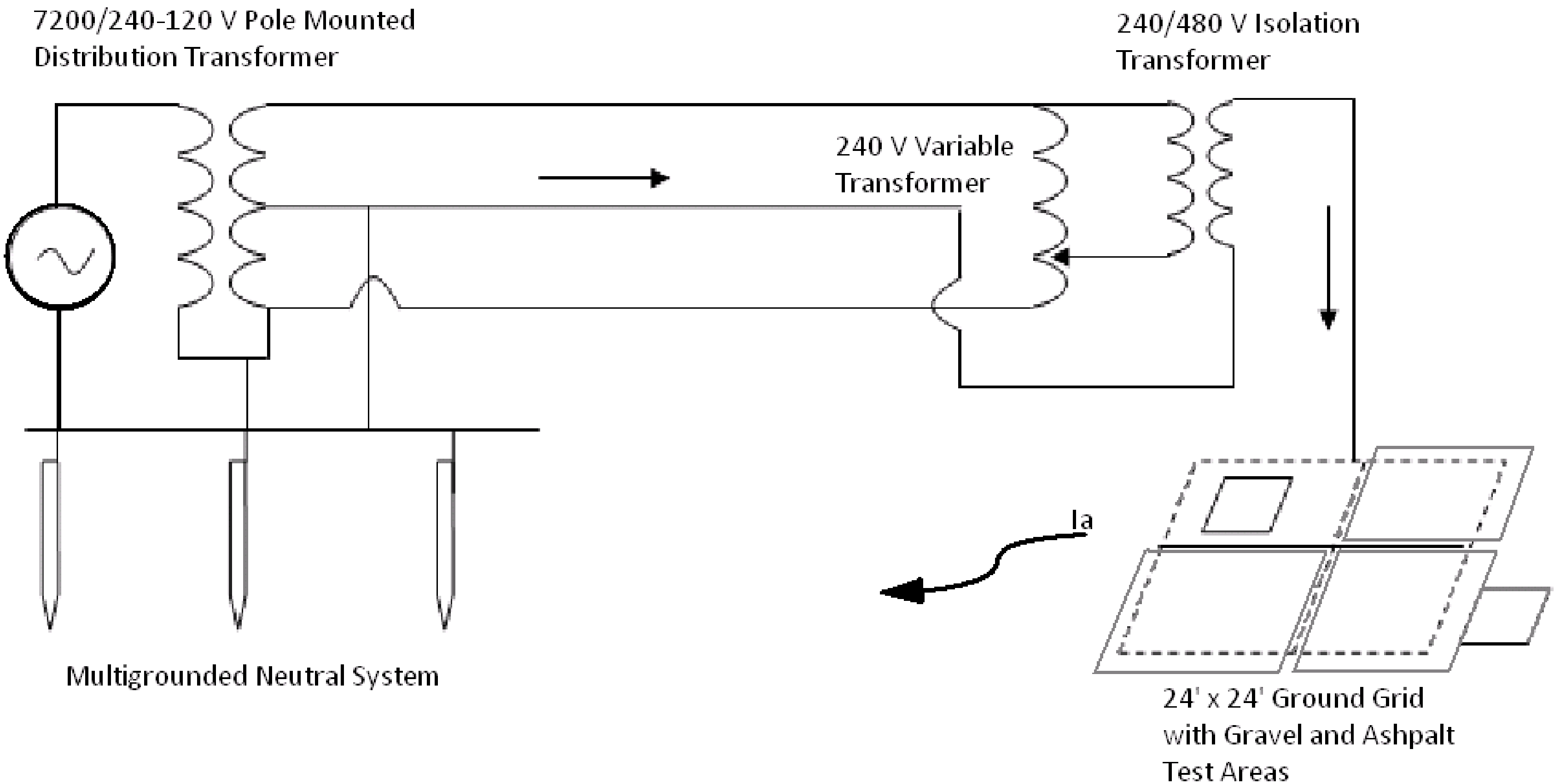
- **INITIAL PROJECT ON RESISTIVITY OF CONCRETE FUNDED BY SOUTHERN COMPANY (PROJECT MANAGER – LANE GARRETT)**
- **FOLLOW-UP PROJECT TO MEASURE TOUCH AND STEP VOLTAGES ON CONCRETE FUNDED BY EPRI (1020031) (PROJECT MANAGER – GEORGE GILA)**
- **BOTH PROJECTS PERFORMED BY NEETRAC (PRINCIPAL INVESTIGATOR – SHASHI PATEL)**
- **NOW A SECOND FOLLOW-UP PROJECT TO MEASURE TOUCH AND STEP VOLTAGES ON ROCK AND ASPHALT FUNDED BY EPRI**

OBJECTIVES

- DETERMINE EFFECTS OF VARIOUS SIZE/TYPE ROCKS ON BODY CURRENT
- DETERMINE EFFECTS OF ROCK MOISTURE CONTENT ON BODY CURRENT
- MEASURE OPEN CIRCUIT TOUCH VOLTAGES (EXPOSURE VOLTAGES)
- MEASURE CLOSED CIRCUIT TOUCH VOLTAGES (EXPOSURE CURRENT)
- DETERMINE THEVENIN EQUIVALENT RESISTANCE IN SERIES WITH FEET

TEST SET UP



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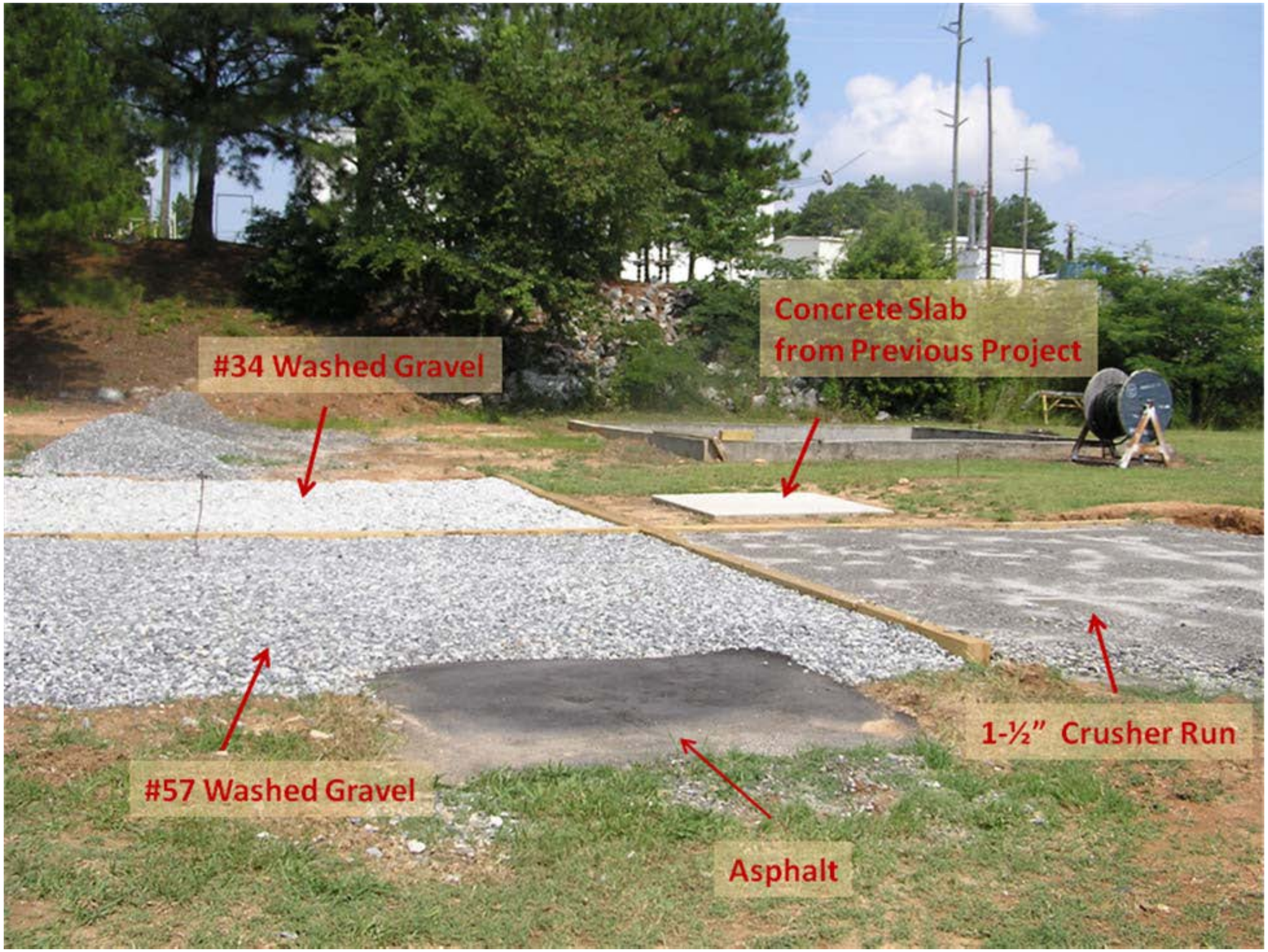
TEST SET UP



#34 Washed Gravel
Concrete Slab
from Previous Project
#57 Washed Gravel
Asphalt
1-½" Crusher Run

WETTING THE TEST AREA

TEST TIMELINE

1. INITIAL TESTS JULY 12, 2010 – DRY CONDITIONS
2. WET CONDITIONS JULY 13 – SPRINKLER + RAINFALL = 4 INCHES IN GAUGE (RE-WETTED DURING TESTING TO MAINTAIN MOISTURE CONTENT
3. ALLOWED TO DRY ONE HOUR AND RE-TESTED
4. RE-TESTED TWO DAYS LATER (JULY 15) AFTER 1 INCH ADDITIONAL RAIN EVENING OF JULY 13
5. RE-TESTED THREE DAYS LATER (JULY 16)
6. FINAL DRY CONDITION TESTING SEPT. 2 AFTER SEVERAL DRY DAYS (NO RAIN)

DIRECT MEASUREMENTS

- Injected current (Ig)
- Ground Potential Rise (GPR) with respect to a remote ground rod located approximately 150' from the ground grid
- Open Circuit Touch Voltage (Vtoc). For this report, the Open Circuit Touch Voltage is defined as the voltage measured between the ground grid conductor and pin driven at a surface location or metallic shoe soles of the worker located at that location.
- Exposure current (Iexp) measured as the voltage across a 1000 Ω resistor representing a human body (For this report, the voltage measured across the 1000 Ω resistor is defined as the closed circuit touch voltage, Vtcc.).
- Open circuit touch voltage (Vtoc) measured between the ground grid riser and the pins driven in the gravel (8" pins), concrete (3/4" anchors) and asphalt (1" nails). (This measurement was used for comparison with the measurement from the metallic soles representing worker's feet.)

