Substation Grounding Tutorial

Joe Gravelle, P.E.
Eduardo Ramirez-Bettoni, P.E.

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Presenter – Joe Gravelle, P.E.

Joe Gravelle earned BSEEE from NDSU in 1988. After graduation Joe worked in the mining industry in northeastern Minnesota for ten years. Joe is a principal engineer in the Substation Engineering department at Xcel Energy and has held many roles in the department since 1998.

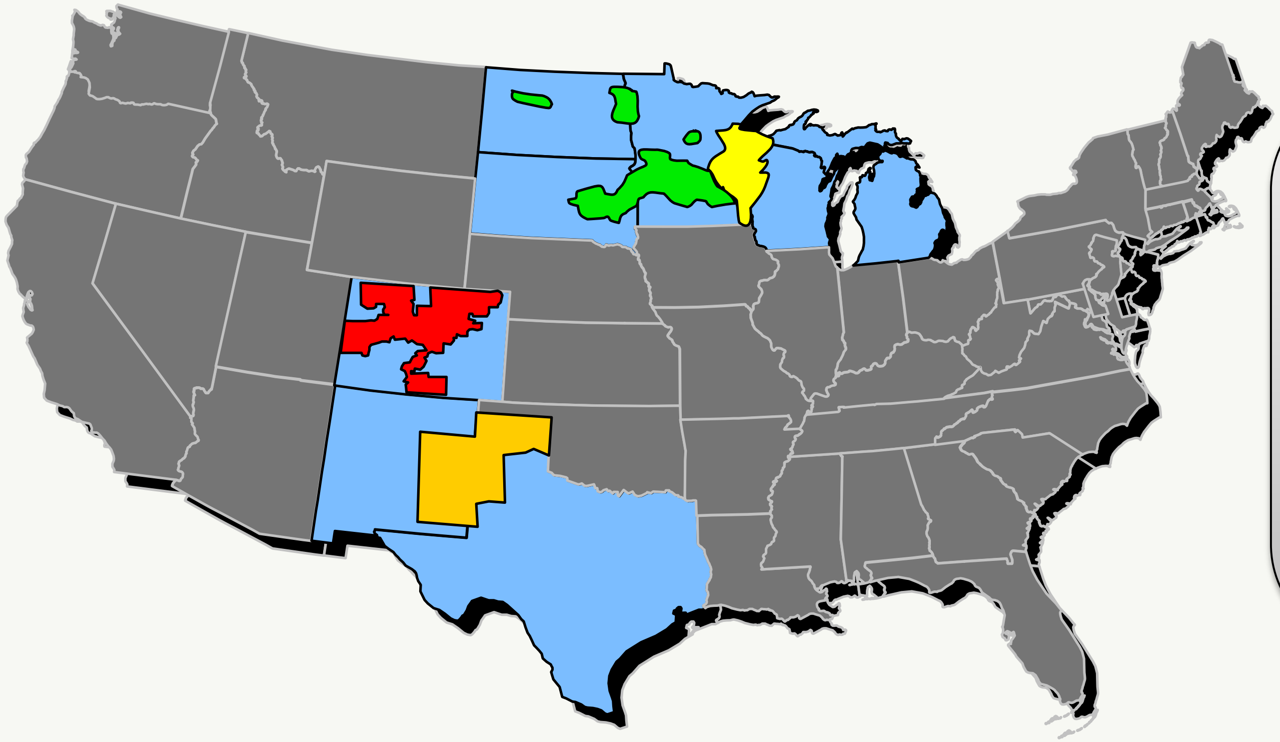
In addition to substation projects, Joe is active in standards work both at Xcel Energy and in IEEE Substations Committee. Joe is currently the vice chair of the Substations Committee and is active in leadership roles and as an active member in several IEEE working groups.

Presenter – Eduardo Ramirez-Bettoni, P.E.

Eduardo obtained a BSEE with Power System emphasis from University of Costa Rica in 2002. Eduardo has international experience in substation construction, O&M, and design in substations up to 500 kV. He has practiced engineering in the U.S., Canada and Costa Rica. Eduardo has a background in protection & control, substation physical design and power system grounding.

Eduardo works as principal engineer for Xcel Energy in the Transmission & Substation Standards (TSS) department. TSS creates standard documents for design, specification and installation practices for transmission & substation facilities. Eduardo is an active member in IEEE Substation working groups.

Xcel Energy



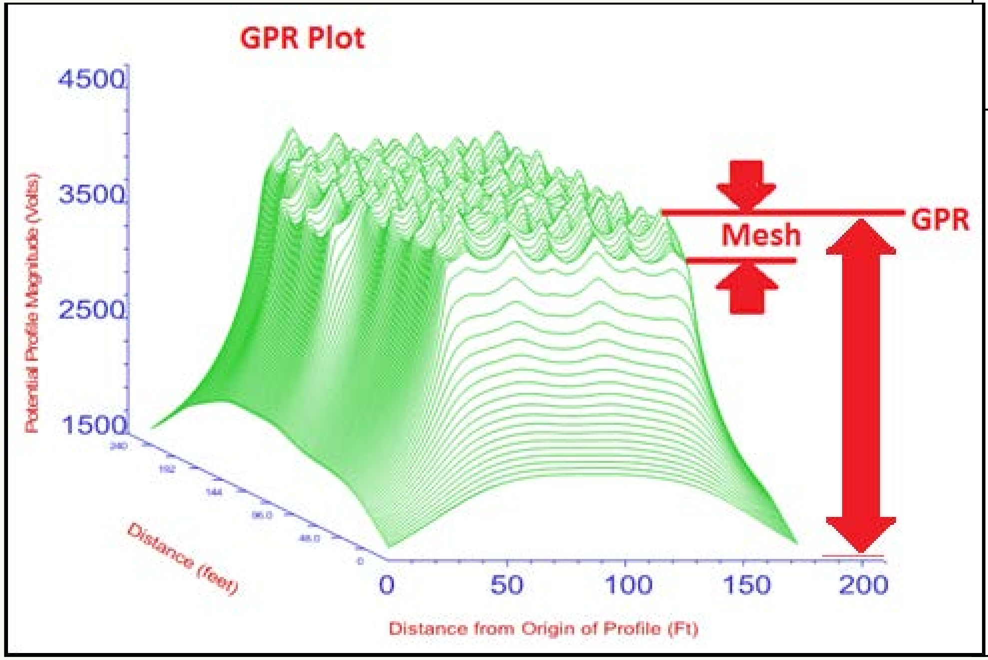
- No. 1 utility wind energy provider in the U.S.
- 3.4 million electric customers
- 2 million natural gas customers
- 12,000 employees

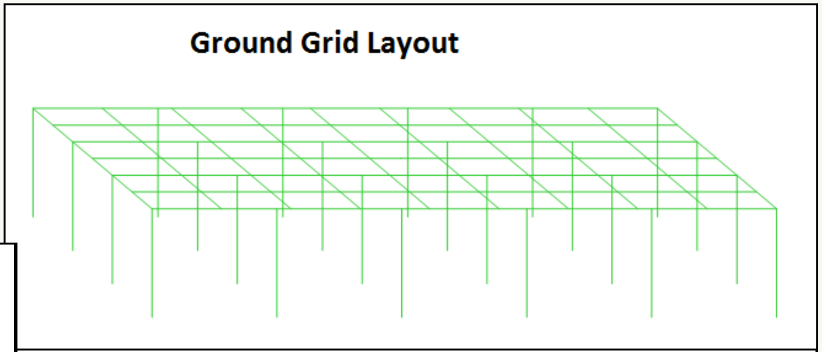
Agenda

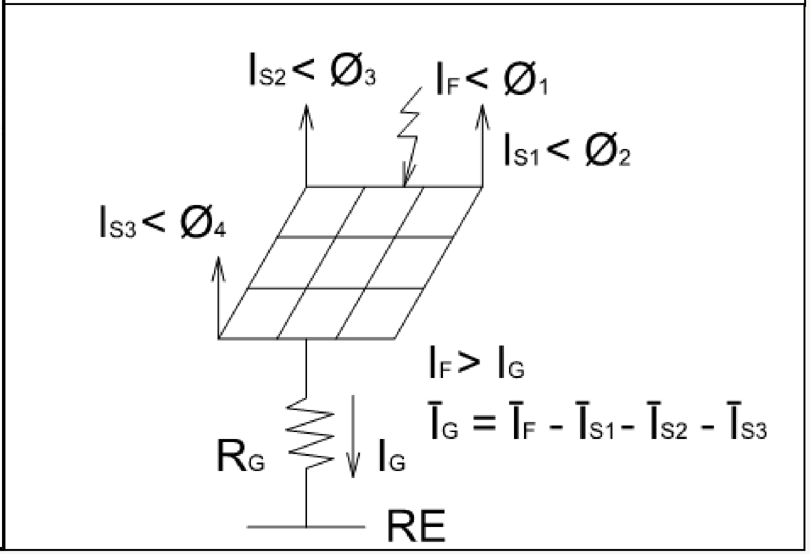
1. Grounding Basics
2. Soil Resistivity Testing and Soil Modelling
3. Design & Modelling of Substation Grid
4. Break
5. Grounding Design Variables
   - Soil model variables
   - Seasonal modelling of soil
   - Crushed rock resistivity
   - Fault current design margin
   - Fault clearing time
   - Summary / Combined effect

Grounding Basics

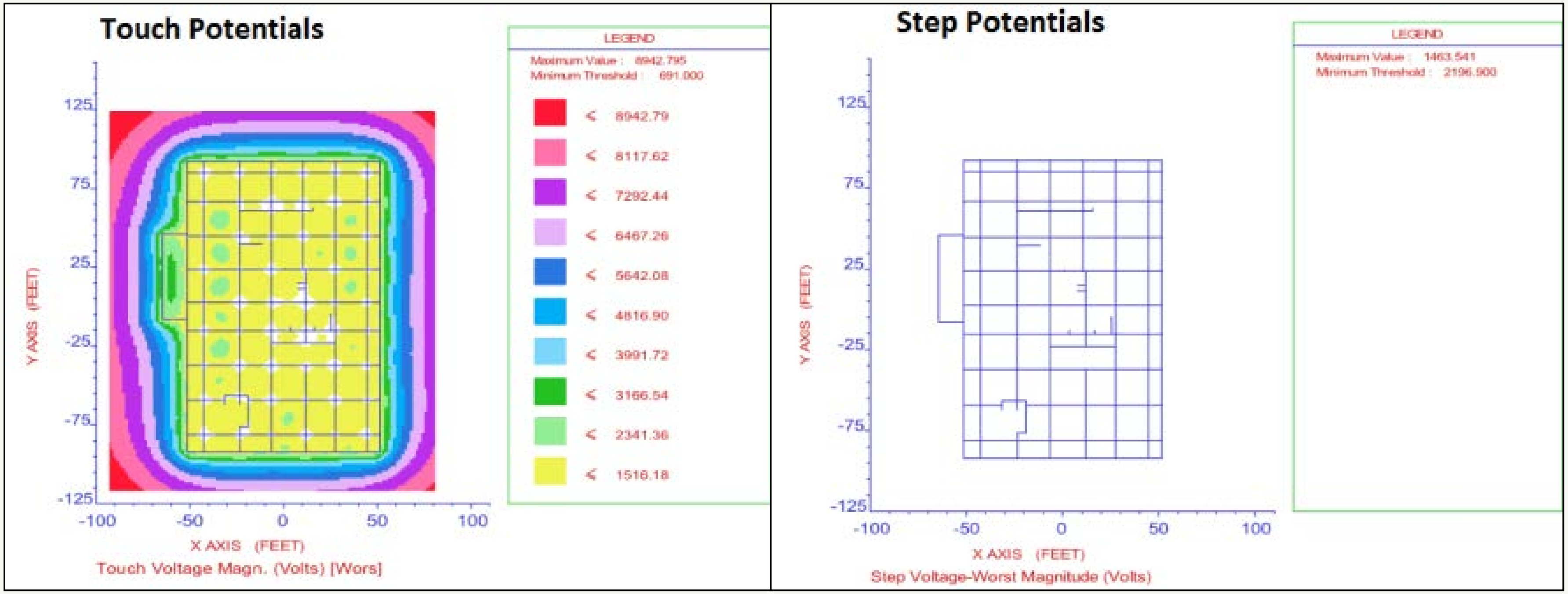
- Definitions per IEEE 80 & 81
- GPR, mesh / step / touch
- Current split