ROCK RESISTIVITY MEASUREMENTS

(a) Bottom Electrode

(b) Top Electrode

(c) Device Filled with #34 Washed Gravel

(d) Device Filled with 1½" Crusher Run Gravel

$$\rho = \frac{RA}{L}$$

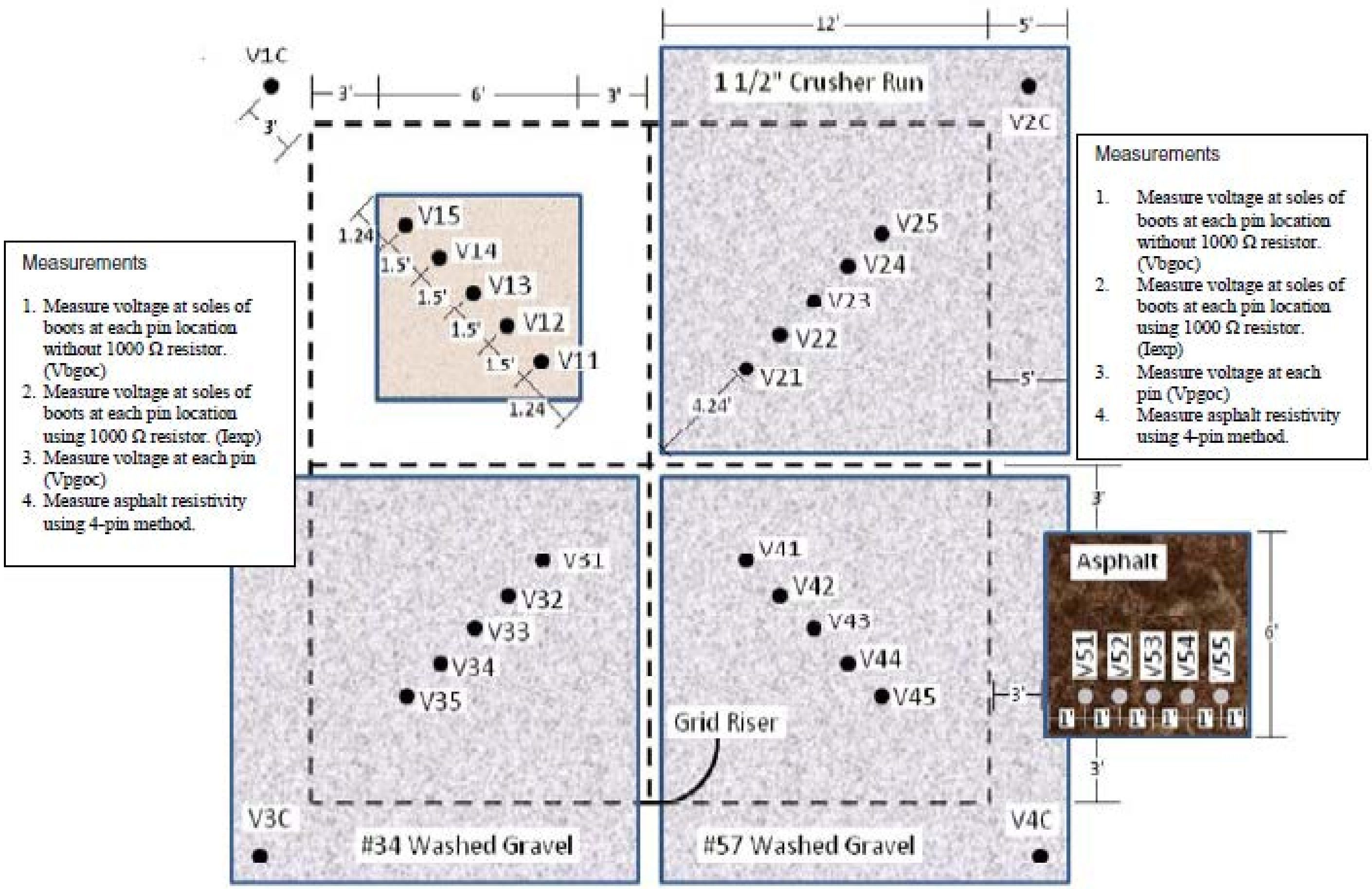
RESISTIVITY OF ASPHALT USING THE FOUR-PIN METHOD

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

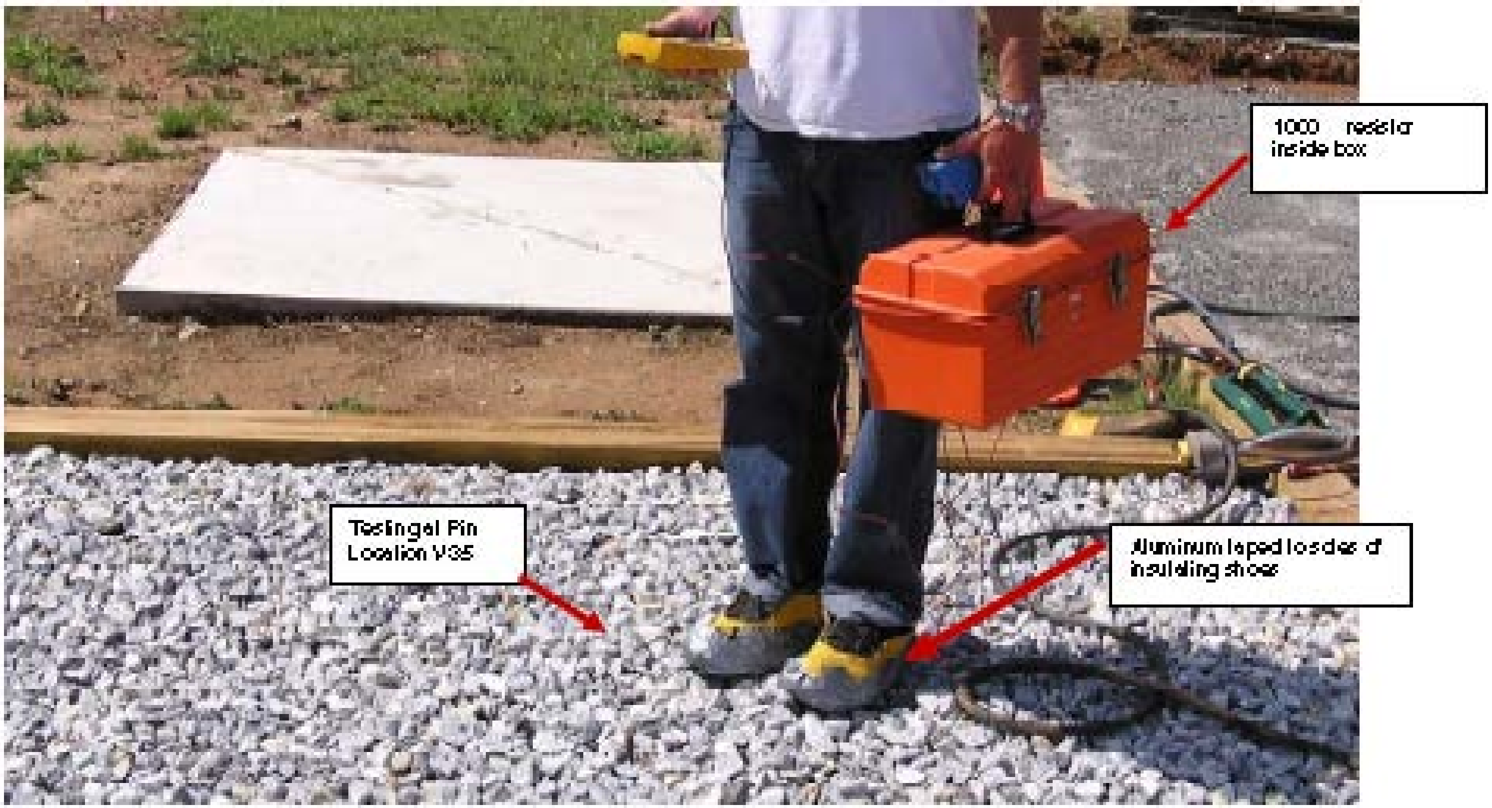
VARIABLES DERIVED FROM MEASURED DATA

- OPEN CIRCUIT STEP VOLTAGE (V_{STOC})
- THEVENIN'S EQUIVALENT RESISTANCE IN SERIES WITH FEET (R_{THEV})

TEST LOCATIONS



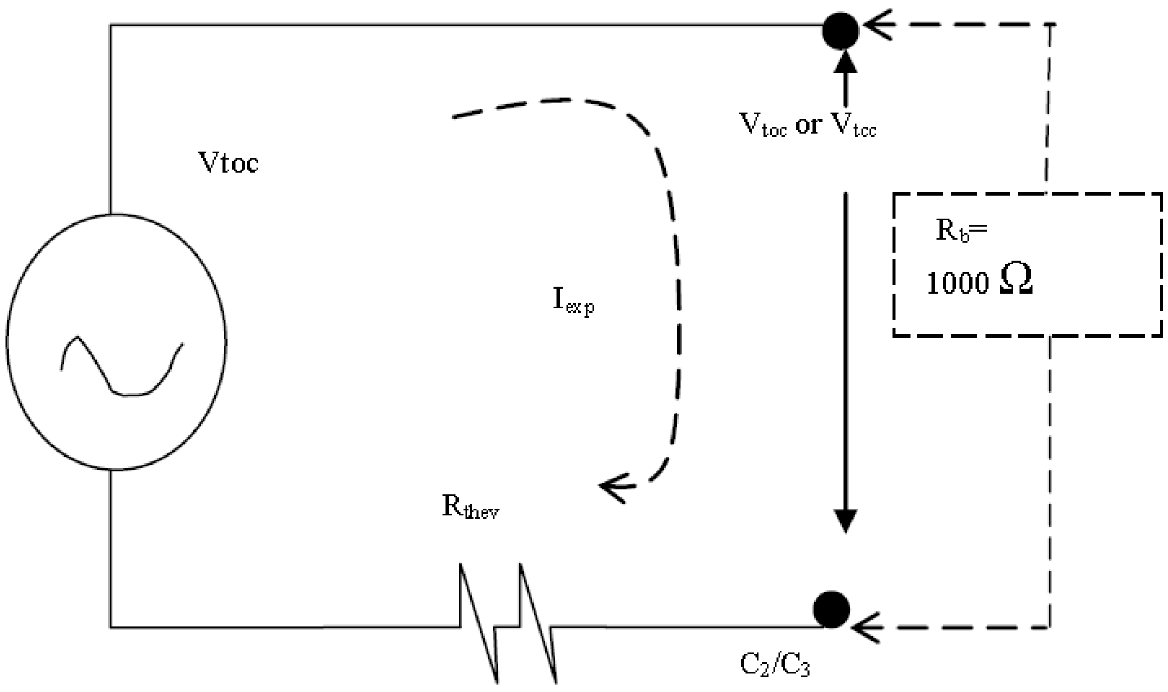
EXPOSURE CURRENT MEASUREMENT



OPEN-CIRCUIT TOUCH ANS STEP VOLTAGES

- USE FLUKE 87 DIGITAL METER
- MEASURE VOLTAGE FROM GRID TO VARIOUS EMBEDDED PINS TO OBTAIN OPEN-CIRCUIT TOUCH VOLTAGE
- OPEN-CIRCUIT STEP VOLTAGE COMPUTED AS DIFFERENCE BETWEEN TOUCH VOLTAGES 3 FT APART

R_{THEV} ????



$$V_{toc} = I_{exp}(R_{thev} + 1000) \;\; OR \;\; R_{thev} = (V_{toc}/I_{exp}) - 1000$$

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RESULTS – CONCRETE V_{toc}

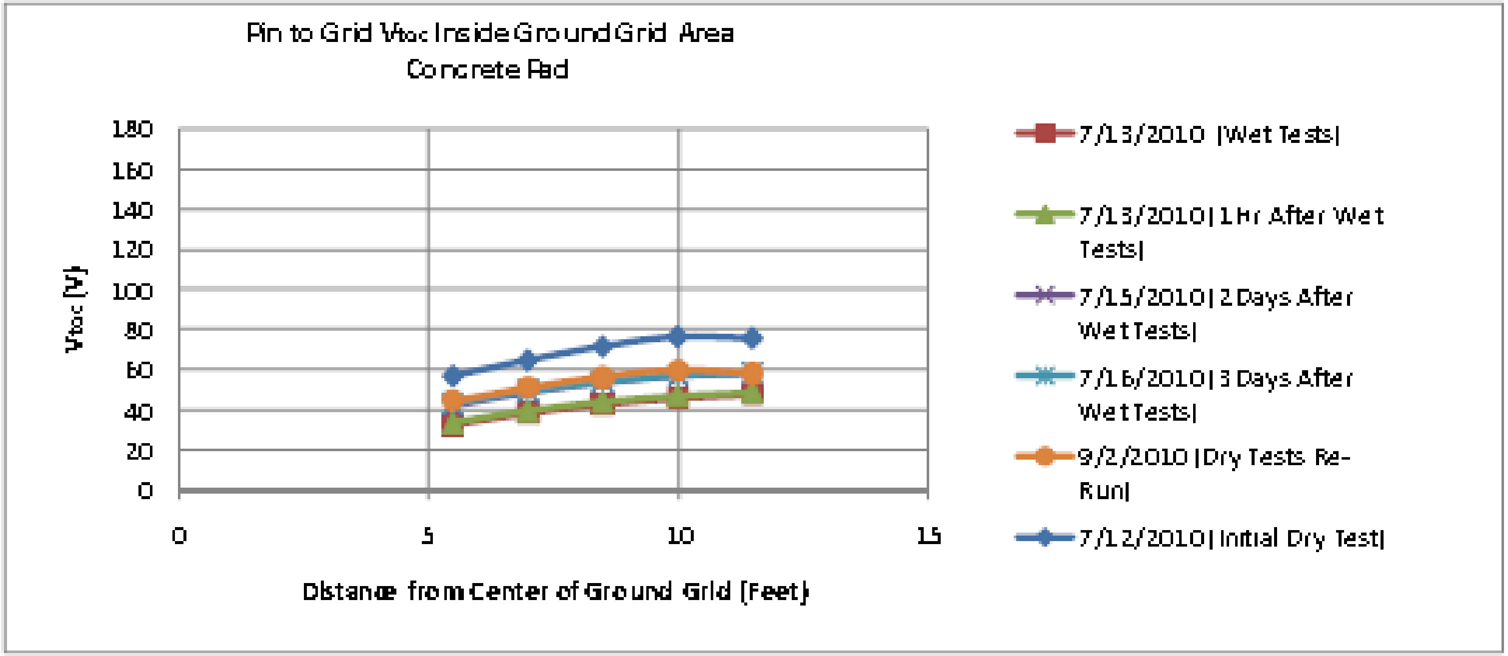

Figure 3-1
Pin to Grid V_{toc} over Concrete Pad

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RESULTS – CRUSHER RUN V_{toc}

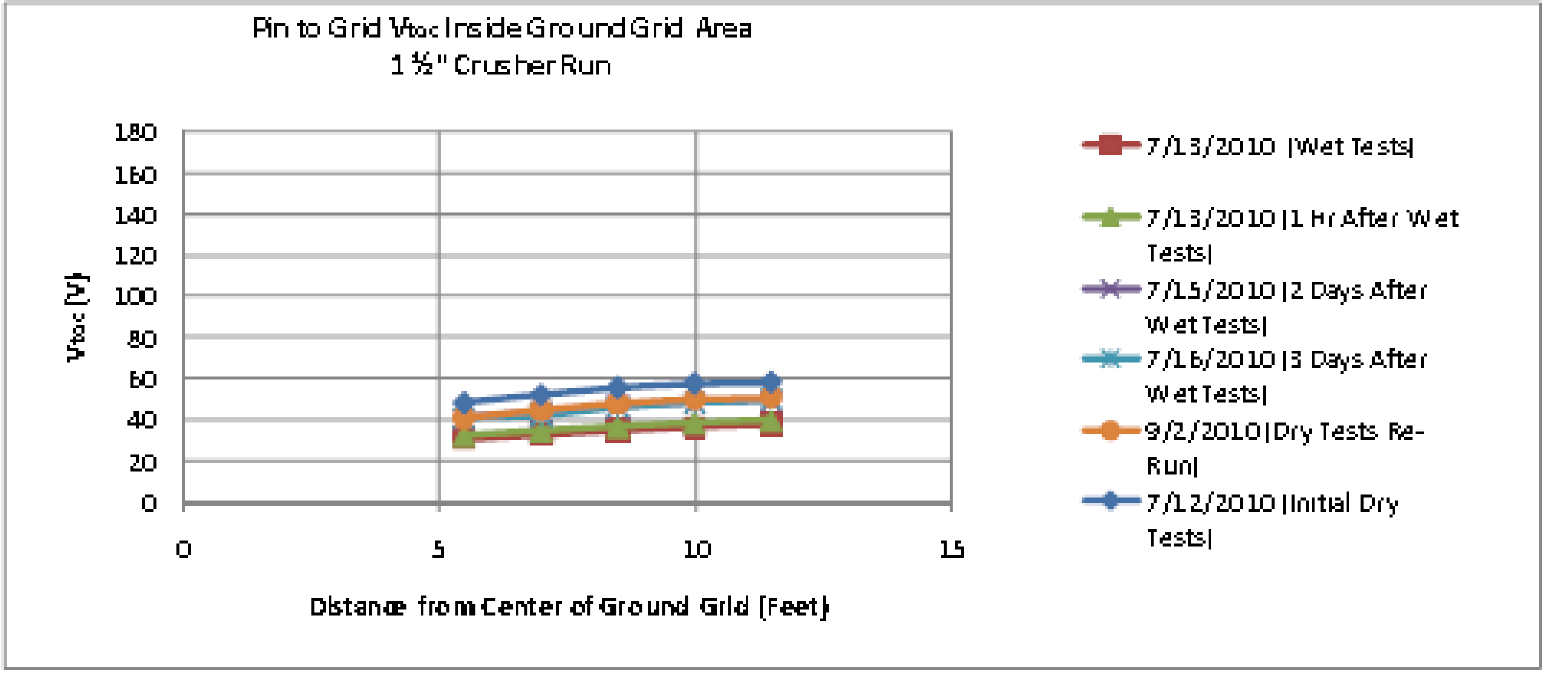


Figure 3-2
Pin to Grid V_{toc} over 1½" Crusher Run

RESULTS - #34 GRAVEL V_{toc}

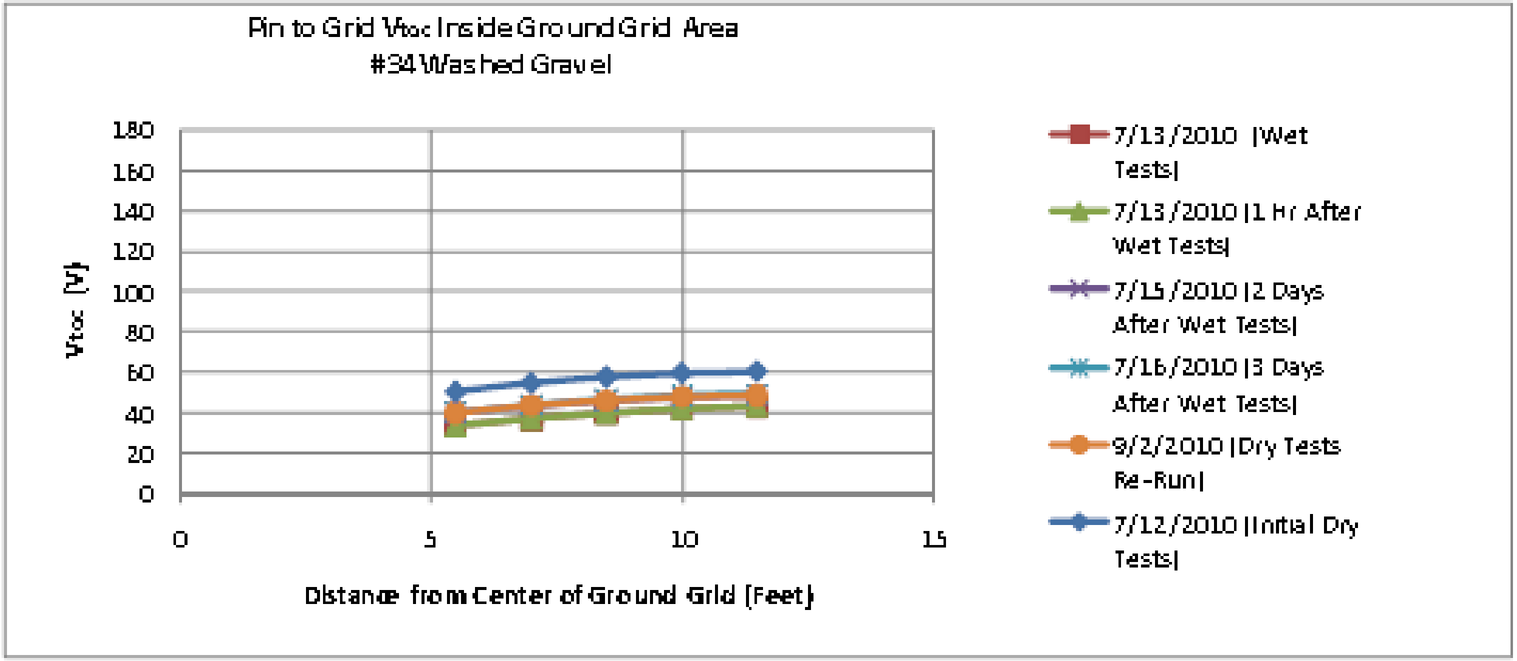


Figure 3-3
Pin to Grid V_{toc} over #34 Gravel

RESULTS - #57 GRAVEL V_{toc}

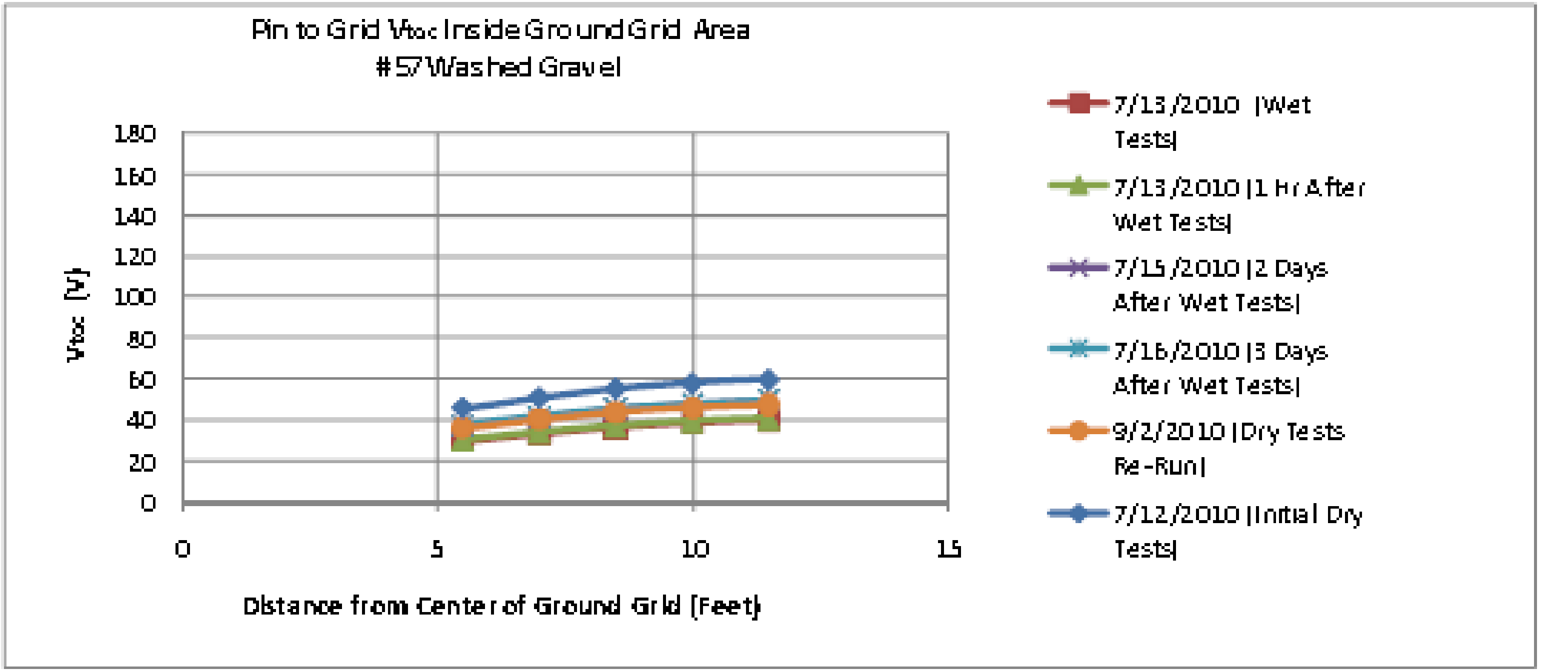


Figure 3-4
Pin to Grid V_{toc} over #57 Gravel

RESULTS – ASPHALT V_{toc}