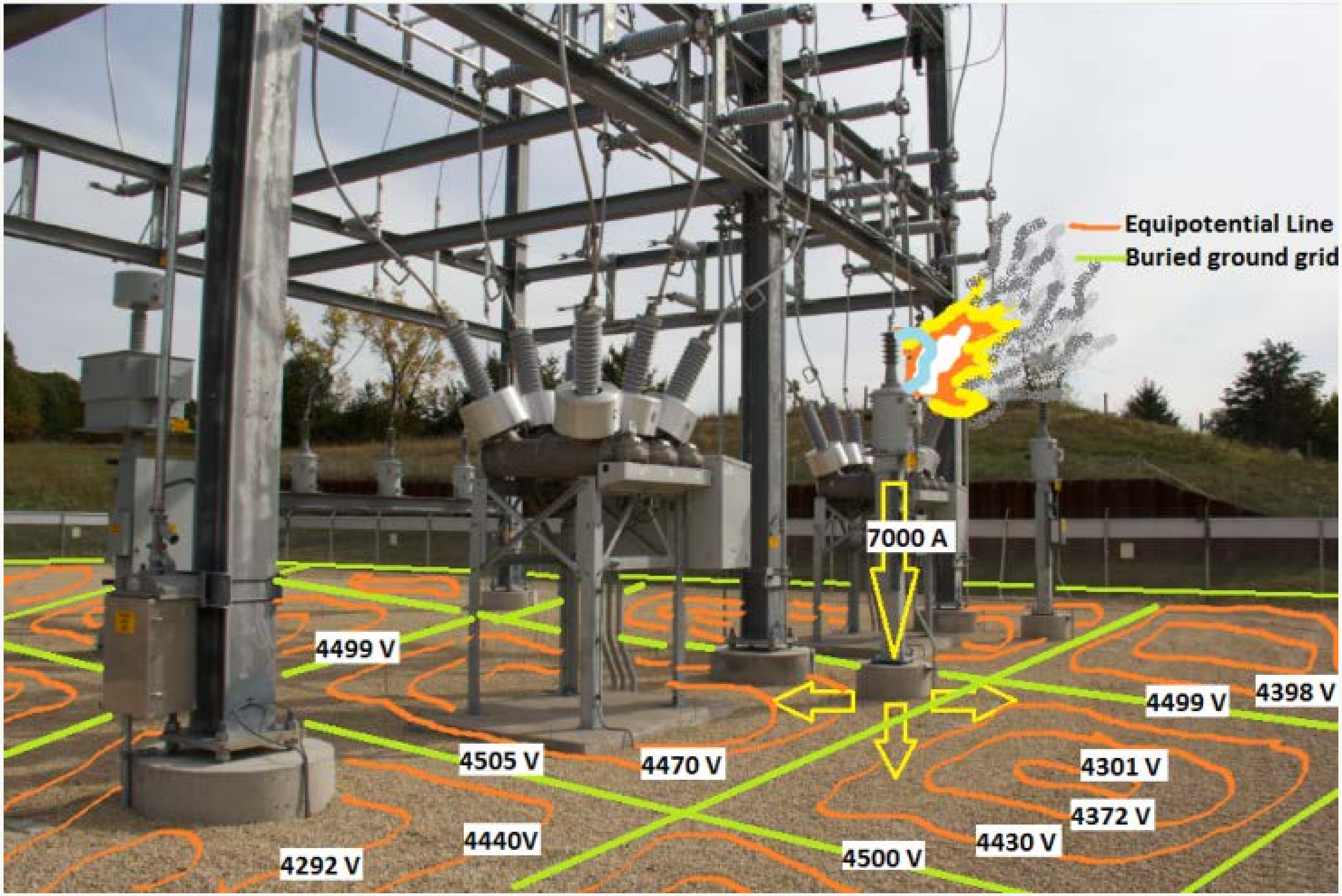
Grounding Basics



- Touch potentials: 3’ hand-to-foot
- Step potentials: 3’ foot-to-foot
- Safe if Calculated Values < Tolerable Max Values

Grounding Basics

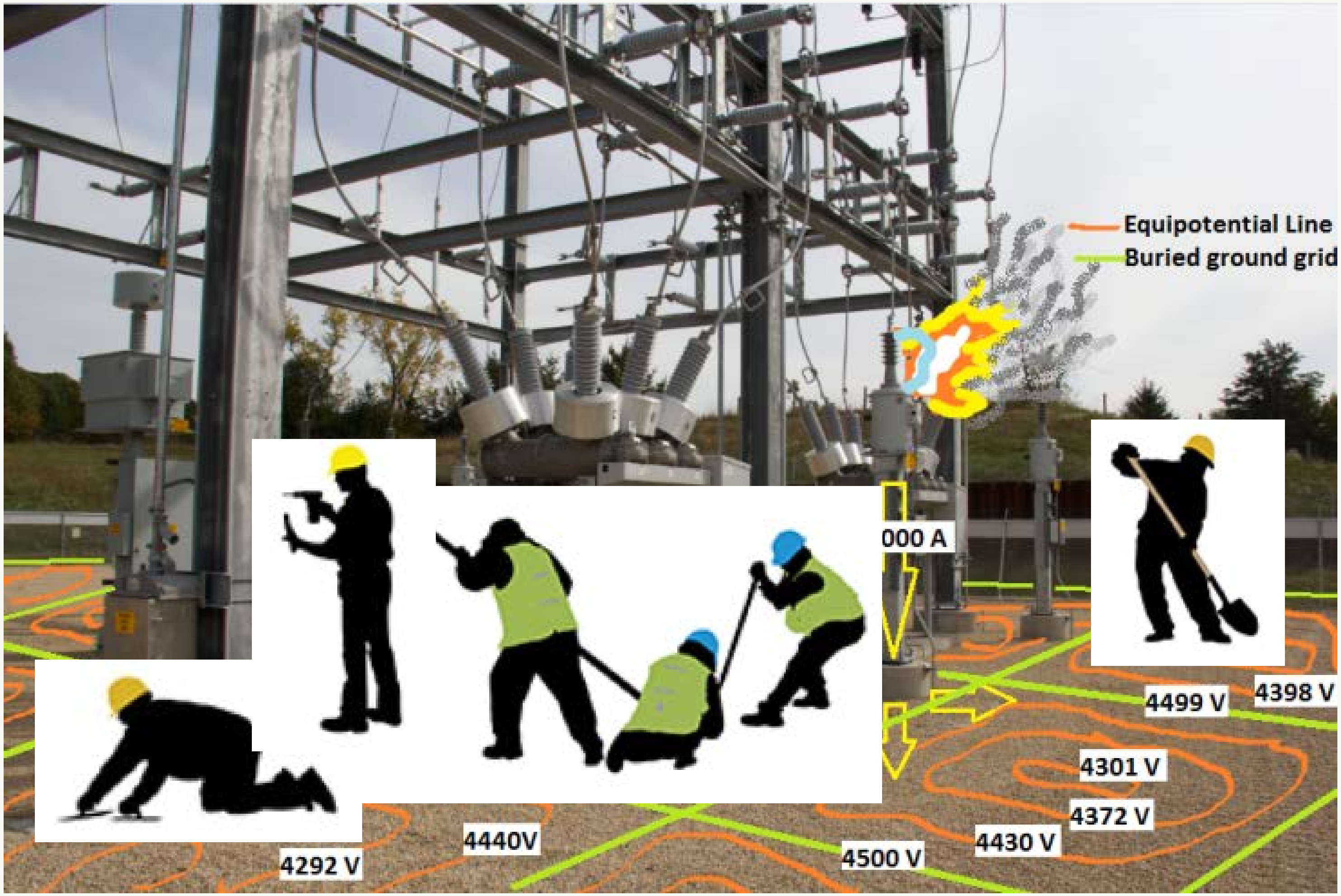
Grounding Basics



Grounding Basics - Example

- Future fault current: 7000 A
- Earth current: 4200 A, (split factor S_f = 60%)
- Grid resistance: 1.07 Ω
- GPR $_{nom}$= 1.07Ω x 4200 A = 4500 V
- Mesh voltage = 210 V
- Body current I_B (500 ms, 50 kg) = 0.116/SQRT(0.5) = 164 mA

Grounding Basics - Example



Grounding Basics

- Body current (I_B) is based on let-go current per experimentation (99.5 % percentile, no ventricular fibrillation)
- Body resistance (R_B) varies based on exposure voltage
- R_B= 500-1000 Ω