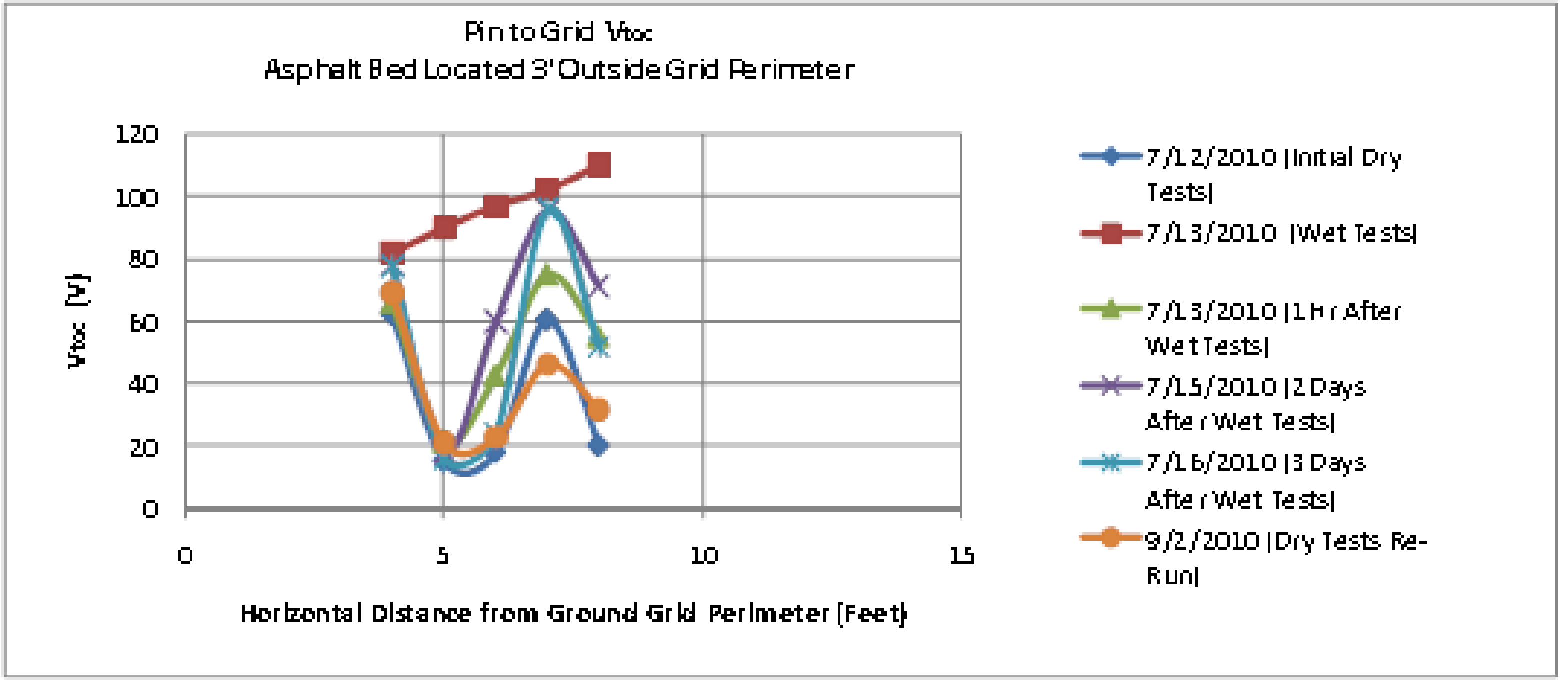


Figure 3-5
Pin to Grid V_{toc} over Asphalt Bed

RESULTS – DRY TESTS V_{toc}

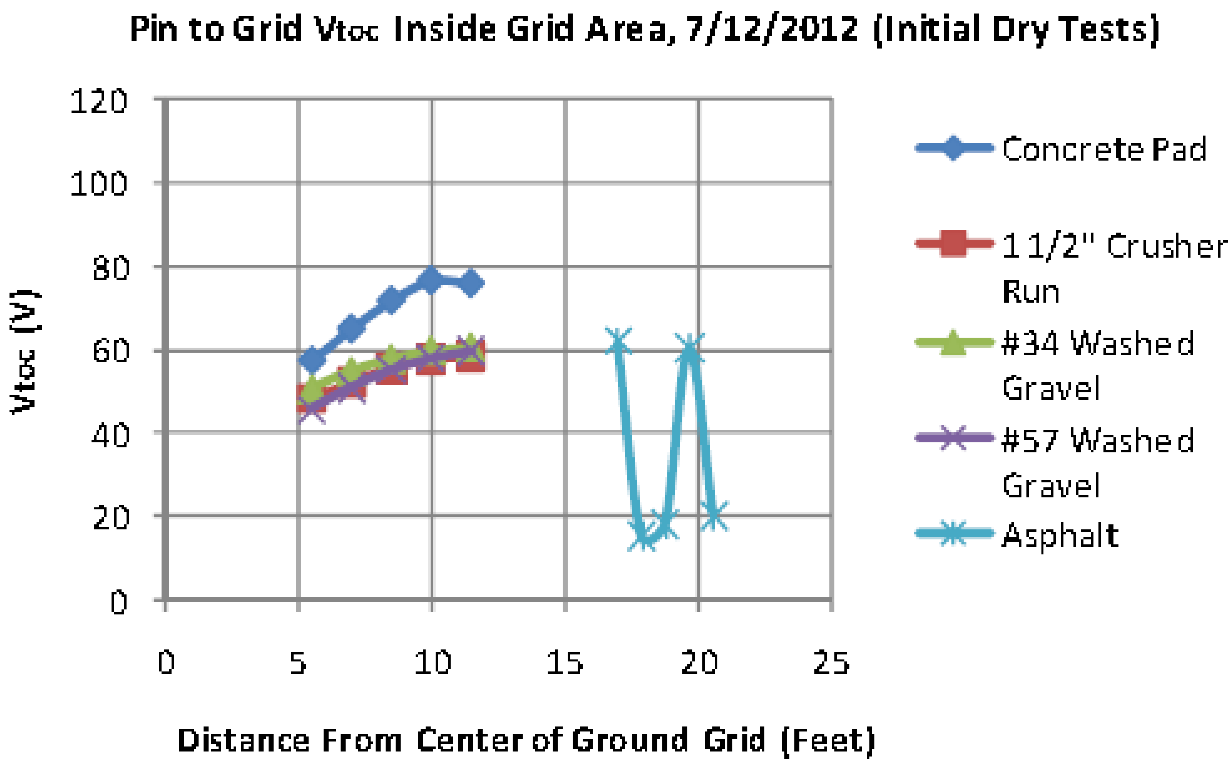


Figure 3-7
Pin to Grid V_{toc}, 7/12/2010 (Initial Dry Test)

RESULTS – WET TESTS V_{toc}

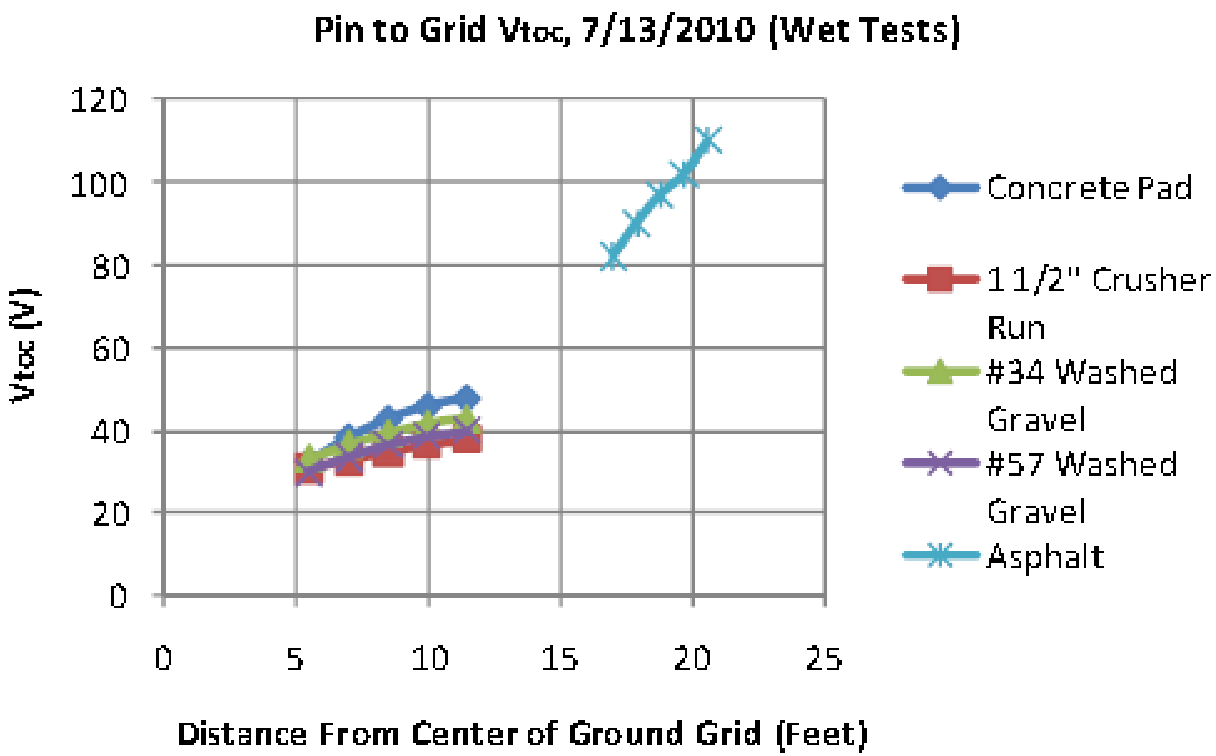


Figure 3-8
Pin to Grid V_{toc}, 7/13/2010 (Wet Tests)