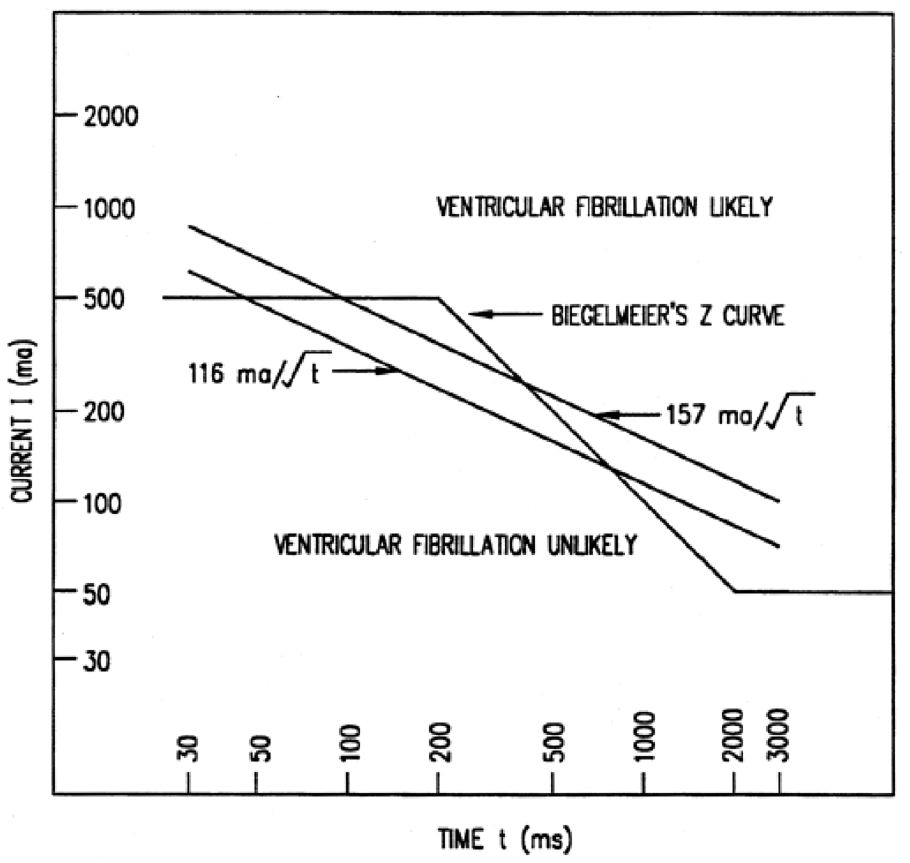


Figure 5—Body current versus time

Source: IEEE 80-2015

Grounding Basics - Example

- Future fault current: 7000 A
- Earth current: 4200 A, (split factor S_f = 60%)
- Grid resistance: 1.07 Ω
- GPR_{nom} = 1.07 Ω x 4200 A = 4500 V
- Mesh voltage = 210 V
- Body current I_B (500 ms, 50 kg) = 0.116 / SQRT(0.5) = 164 mA

Example - Body Voltage

- Tolerable potential across 50 kg body, body only

Percentile	IB (A)	RB (Ω)	VB (V)	Body Configuration
95%	0.164	1000	164	Hand-hand; Foot-foot
95%	0.164	750	123	Hand-both feet
95%	0.164	500	82	Both hands-both feet
95%	0.164	700	115	Hand-trunk

- $V_B = I_B \times R_B$ (for TPG calculations)

Example-Touch potential (no rock)

- Tolerable potential across 50 kg body, step voltage, no surface rock
- Homogeneous soil resistivity: 100 Ω-m
- Accounts for foot resistance to surface, $V_{t,\ 50kg} = I_B \times (R_B + 1.5\rho)$

Percentile	IB (A)	RB (Ω)	Vtouch (V)	Body Configuration
95%	0.164	1000	201	Hand-hand; Foot-foot
95%	0.164	750	148	Hand-both feet
95%	0.164	500	107	Both hands-both feet
95%	0.164	700	140	Hand-trunk

$$E_{touch} = I_B(R_B + 1.5\rho)$$

and

$$E_{step} = I_B(R_B + 6.0\rho)$$

Source: IEEE 80-2015

Example-Touch potential (with rock)

$$E_{touch50} = (1000 + 1.5C_s \times \rho_s)\frac{0.116}{\sqrt{t_s}}$$

for body weight of 70 kg

$$E_{touch70} = (1000 + 1.5C_s \times \rho_s)\frac{0.157}{\sqrt{t_s}}$$

$$C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09}$$

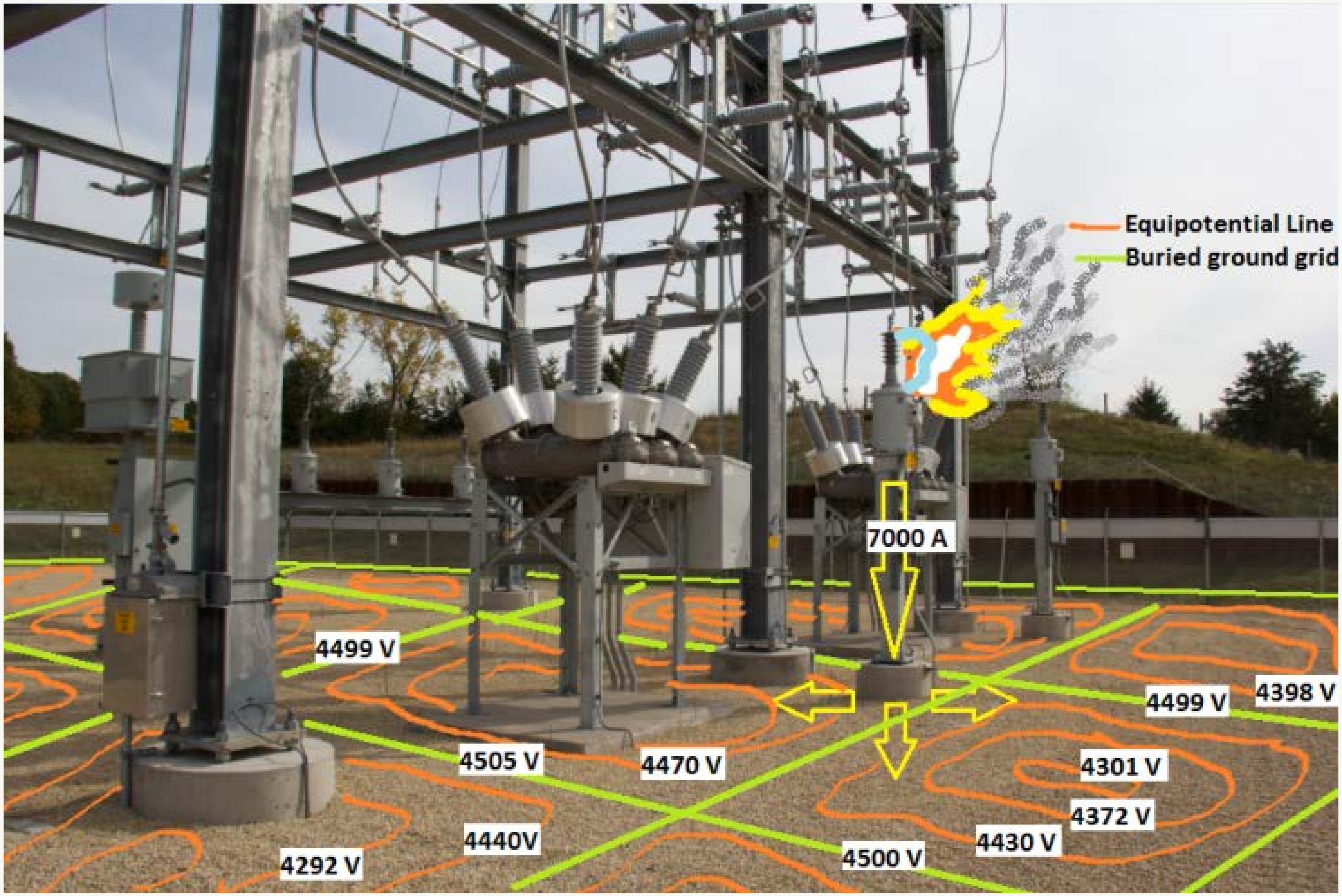
Example-Touch potential (with rock)

- Tolerable potential across 50 kg body, step voltage, 4” of 2000 Ω-m surface rock; homogeneous soil resistivity: 100 Ω-m

Percentile	IB (A)	RB (Ω)	Vtouch (V)	Body Configuration
95%	0.164	1000	513	Hand-foot
95%	0.164	750	473	Hand-both feet
95%	0.164	500	432	Both hands-both feet
95%	0.164	700	464	Hand-trunk

- $V_{t,50kg} = I_B \text{ x } (R_B+1.5\text{x}C_s\text{x}\rho)$; (Cs=0.71)

Grounding Basics



Grounding Basics

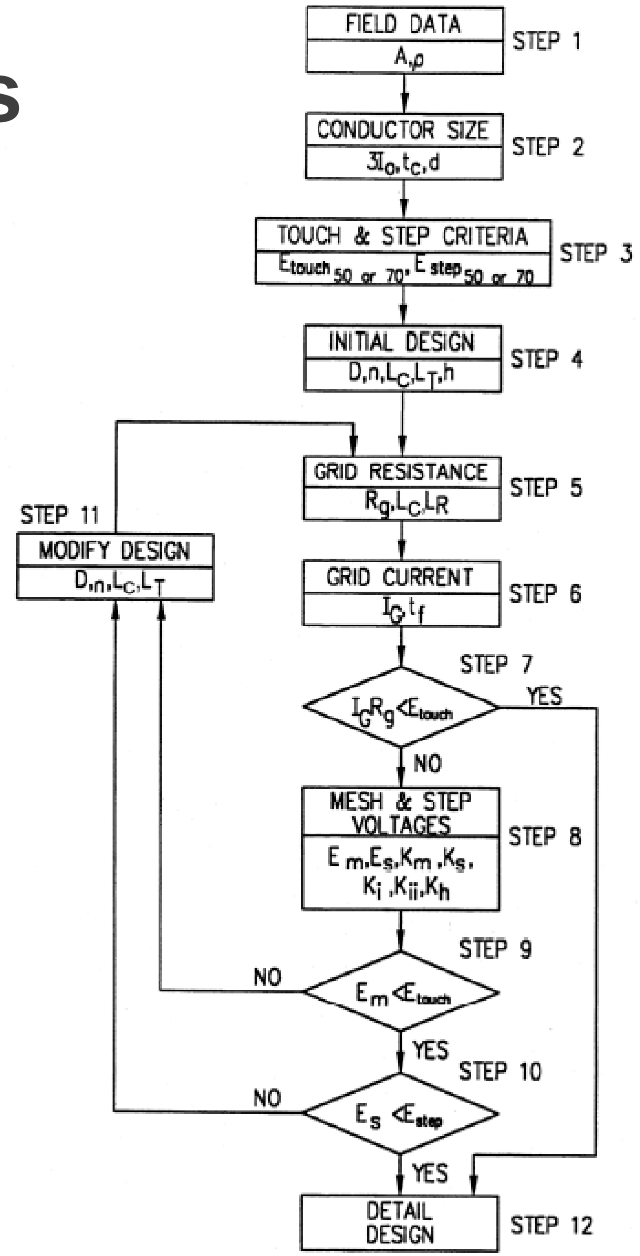
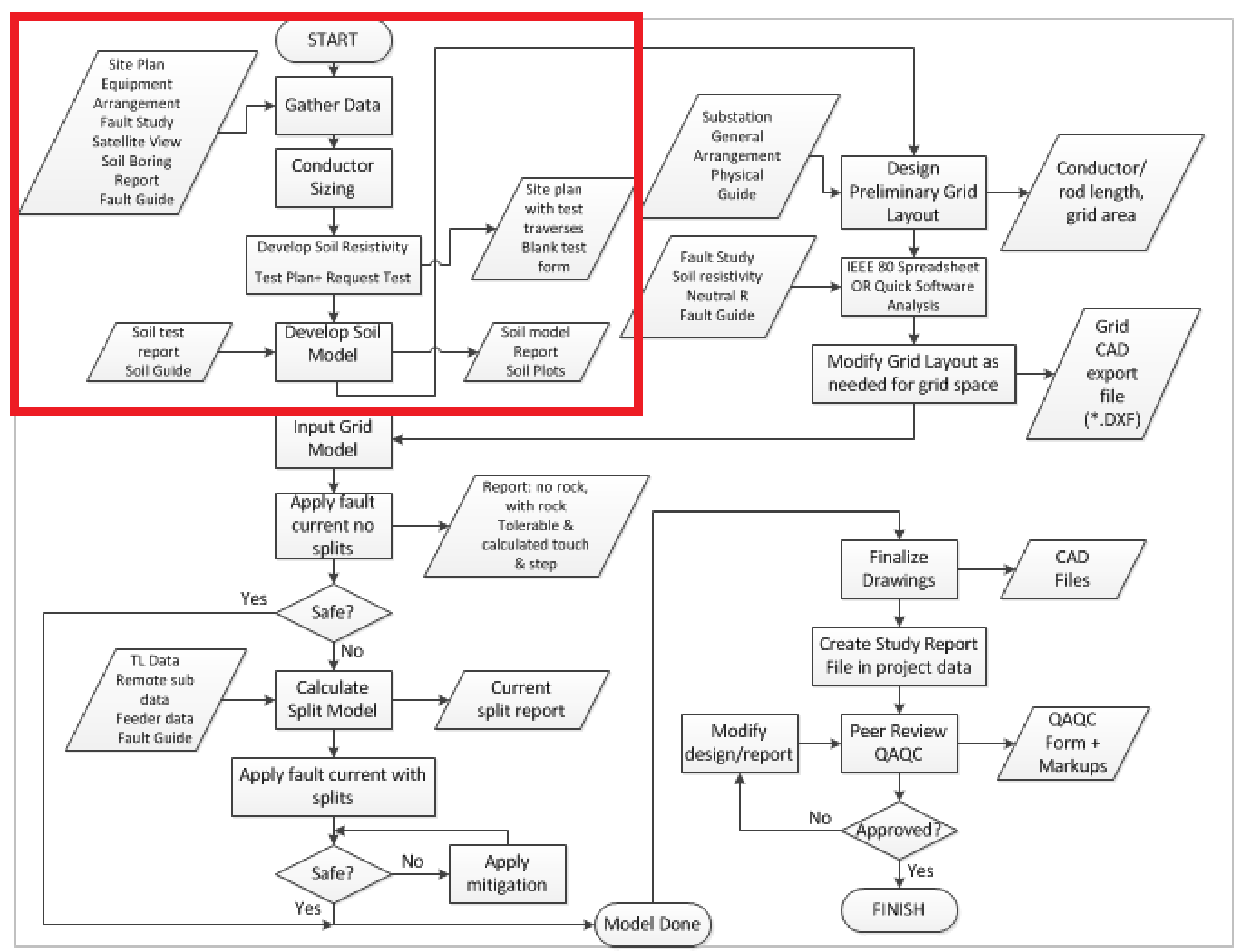