RESULTS – 1HR AFTER WET V_{toc}

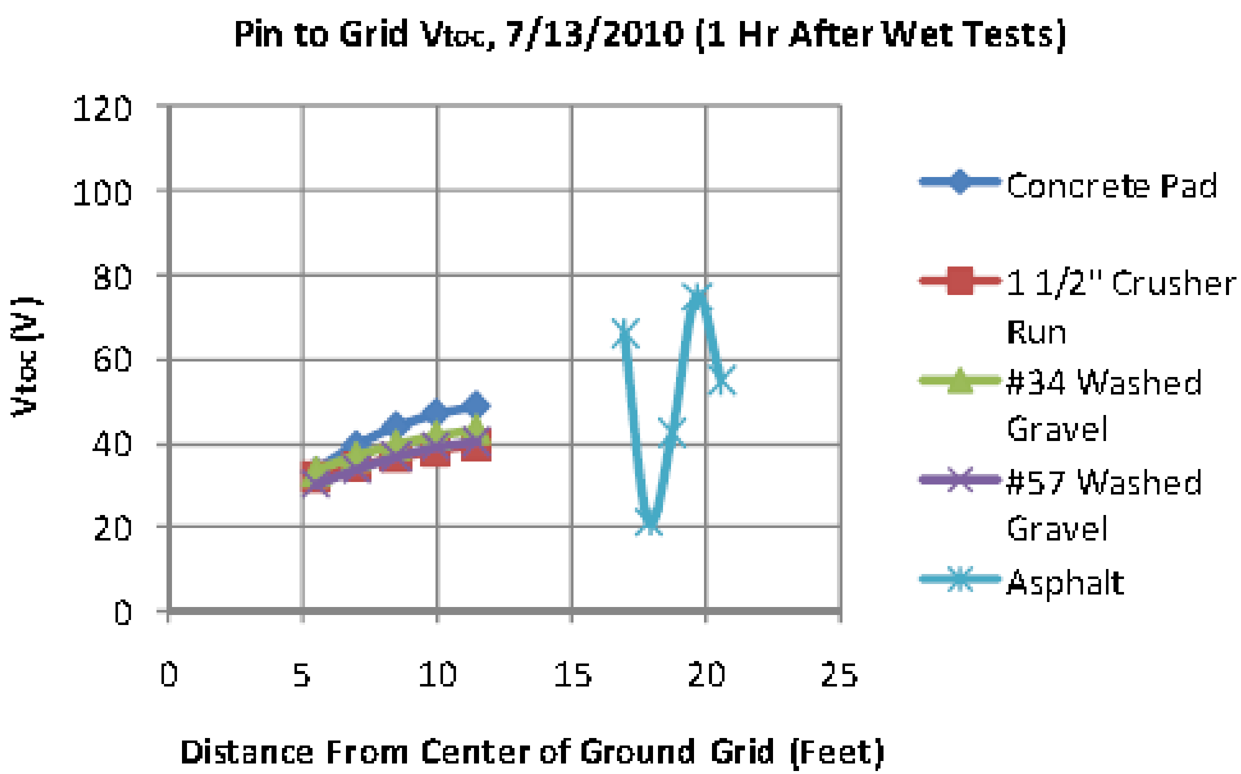
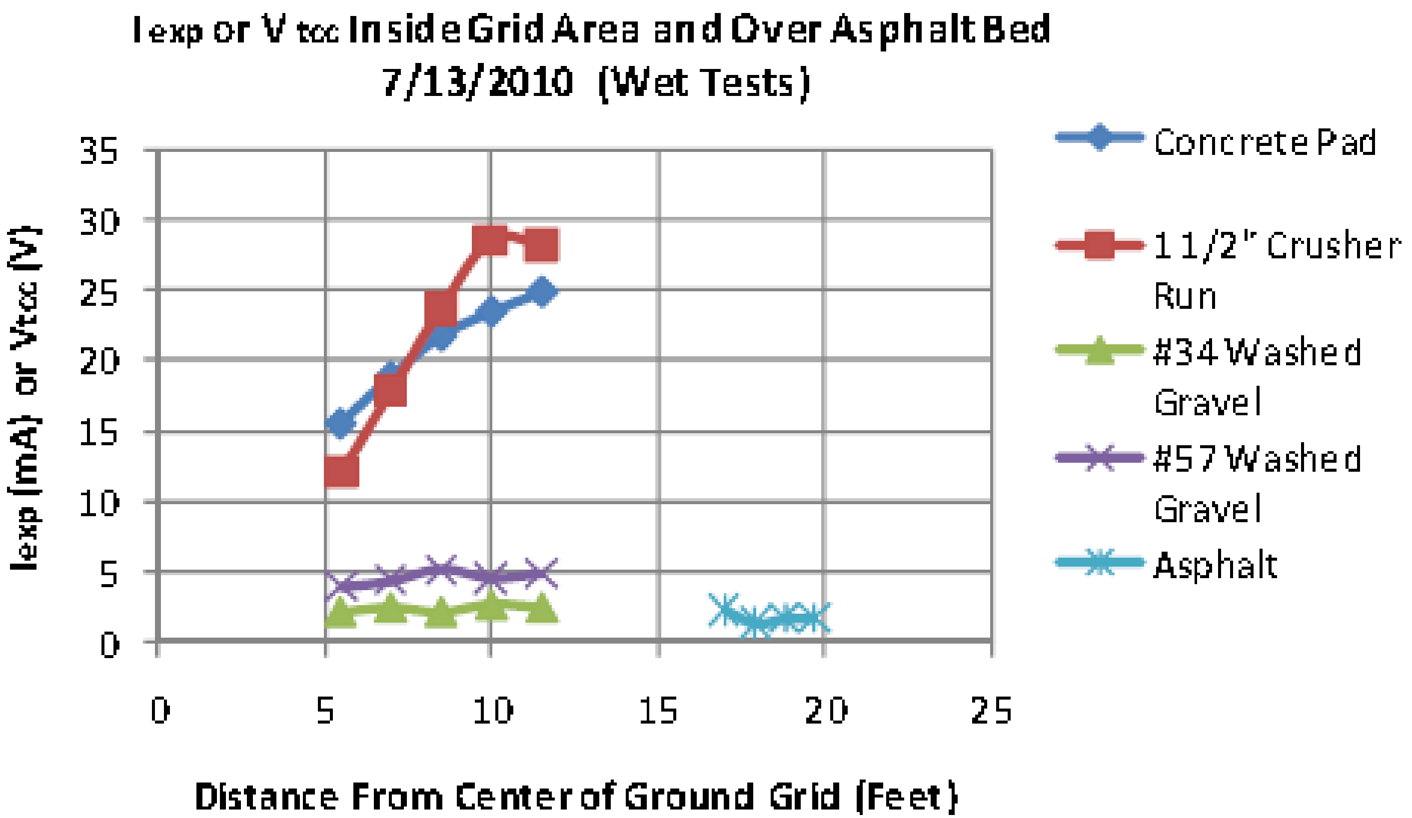


Figure 3-9
Pin to Grid V_{toc} (1 Hr after Wet Tests)

RESULTS – WET TESTS I_{exp}



RESULTS – 1HR WET TESTS I_{exp}

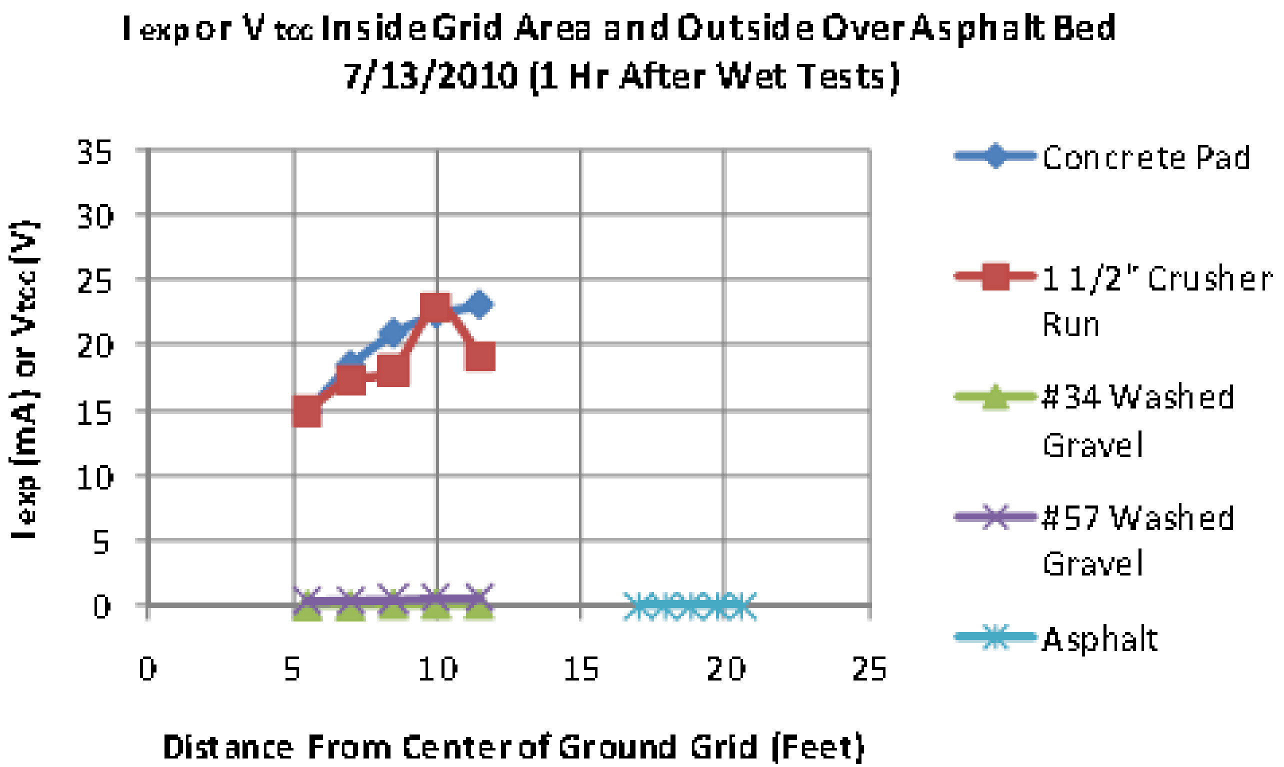


Figure 3-24
I_{exp} or V_{tcc} (1 Hr After Wet Tests)

RESULTS – DRY TESTS RE-RUN I_{exp}

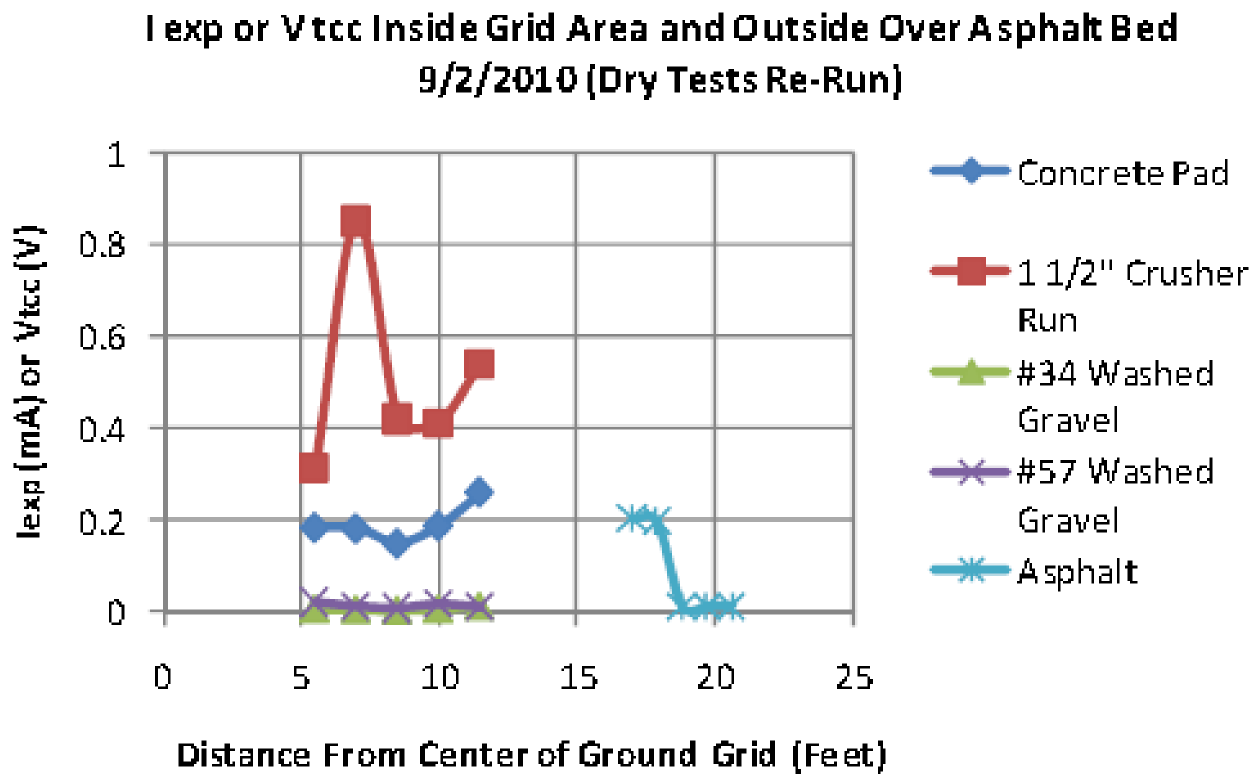


Figure 3-27
I_{exp} or V_{tcc}, (Dry Tests Re-run)