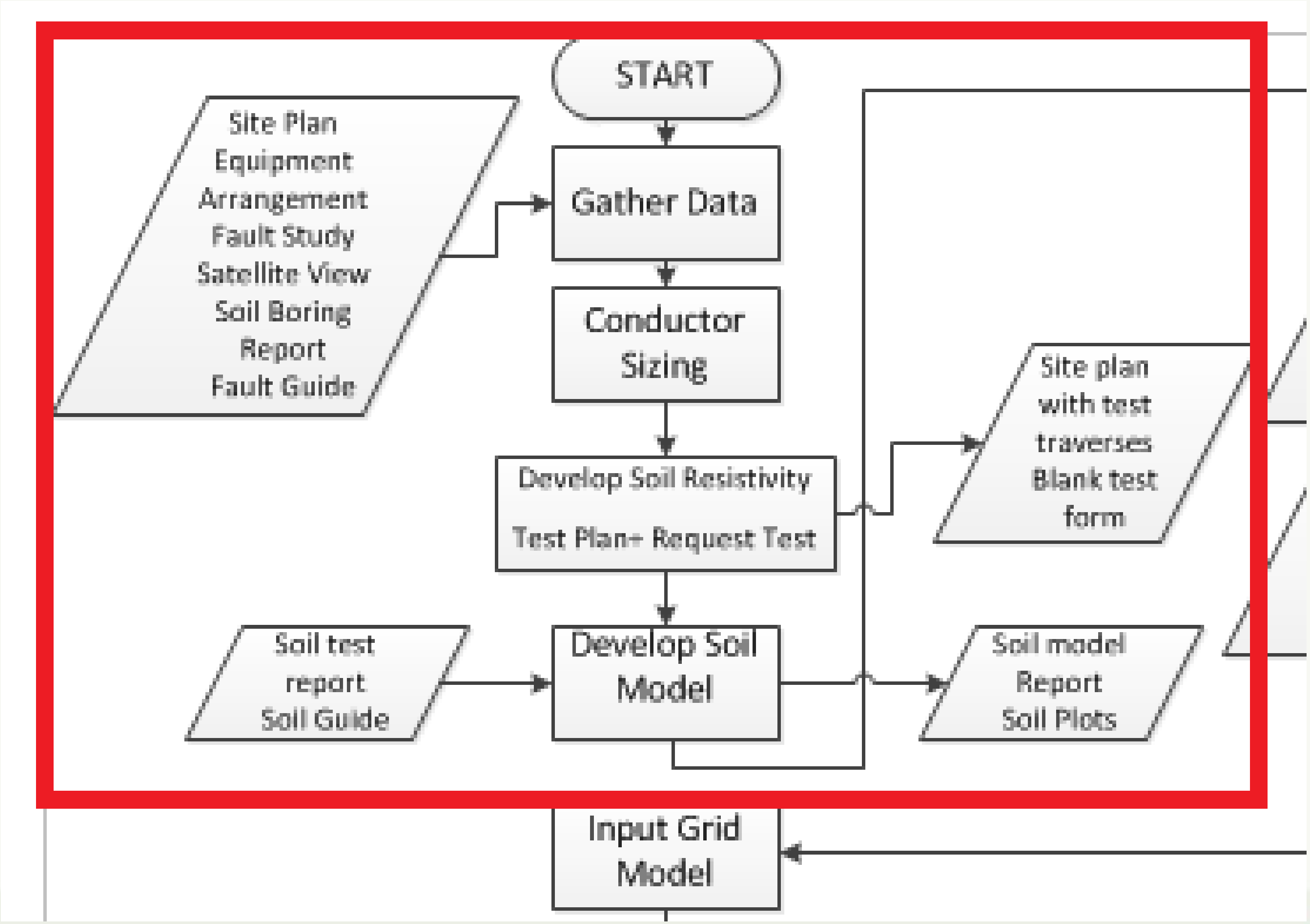
Figure 32—Design procedure block diagram

Source: IEEE 80-2015

Grounding Basics

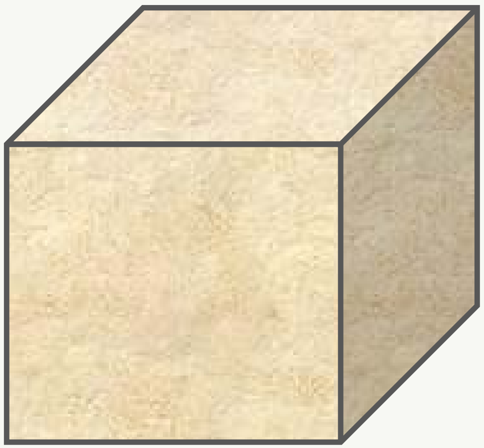


Soil Analysis

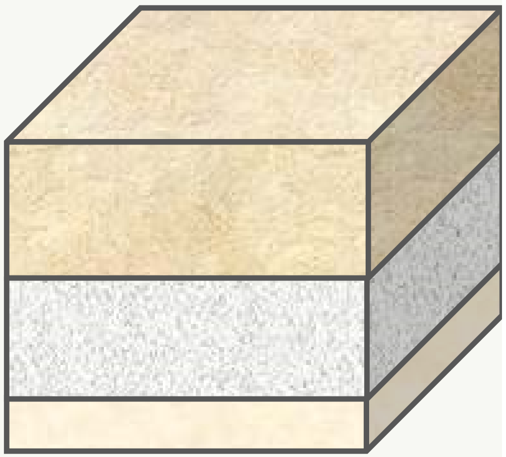


Soil Resistivity Modelling

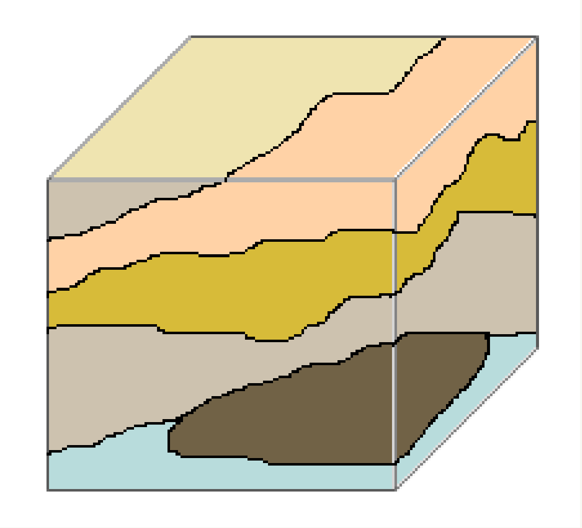
- Soil Basics



Homogeneous



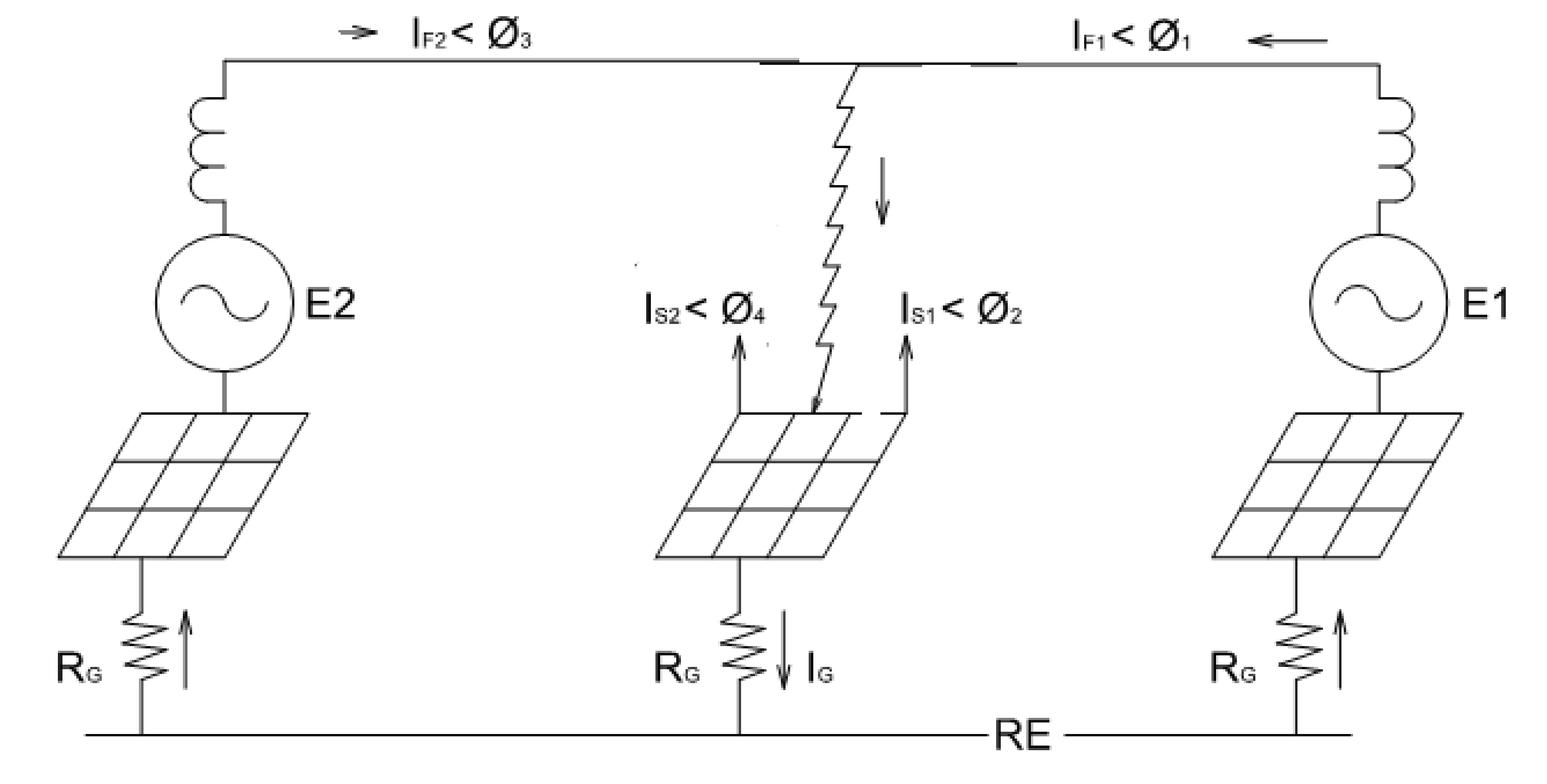
Multi - Layered



Actual soil

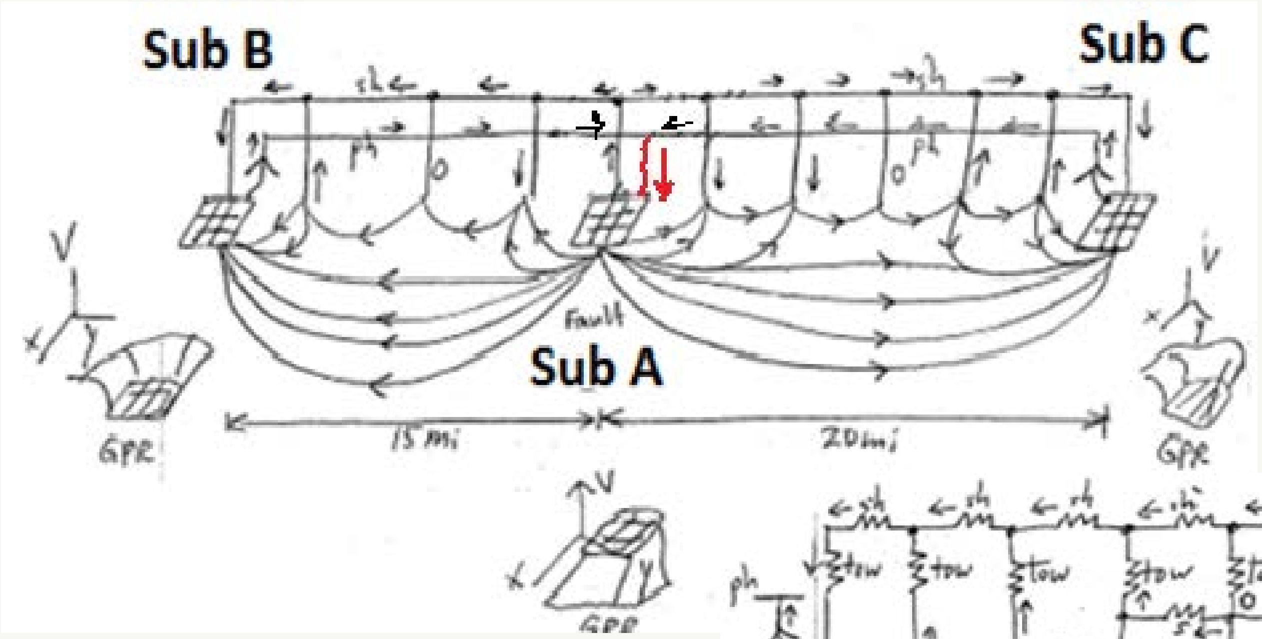
Soil Resistivity

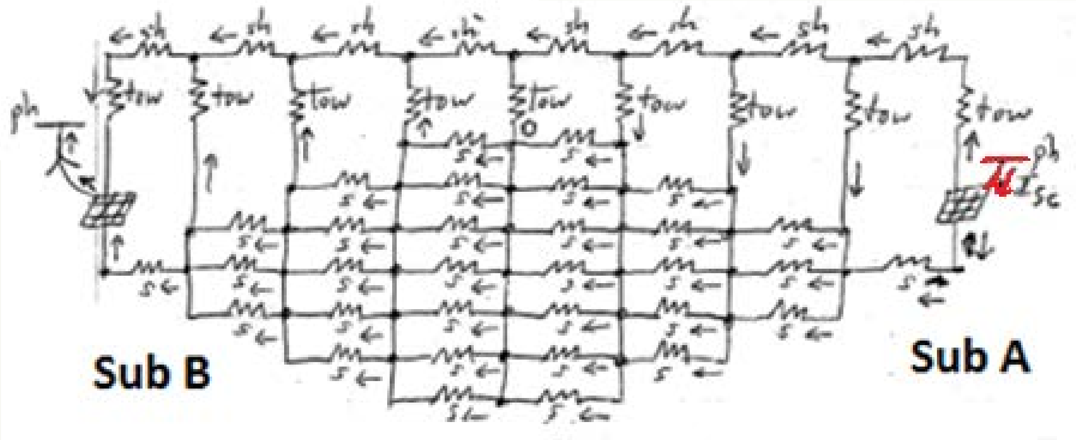
- The soil is part of the fault circuit
- Actual circuit