RESULTS – I_{exp} TESTS OUTSIDE GRID

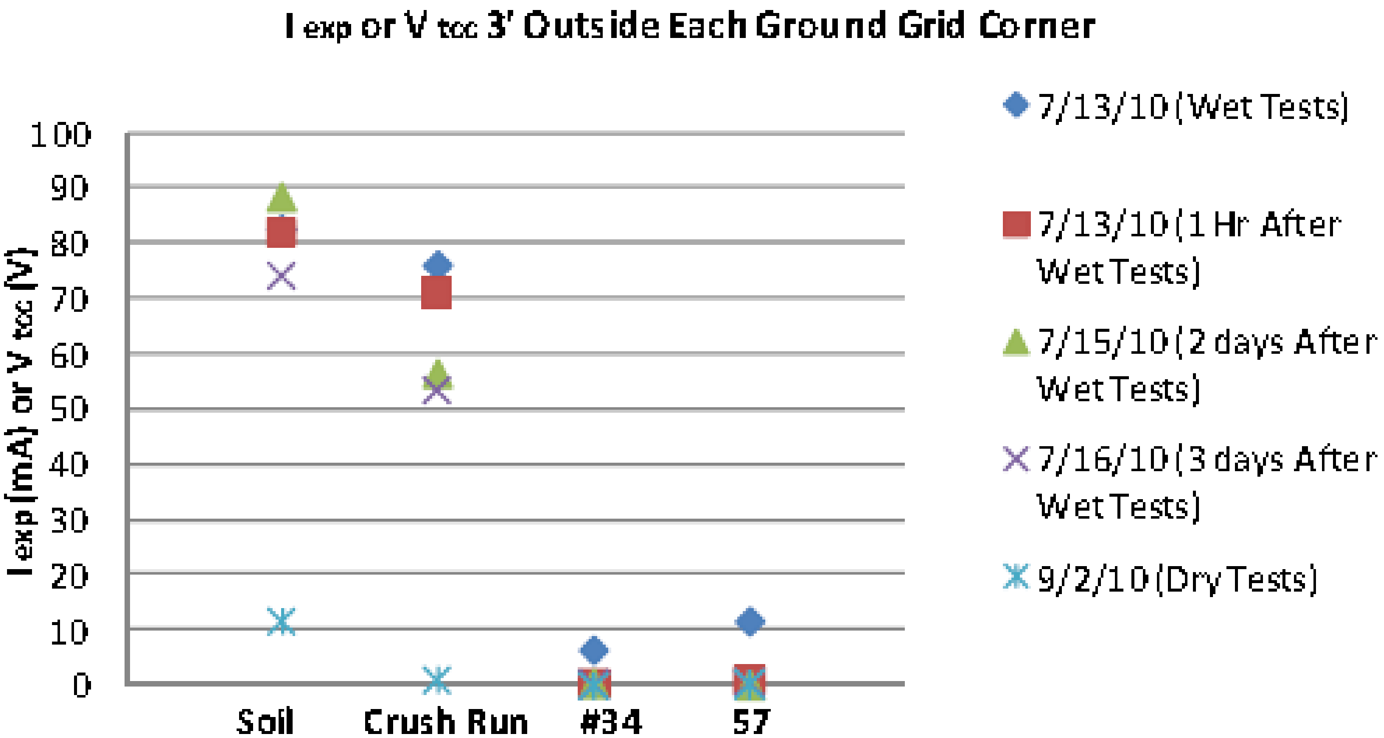


Figure 3-28
I_{exp} or V_{tcc} (Corner Points, All Weather)

KEY OBSERVATIONS

- Between wet and dry conditions, the wet condition causes the maximum exposure current for each type of surfacing material including the native soil.
- In wet conditions, the exposure currents are significantly higher for concrete and 1 ½" crusher run compared to washed gravels (#34 and #57) and asphalt. (Note that the concrete pad has no rebar)
- In wet conditions, the performance of 1½" crusher run and concrete is almost the same as the native soil.
- Between #34 and #57 washed gravel, the performance of #34 gravel is slightly better due to larger sized rocks.
- The exposure currents on washed gravel (#34 and #57) and asphalt beds reduce dramatically within an hour from wetting. In comparison, 1 ½" crusher run took three days of drying to reduce the exposure current level to that of washed gravel.
- As expected, the highest exposure currents were measured three feet outside the ground grid corners.
- In the case of washed gravel and asphalt, the change in exposure currents is much more dramatic (several orders of magnitudes) compared to the change in the open circuit touch voltage.

RESULTS – WET TESTS R_{thev}

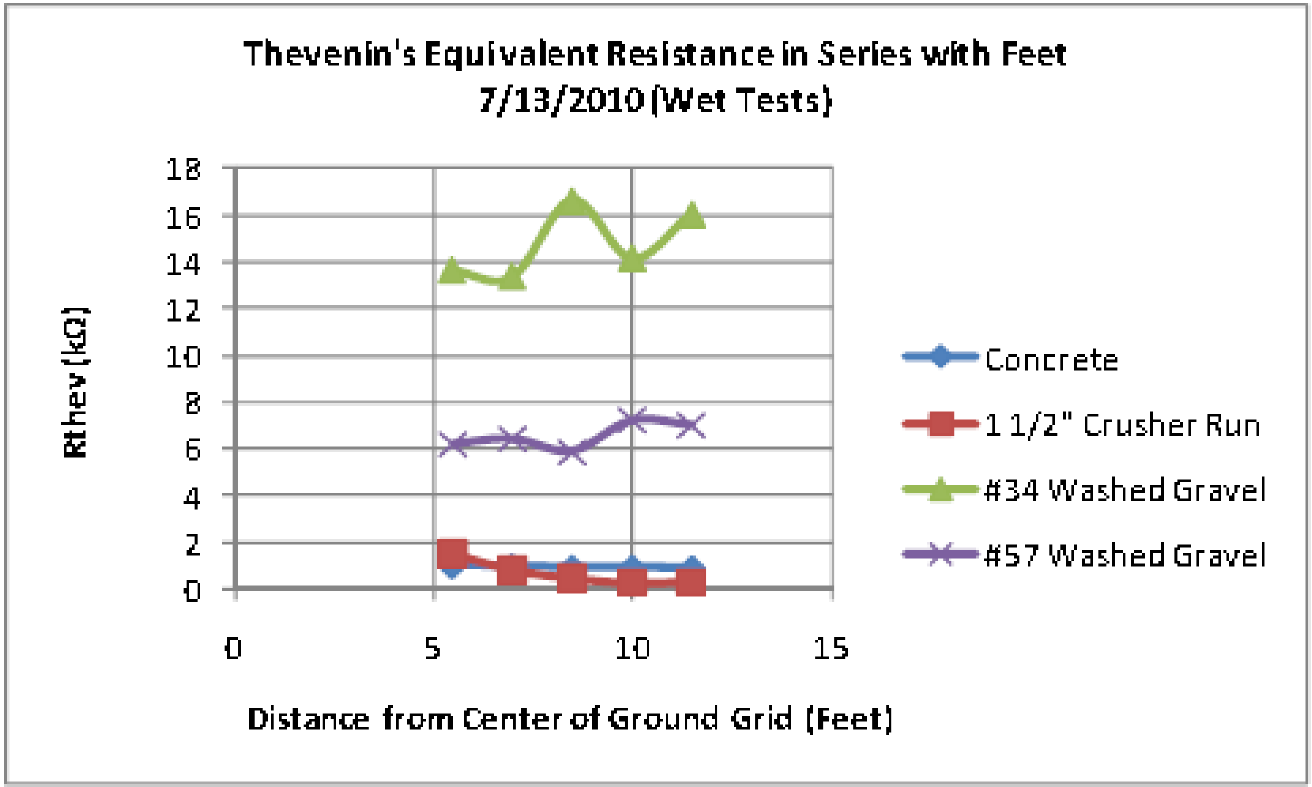


Figure 3-29
R_{thev} , (7/13/2010, Wet Tests)

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RESULTS – 1HR WET TESTS R_{thev}

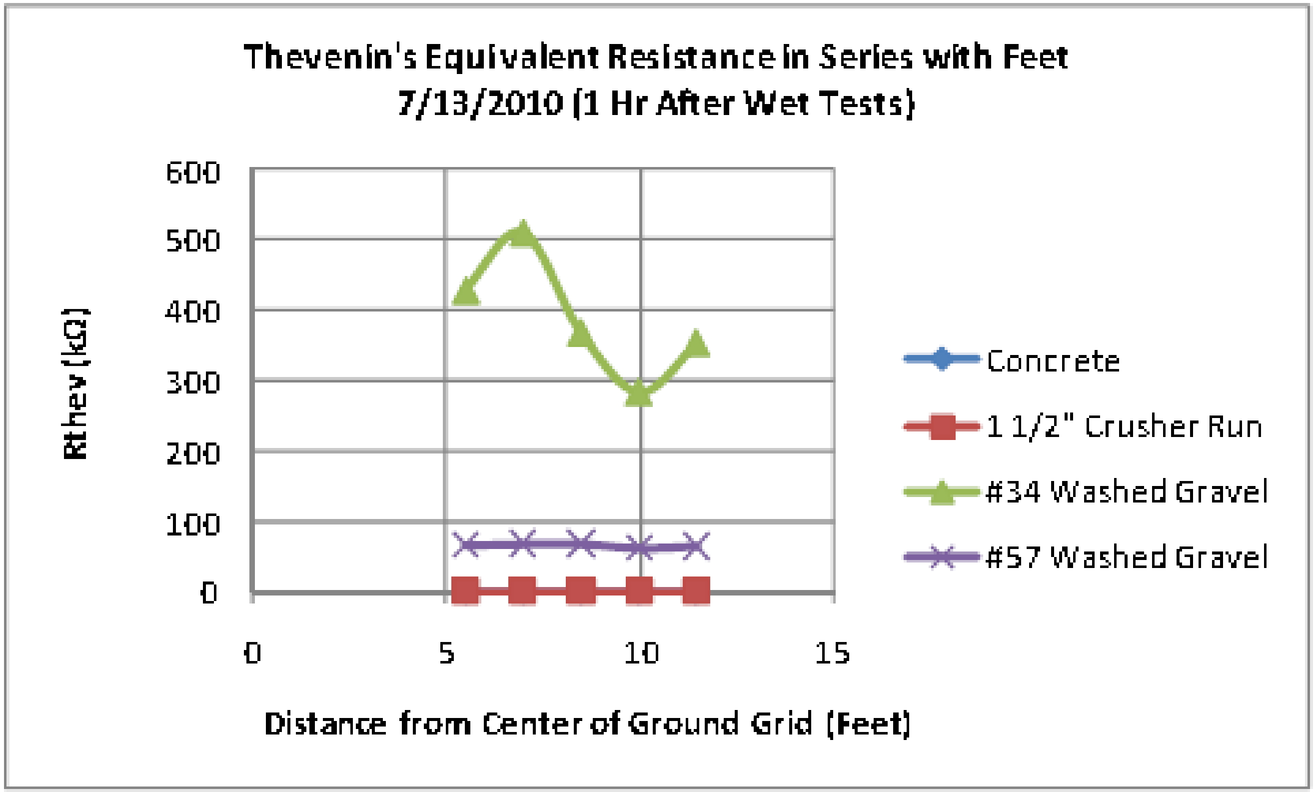

Figure 3-30
R_{thev} (1 Hr After Wet Tests)

RESULTS – DRY TESTS RE-RUN R_{thev}

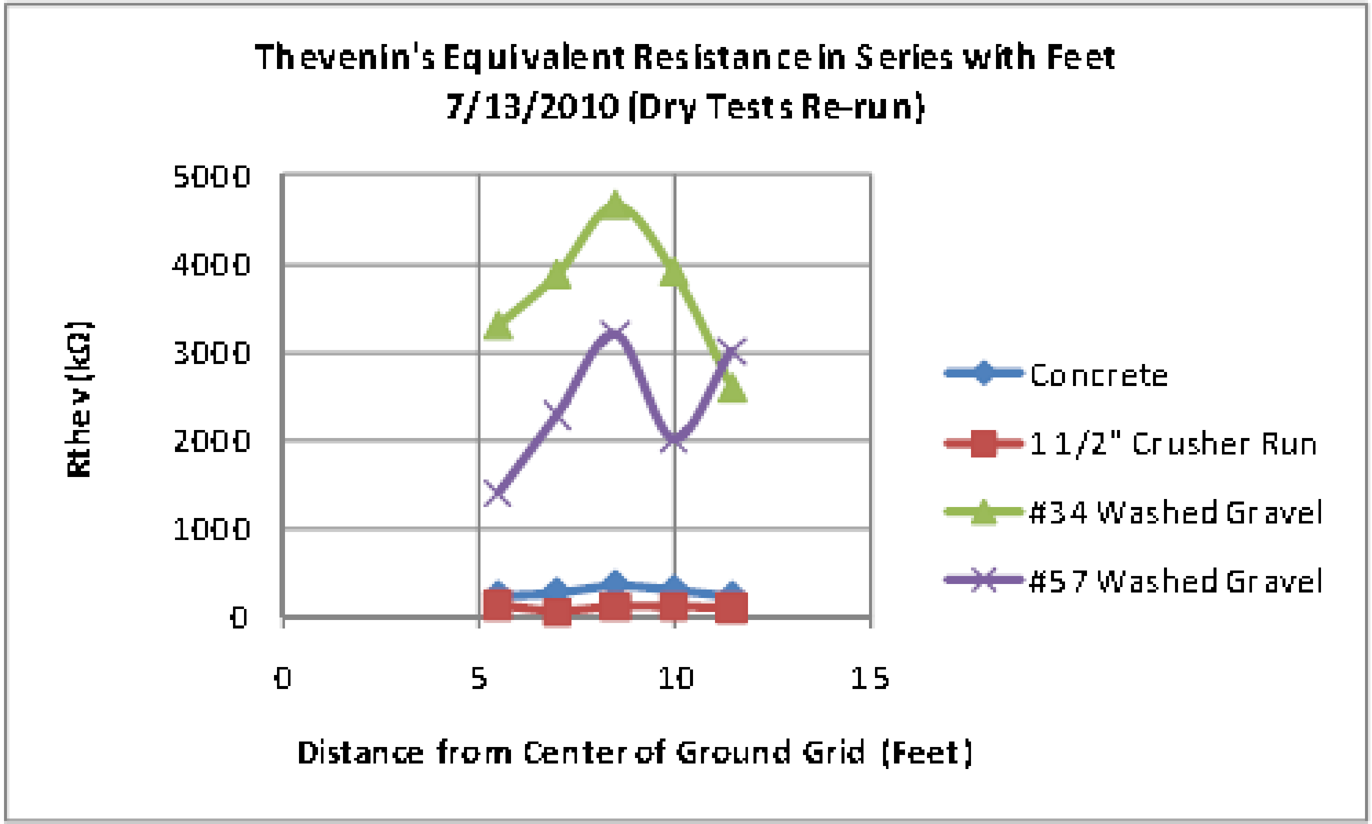

Figure 3-33
R_{thev}, (Dry Tests Re-run)

RESISTIVITY - ASPHALT

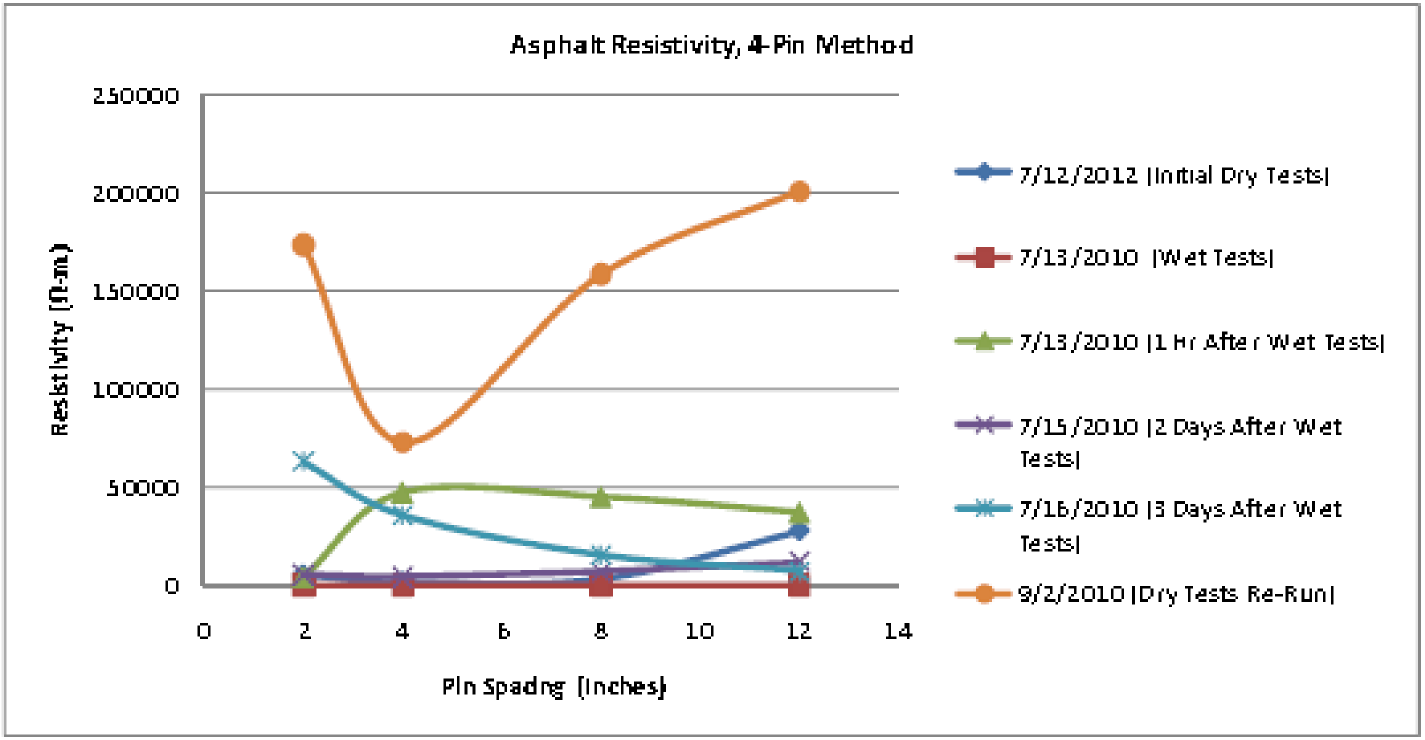

Figure 3-35
Asphalt Resistivity at Different Pin Spacing and Moisture Conditions

PROBLEMS WITH PIN CONTACT RESISTANCE IN ASPHALT

RESISTIVITY – DRY GRAVEL

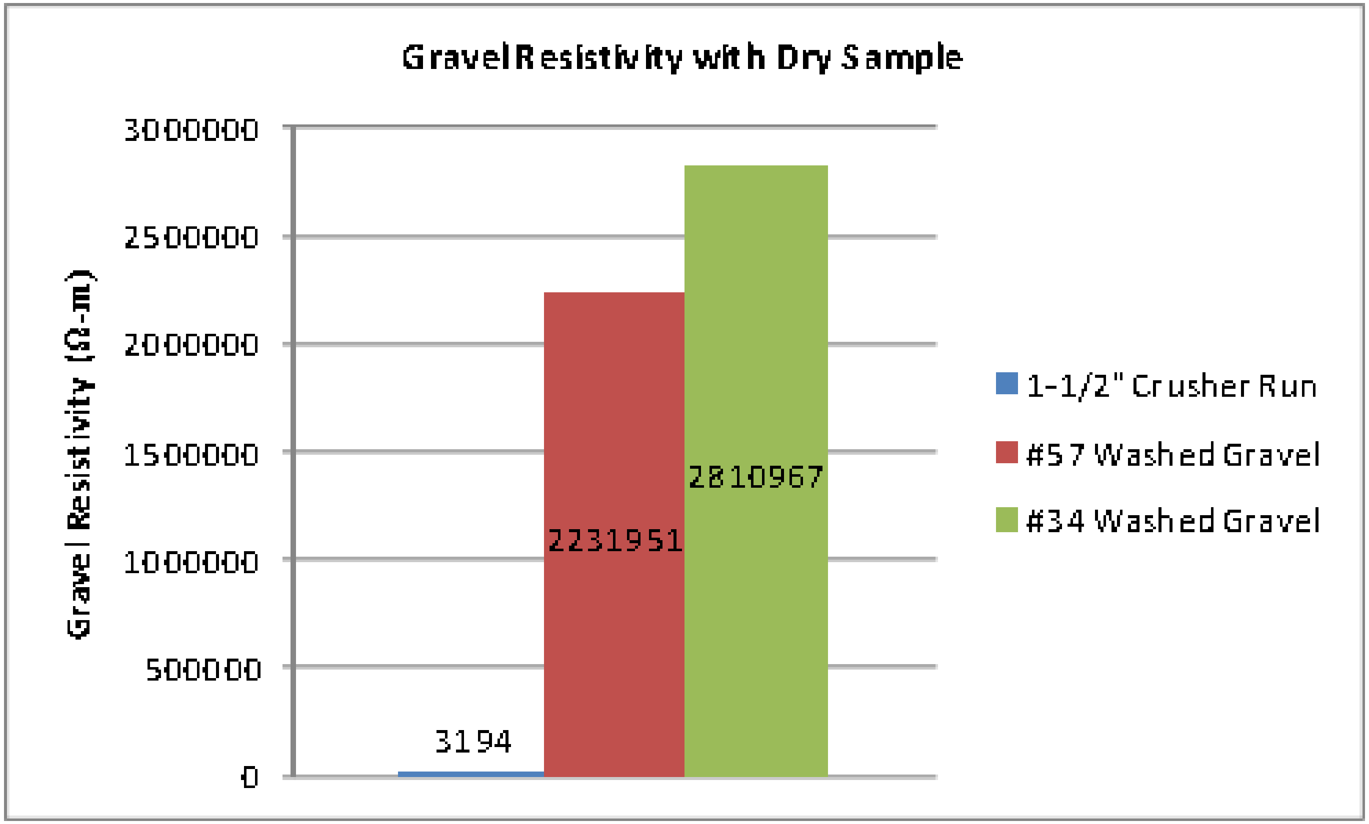

Figure 3-38
Resistivity of Gravel Samples (Sample Dry)

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RESISTIVITY – SATURATED GRAVEL

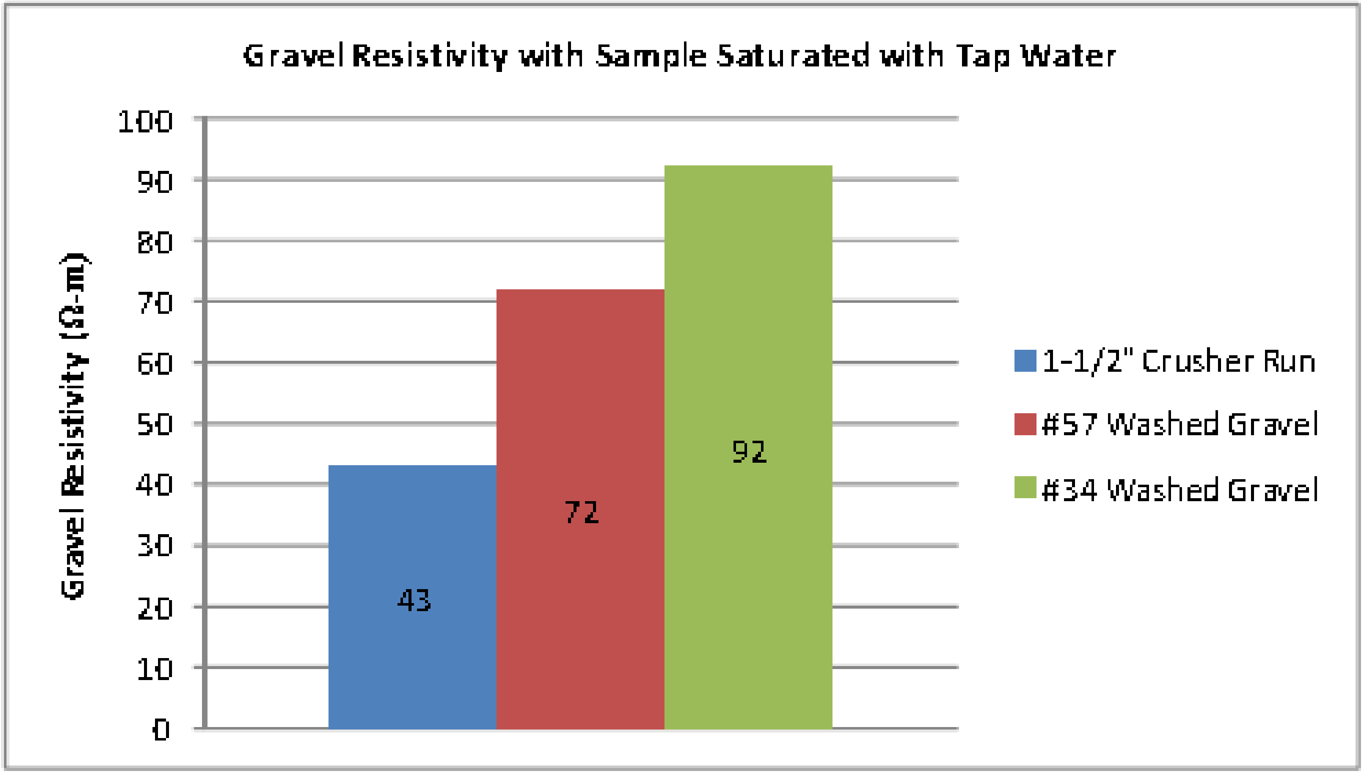

Figure 3-36
Resistivity of Gravel Samples (Sample Saturated with Tap Water)