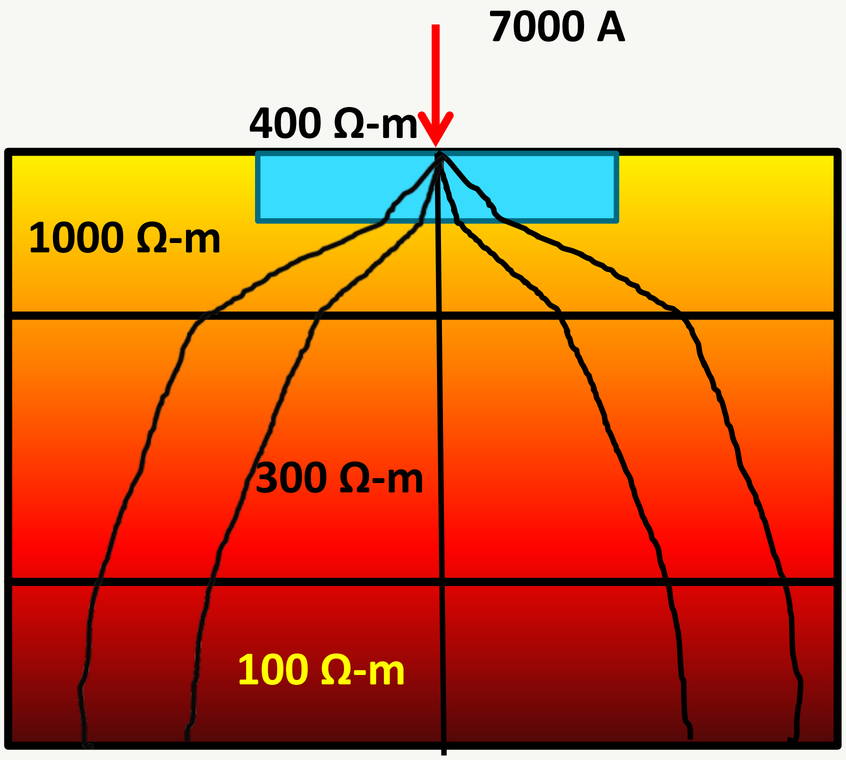
Soil Resistivity

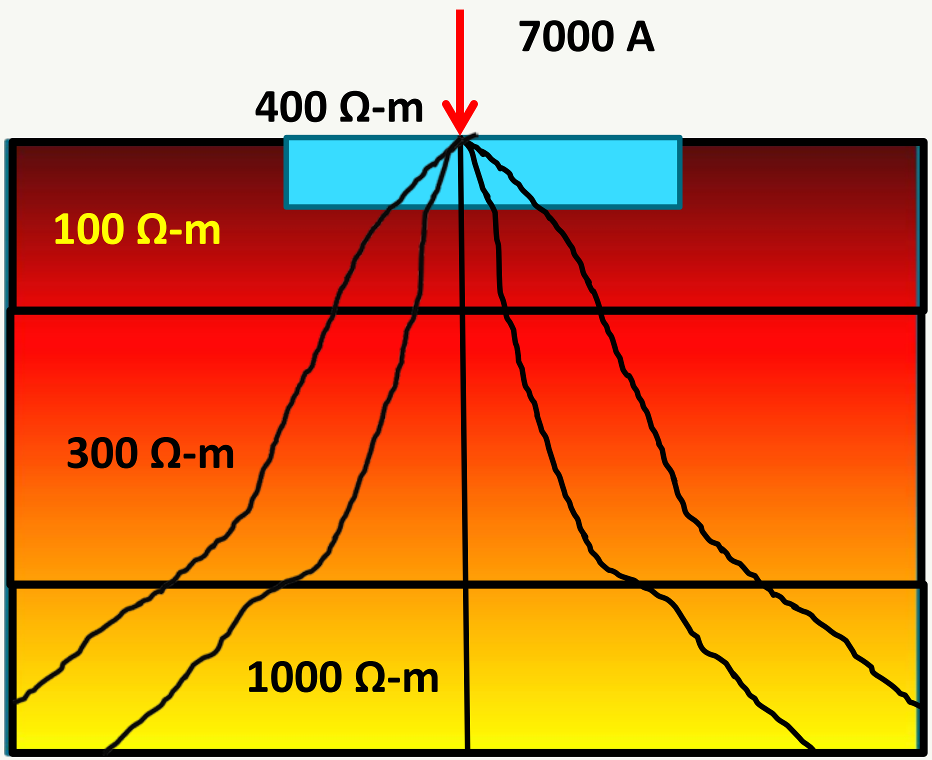
- The soil is part of the fault circuit



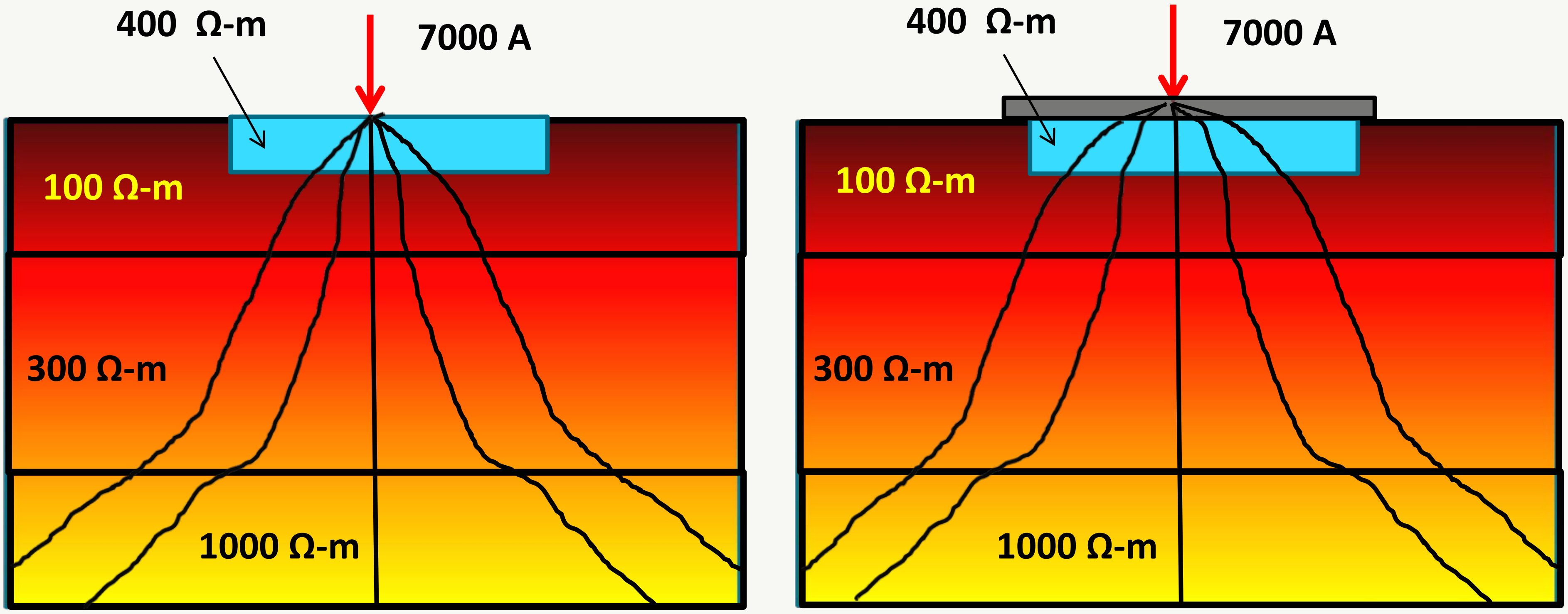


Soil Resistivity





Rock Resistivity



Preparation Soil Resistivity Testing

- Soil boring report
- Substation location & grading plans
- Substation size, site area
- Propose traverses
- Sources of interference
- Resistivity test schedule
- Grading schedule
- Test form
- Test equipment check list

Geotechnical Exploration & Review

SUBSURFACE BORING LOG

AET No: 01-06891 — Log of Boring No. SB-1 (p. 1 of 2)

Project: Big Rock Substation; I-90 & County Road J; Rockland, WI

Surface Elevation 776.7 — UTM Zone 15N Co. Coordinates: N 15954464 E 2189072

DEPTH IN FEET	MATERIAL DESCRIPTION	GEOLOGY	N	MC	SAMPLE TYPE	REC IN.	WC	DEN	LL	PL	%-#200
0–2	SILTY SAND, trace roots, fine grained, dark brown to brown, moist, very loose (SM)	TOPSOIL TO COARSE ALLUVIUM	1	M	SS	24					
2–7	SAND WITH SILT, fine grained, yellowish brown, a little brown, moist, very loose to loose (SP-SM)	COARSE ALLUVIUM	2	M	SS	20					
			[illegible]	M	SS	22					
7–12	SAND WITH SILT, fine grained, yellowish brown, moist, medium dense (SP-SM)	REDEPOSITED SANDSTONE	14	M	SS	[illegible]					
			16	M	SS	20					
12–17	WEATHERED SANDSTONE, yellowish brown, very dense [Textural Classification: SAND WITH SILT, fine to medium grained, light brown and yellowish brown, moist, very dense (SP-SM)]	JORDAN FORMATION	83	M	SS	17					
			65/.5	M	SS	7					
17–	SANDSTONE, light brown and yellowish brown, moist to wet, very dense		50/.4	M	SS	6					

DEPTH	DRILLING METHOD
0-24½'	3.25" HSA

BORING COMPLETED: 7/8/16

DR: GM LG: LD Rig: 67C

WATER LEVEL MEASUREMENTS

DATE	TIME	SAMPLED DEPTH	CASING DEPTH	CAVE-IN DEPTH	DRILLING FLUID LEVEL	WATER LEVEL
7/8/16	8:25	24.9	24.5	24.5		22.0
7/8/16	10:20	24.9	None	21.7		21.0

NOTE: REFER TO THE ATTACHED SHEETS FOR AN EXPLANATION OF TERMINOLOGY ON THIS LOG

Sand with Silt, fine grained, yellowish brown, moist medium dense (SP-SM)

WEATHERED SANDSTONE, yellowish Brown, very dense, [Textural Classification: SAND WITH SILT, fine to medium grained, light brown and yellowish brown, moist, very dense (SP-SM)]

Water Table

Soil Resistivity Testing

- Wenner
- Schlumberger

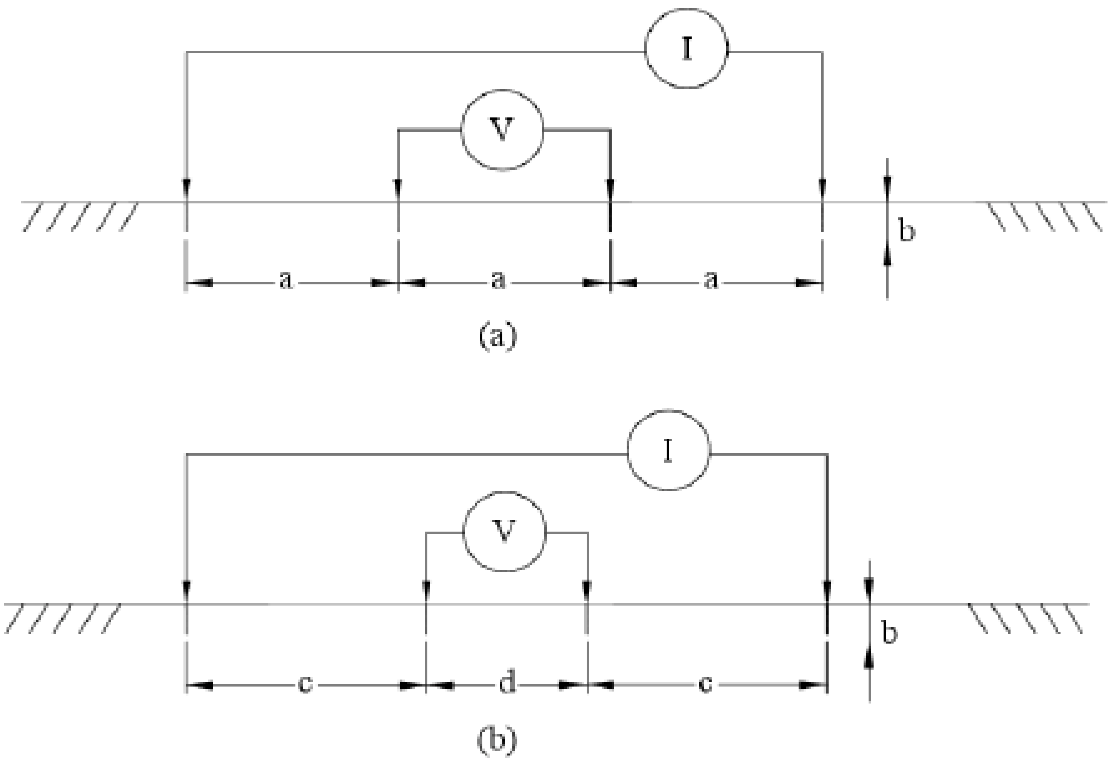
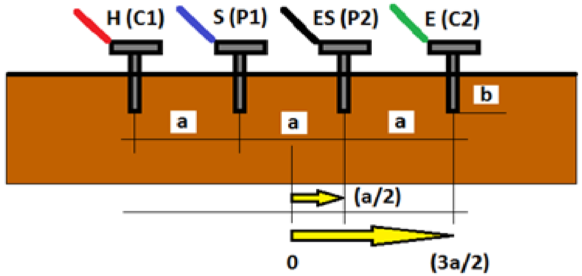


Figure 2 —Four point method: (a) equally spaced test probes and (b) unequally spaced test probes

Source: IEEE 81-2012

Soil Resistivity Testing - Wenner

19. Test Probes Array

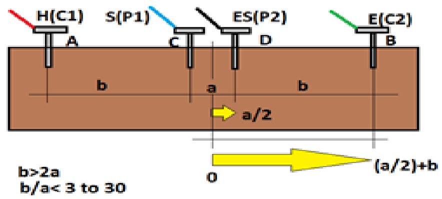


20. Table 1 - Field Test Data

				TRAVERSE 1			TRAVERSE 2			TRAVERSE 3			TRAVERSE 4			
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Spacing a (ft)	Depth b (in)	P-Probe (a/2) (ft)	C-Probe (3a/2) (ft)	Resistance R (Ω)	Resistivity ρ (Ω-m)	Verification ρ [2] (Ω-m)	Resistance R (Ω)	Resistivity ρ (Ω-m)	Verification ρ [2] (Ω-m)	Resistance R (Ω)	Resistivity ρ (Ω-m)	Verification ρ [2] (Ω-m)	Resistance R (Ω)	Resistivity ρ (Ω-m)	Verification ρ [2] (Ω-m)	(b/a) .[3] (%)
1	1	0.5	1.5			0.0			0.0			0.0			0.0	8.3
2	2	1.0	3.0			0.0			0.0			0.0			0.0	8.3
3	3	1.5	4.5			0.0			0.0			0.0			0.0	8.3
4	6	2.0	6.0			0.0			0.0			0.0			0.0	12.5
5	12	2.5	7.5			0.0			0.0			0.0			0.0	20.0
8	12	4.0	12.0			0.0			0.0			0.0			0.0	12.5
12	12	6.0	18.0			0.0			0.0			0.0			0.0	8.3
18	12	9.0	27.0			0.0			0.0			0.0			0.0	5.6
27	12	13.5	40.5			0.0			0.0			0.0			0.0	3.7
40	12	20.0	60.0			0.0			0.0			0.0			0.0	2.5
60	12	30.0	90.0			0.0			0.0			0.0			0.0	1.7
90	12	45.0	135.0			0.0			0.0			0.0			0.0	1.1
100	12	50.0	150.0			0.0			0.0			0.0			0.0	1.0
125	12	62.5	187.5			0.0			0.0			0.0			0.0	0.8
150	12	75.0	225.0			0.0			0.0			0.0			0.0	0.7
200	12	100.0	300.0			0.0			0.0			0.0			0.0	0.5
300	12	150.0	450.0			0.0			0.0			0.0			0.0	0.3
450	12	225.0	675.0			0.0			0.0			0.0			0.0	0.2
675	12	337.5	1012.5			0.0			0.0			0.0			0.0	0.1
1000	12	500.0	1500.0			0.0			0.0			0.0			0.0	0.1

Soil Resistivity Testing - Schlumberger

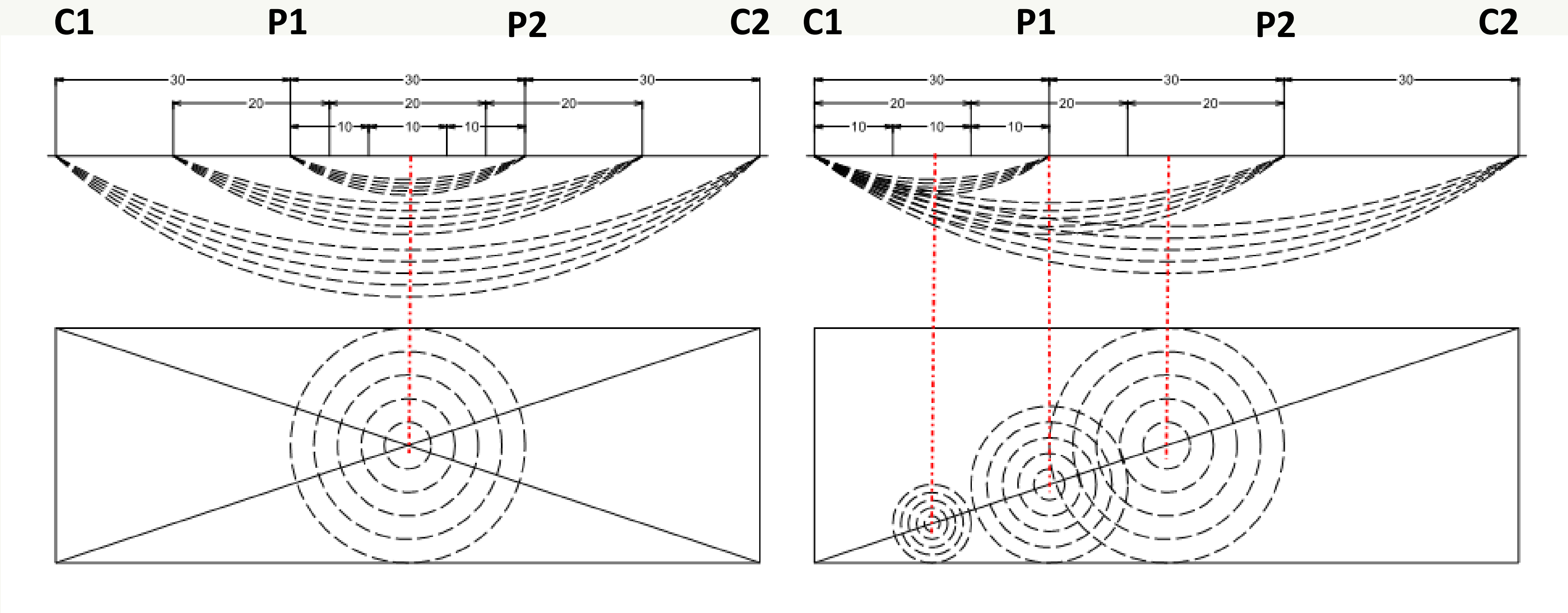
19. Test Probes Array



20. Table 1 - Field Test Data

				TRAVERSE 1			TRAVERSE 2			TRAVERSE 3			TRAVERSE 4			
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
C-D Spacing a (ft)	A-C Spacing b (ft)	P1, P2- Probe (a/2) (ft)	C1,C2- Probe (a/2+b) (ft)	Measured Resistance R (Ω)	Measured Resistivity ρ (Ω-m)	Verification ρ (2) (Ω-m)	Measured Resistance R (Ω)	Measured Resistivity ρ (Ω-m)	Verification ρ (2) (Ω-m)	Measured Resistance R (Ω)	Measured Resistivity ρ (Ω-m)	Verification ρ (2) (Ω-m)	Measured Resistance R (Ω)	Measured Resistivity ρ (Ω-m)	Verification ρ (2) (Ω-m)	(b/a) -(3) (%)
2	6	1.0	7.0			0.0			0.0			0.0			0.0	3.0
2	10	1.0	11.0			0.0			0.0			0.0			0.0	5.0
2	15	1.0	16.0			0.0			0.0			0.0			0.0	7.5
2	20	1.0	21.0			0.0			0.0			0.0			0.0	10.0
2	25	1.0	26.0			0.0			0.0			0.0			0.0	12.5
2	30	1.0	31.0			0.0			0.0			0.0			0.0	15.0
2	40	1.0	41.0			0.0			0.0			0.0			0.0	20.0
2	50	1.0	51.0			0.0			0.0			0.0			0.0	25.0
2	60	1.0	61.0			0.0			0.0			0.0			0.0	30.0
4	70	2.0	72.0			0.0			0.0			0.0			0.0	17.5
4	80	2.0	82.0			0.0			0.0			0.0			0.0	20.0
4	90	2.0	92.0			0.0			0.0			0.0			0.0	22.5
4	100	2.0	102.0			0.0			0.0			0.0			0.0	25.0
6	125	3.0	128.0			0.0			0.0			0.0			0.0	20.8
6	150	3.0	153.0			0.0			0.0			0.0			0.0	25.0
10	200	5.0	205.0			0.0			0.0			0.0			0.0	20.0
10	250	5.0	255.0			0.0			0.0			0.0			0.0	25.0
10	300	5.0	305.0			0.0			0.0			0.0			0.0	30.0
20	350	10.0	360.0			0.0			0.0			0.0			0.0	17.5
20	400	10.0	410.0			0.0			0.0			0.0			0.0	20.0
20	450	10.0	460.0			0.0			0.0			0.0			0.0	22.5
20	500	10.0	510.0			0.0			0.0			0.0			0.0	25.0
20	550	10.0	560.0			0.0			0.0			0.0			0.0	27.5
20	600	10.0	610.0			0.0			0.0			0.0			0.0	30.0
30	650	15.0	665.0			0.0			0.0			0.0			0.0	21.7
30	700	15.0	715.0			0.0			0.0			0.0			0.0	23.3
30	750	15.0	765.0			0.0			0.0			0.0			0.0	25.0
30	800	15.0	815.0			0.0			0.0			0.0			0.0	26.7
30	850	15.0	865.0			0.0			0.0			0.0			0.0	28.3

Soil Resistivity Testing



Error Range Based on Probe Spacing

Probe spacing (% grid length)	Error range (%)	
	Grid resistance	Touch and step voltage (in % of grid GPR)
40%	–50% to +30%	–20% to +110%
100%	–33% to +9%	–8% to +50%
300%	–17% to +9%	–8% to +20%

Table 4 - IEEE 81- 2013

Soil Resistivity Test Layout

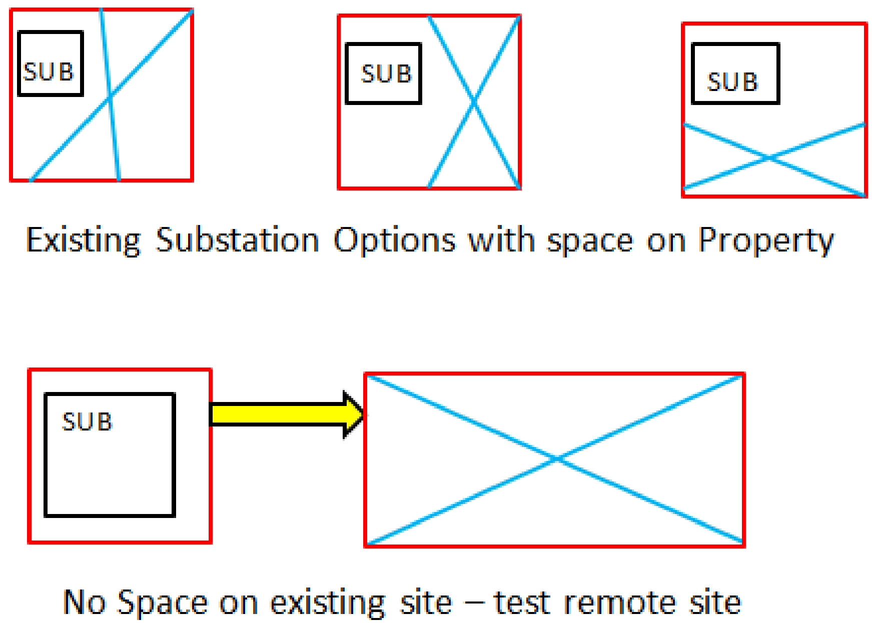


Figure X. Examples of traverses in existing substation sites.