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RESISTIVITY – DRAINED GRAVEL

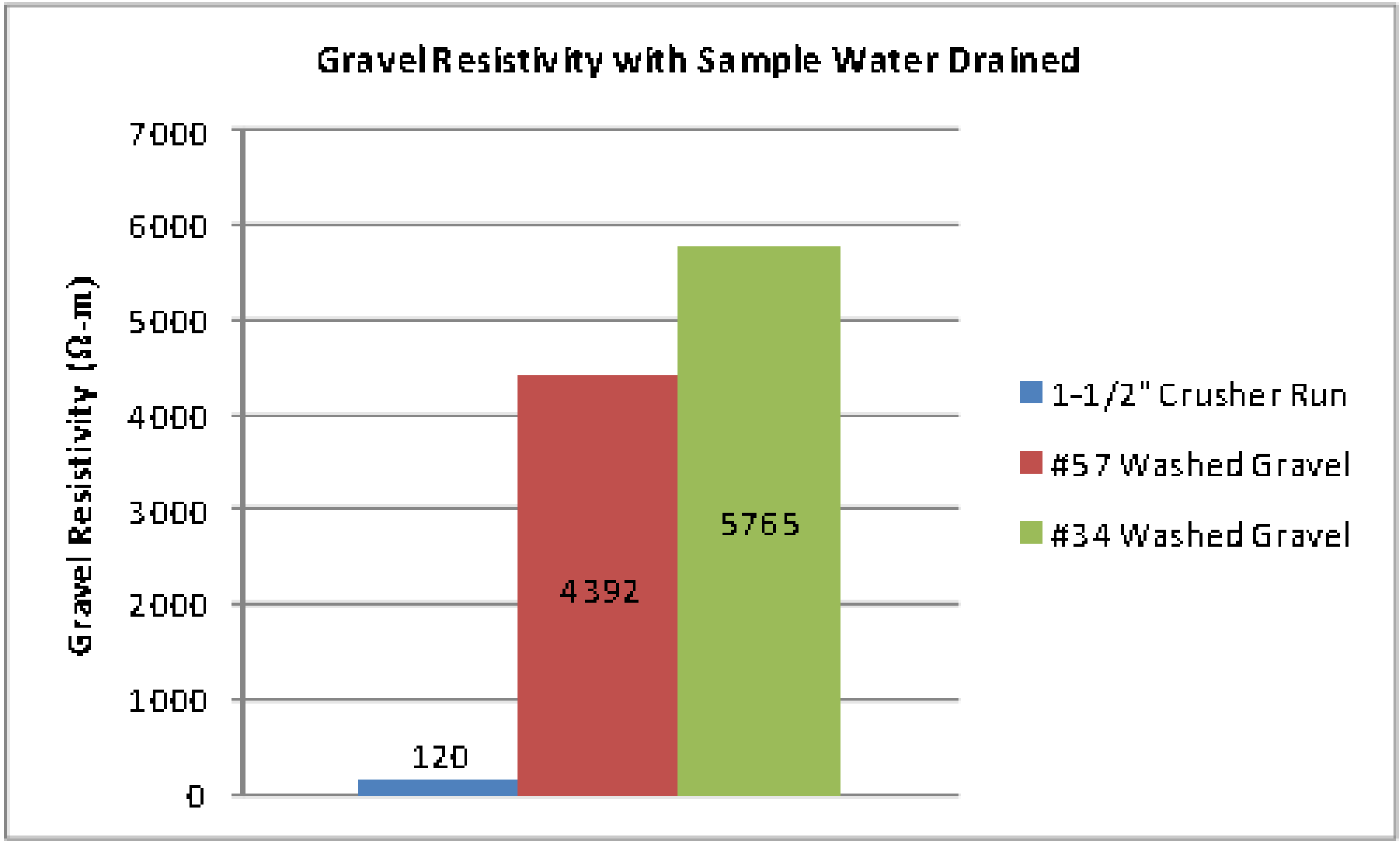

Figure 3-37
Resistivity of Gravel Samples (Sample with Water Drained)

SO WHAT ARE THE WORST CASE DESIGN ASSUMPTIONS?

LOOKING AT COMPUTED (OPEN-CIRCUIT) TOUCH VOLTAGES INDEPENDENTLY FROM TOLERABLE VOLTAGES, ONE MIGHT THINK WORST CASE IS FOR VERY DRY SOIL (HIGH RESISTIVITY AND CORRESPONDING HIGH TOUCH VOLTAGES) AND VERY WET SURFACE COVER (LOW RESISTIVITY AND LOW R_{thev})

HOWEVER, UPON FURTHER REVIEW….

THESE TESTS INDICATE WORST CASE IS FOR BOTH SOIL AND SURFACE COVER BEING VERY WET – GIVES HIGHEST BODY CURRENT I_{exp}

THEREFORE, ANY STANDARDIZED ROCK RESISTIVITY TESTING SHOULD BE DONE FOR WET ROCK CONDITIONS. BUT HOW WET? SATURATED OR DRAINED? TBD

COMPARISON TO STD 80 (NOT PART OF THIS PROJECT)

SAMPLE	LOCATION	SAMPLE r	SOIL r	Voc	Icc mA	Rthev C	Cs 80	Rthev 80
1-1/2 CRUSHER RUN RERUN	V11	3195	195	40.8	0.315	128523.8	0.71	3395.948
1-1/2 CRUSHER RUN RERUN	V12	3195	195	44.7	0.85	51588.24	0.71	3395.948
1-1/2 CRUSHER RUN RERUN	V13	3195	195	47.3	0.42	111619	0.71	3395.948
1-1/2 CRUSHER RUN RERUN	V14	3195	195	47.3	0.412	113805.8	0.71	3395.948
1-1/2 CRUSHER RUN RERUN	V15	3195	195	49.3	0.54	90296.3	0.71	3395.948
1-1/2 CRUSHER RUN RERUN	V1C	3195	195	113.7	0.85	132764.7	0.71	3395.948
1-1/2 CRUSHER RUN WET	V11	43	195	30.3	12.1	1504.132	2.10	135.2586
1-1/2 CRUSHER RUN WET	V12	43	195	32.5	17.9	815.6425	2.10	135.2586
1-1/2 CRUSHER RUN WET	V13	43	195	34.5	23.7	455.6962	2.10	135.2586
1-1/2 CRUSHER RUN WET	V14	43	195	35.8	28.5	256.1404	2.10	135.2586
1-1/2 CRUSHER RUN WET	V15	43	195	36.8	28.2	304.9645	2.10	135.2586
1-1/2 CRUSHER RUN WET	V1C	43	195	102.6	76	350	2.10	135.2586
1-1/2 CRUSHER RUN 1HR	V11	120	195	32.1	14.9	1154.362	1.19	214.9138
1-1/2 CRUSHER RUN 1HR	V12	120	195	34.5	17.3	994.2197	1.19	214.9138
1-1/2 CRUSHER RUN 1HR	V13	120	195	36.6	18.1	1022.099	1.19	214.9138
1-1/2 CRUSHER RUN 1HR	V14	120	195	38.2	22.9	668.1223	1.19	214.9138
1-1/2 CRUSHER RUN 1HR	V15	120	195	39.3	19.1	1057.592	1.19	214.9138
1-1/2 CRUSHER RUN 1HR	V1C	120	195	102.2	71.2	435.3933	1.19	214.9138

COMPARISON TO STD 80 (NOT PART OF THIS PROJECT)

SAMPLE	LOCATION	SAMPLE ρ	SOIL ρ	Voc	Icc mA	Rthev C		Cs 80	Rthev 80
#57 RERUN	V41	2232620	195	29.1	0.0208	1398038		0.69	2309698
#57 RERUN	V42	2232620	195	29.2	0.0128	2280250		0.69	2309698
#57 RERUN	V43	2232620	195	29.4	0.0092	3194652		0.69	2309698
#57 RERUN	V44	2232620	195	34.7	0.0173	2004780		0.69	2309698
#57 RERUN	V45	2232620	195	30.7	0.0102	3008804		0.69	2309698
#57 RERUN	V4C	2232620	195	69	0.0202	3414842		0.69	2309698
#57 WET	V41	72	195	28.7	4	6175		1.53	165.2586
#57 WET	V42	72	195	32.6	4.4	6409.091		1.53	165.2586
#57 WET	V43	72	195	35.7	5.2	5865.385		1.53	165.2586
#57 WET	V44	72	195	37.8	4.6	7217.391		1.53	165.2586
#57 WET	V45	72	195	39.3	4.9	7020.408		1.53	165.2586
#57 WET	V4C	72	195	100.4	11.3	7884.956		1.53	165.2586
#57 1HR	V41	4392	195	28.8	0.423	67085.11		0.70	4634.224
#57 1HR	V42	4392	195	32.5	0.464	69043.1		0.70	4634.224
#57 1HR	V43	4392	195	35.9	0.512	69117.19		0.70	4634.224
#57 1HR	V44	4392	195	38.2	0.598	62879.6		0.70	4634.224
#57 1HR	V45	4392	195	39.6	0.592	65891.89		0.70	4634.224
#57 1HR	V4C	4392	195	97.6	0.74	130891.9		0.70	4634.224

COMPARISON TO STD 80 (NOT PART OF THIS PROJECT)

SAMPLE	LOCATION	SAMPLE ρ	SOIL ρ	Voc	Icc mA	Rthev C		Cs 80	Rthev 80
#34 RERUN	V31	2811809	195	24.2	0.0073	3314068		0.69	2908859
#34 RERUN	V32	2811809	195	24.1	0.0062	3886097		0.69	2908859
#34 RERUN	V33	2811809	195	23.8	0.0051	4665667		0.69	2908859
#34 RERUN	V34	2811809	195	27.4	0.007	3913286		0.69	2908859
#34 RERUN	V35	2811809	195	34.7	0.0133	2608023		0.69	2908859
#34 RERUN	V3C	2811809	195	60.6	0.0134	4521388		0.69	2908859
#34 WET	V31	92	195	32.2	2.2	13636.36		1.35	185.9483
#34 WET	V32	92	195	35.9	2.5	13360		1.35	185.9483
#34 WET	V33	92	195	38.8	2.2	16636.36		1.35	185.9483
#34 WET	V34	92	195	40.9	2.7	14148.15		1.35	185.9483
#34 WET	V35	92	195	42.6	2.5	16040		1.35	185.9483
#34 WET	V3C	92	195	108.8	6.1	16836.07		1.35	185.9483
#34 1HR	V31	5765	195	31.3	0.084	371619		0.70	6054.569
#34 1HR	V32	5765	195	34.5	0.081	424925.9		0.70	6054.569
#34 1HR	V33	5765	195	38.1	0.156	243230.8		0.70	6054.569
#34 1HR	V34	5765	195	39.9	0.171	232333.3		0.70	6054.569
#34 1HR	V35	5765	195	41.5	0.158	261658.2		0.70	6054.569
#34 1HR	V3C	5765	195	103.9	0.372	278301.1		0.70	6054.569

REASONS FOR GREAT DIFFERENCES BETWEEN MEASURED & STD 80?

- MUTUAL RESISTANCE BETWEEN FEET AND GRID , PLUS BETWEEN FEET IS IGNORED IN STD 80
- UNKNOWN "TRUE" RESISTIVITY OF SOIL FOR EACH CONDITION
- **STD 80 ASSUMES PERFECT CONTACT WITH SURFACE, WHILE THERE MIGHT BE SIGNIFICANT CONTACT RESISTANCE IN MEASUREMENTS**

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