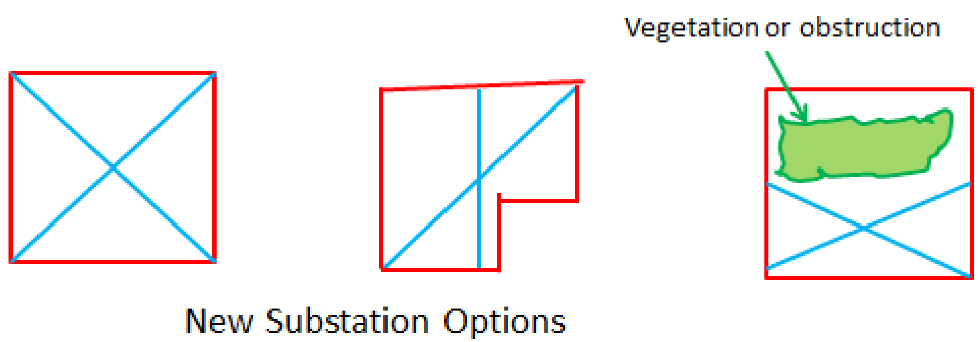
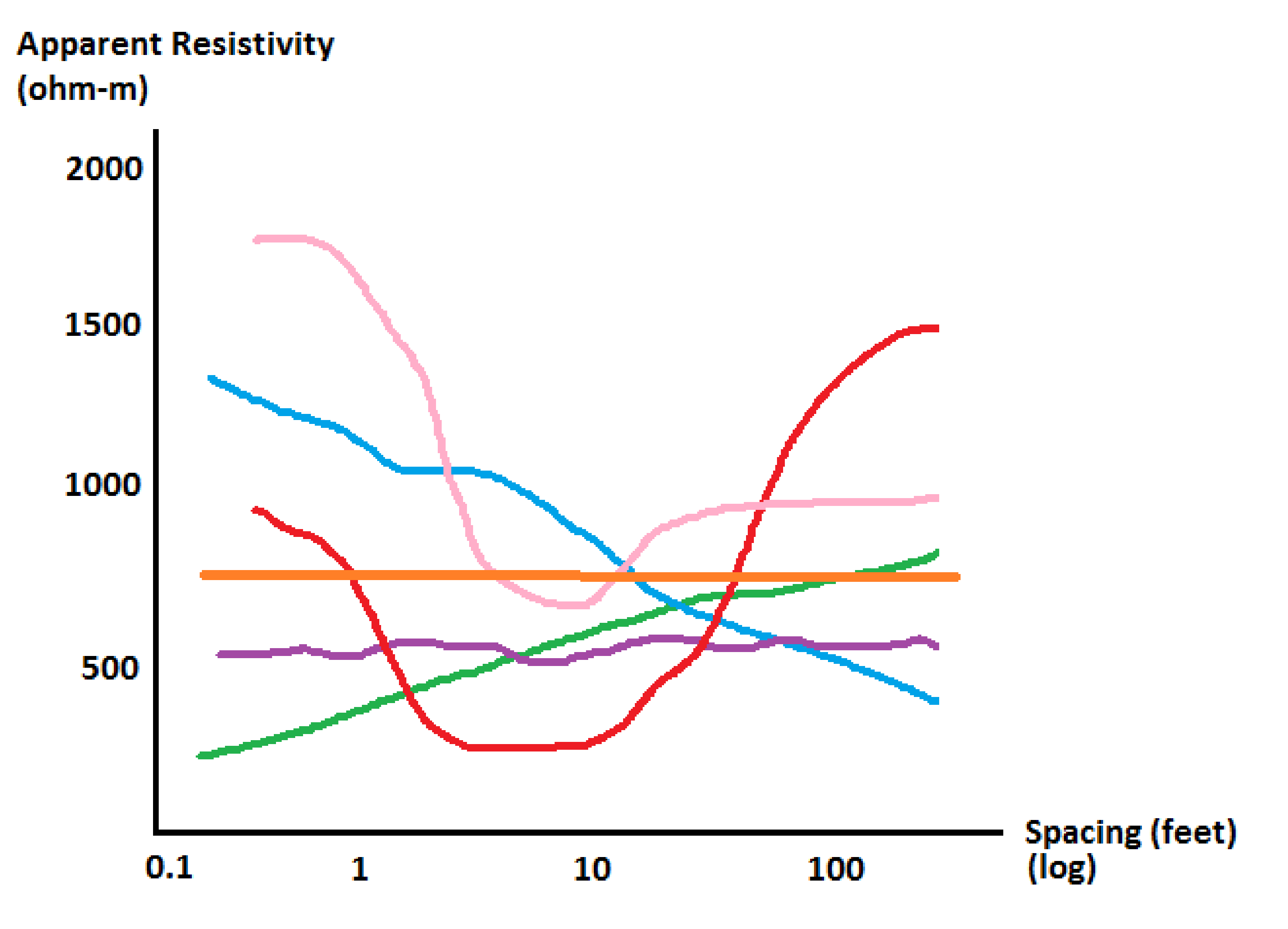


Figure X. Examples of traverses in new substation sites.

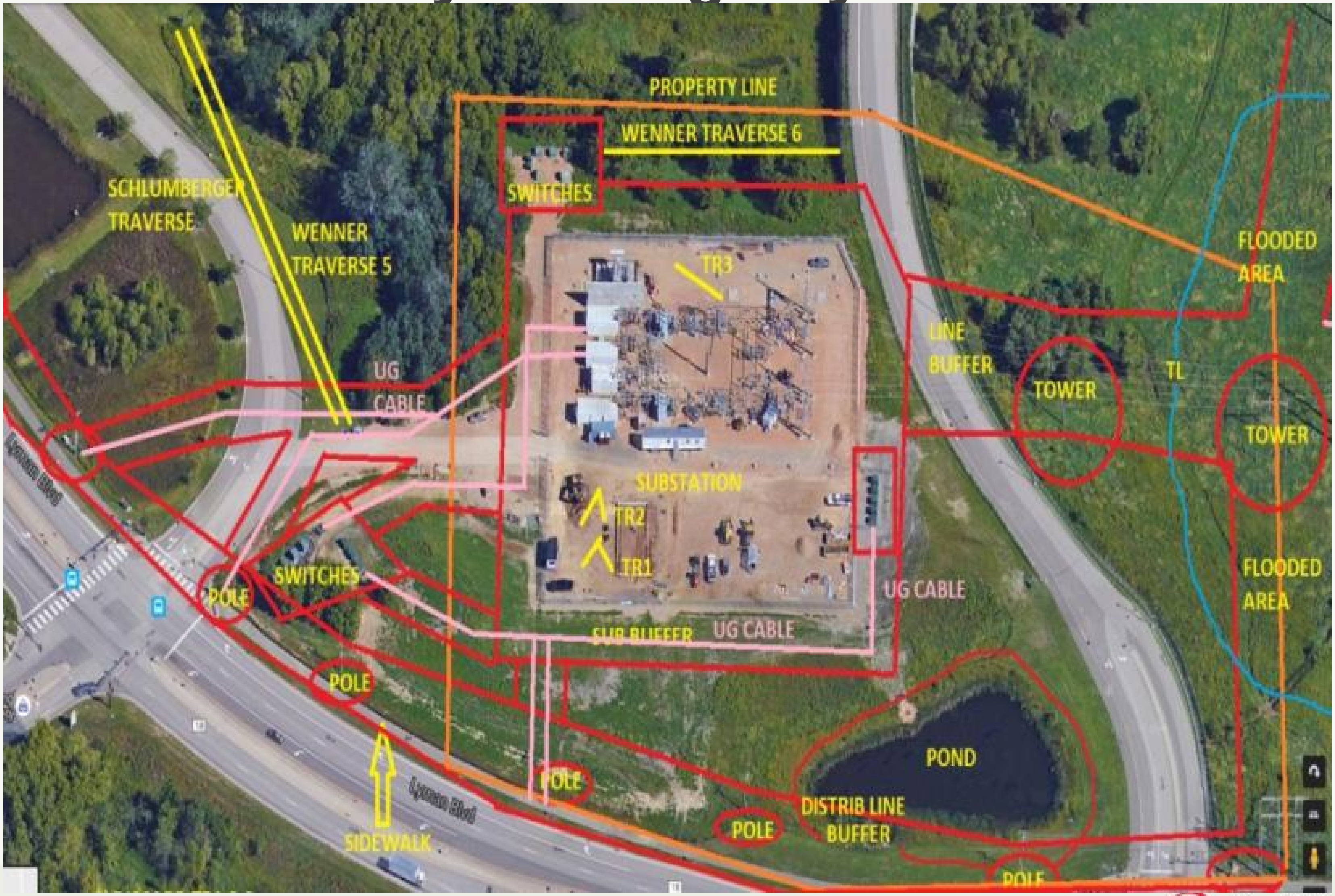
Grounding Design Variables

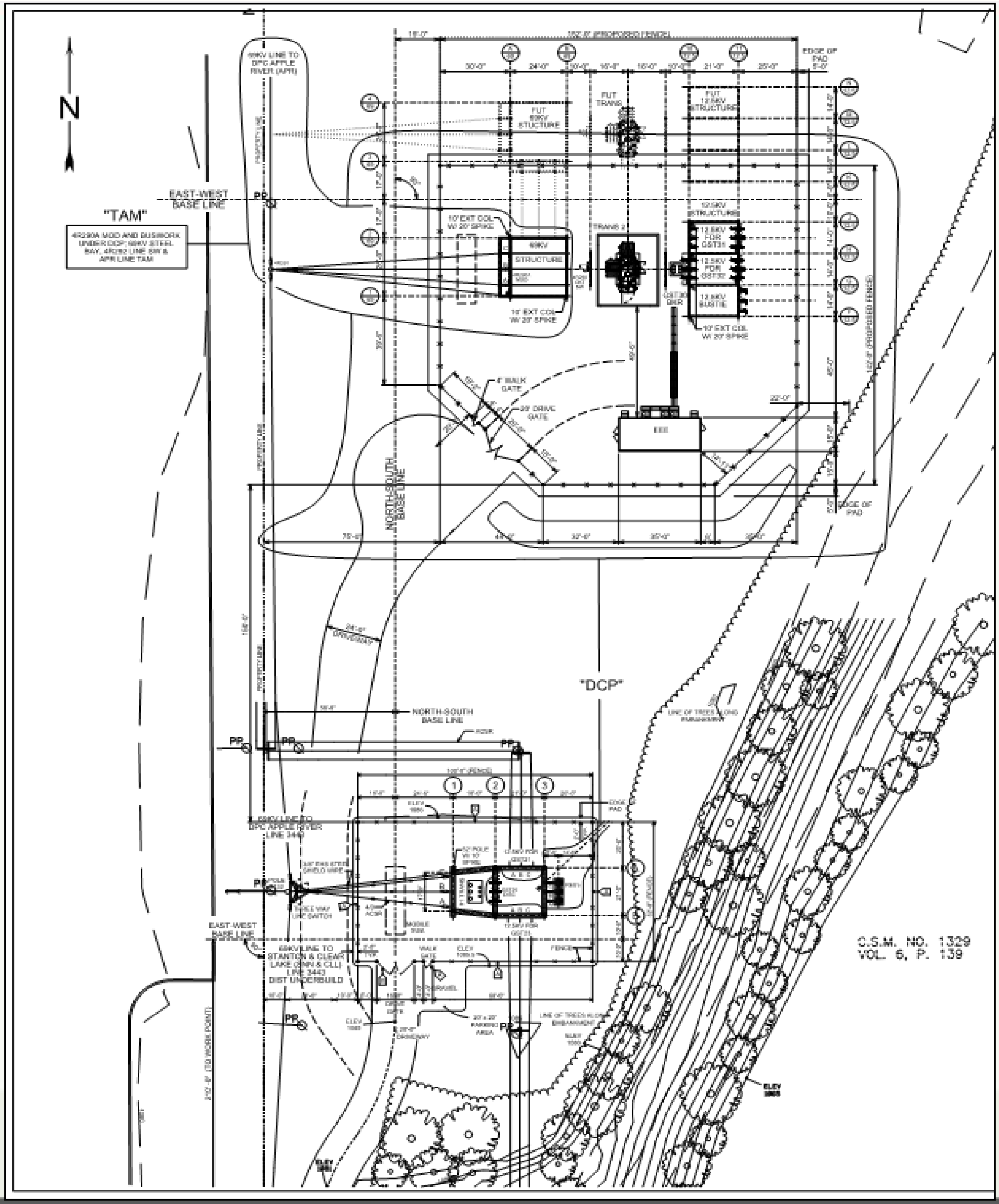


Soil Resistivity Testing Summary

- How many traverses are required?
- Are there sources of interference?
- What is the correct layout of traverses?
- What pin spacing should we use?
- What do I do if there is not adequate space?

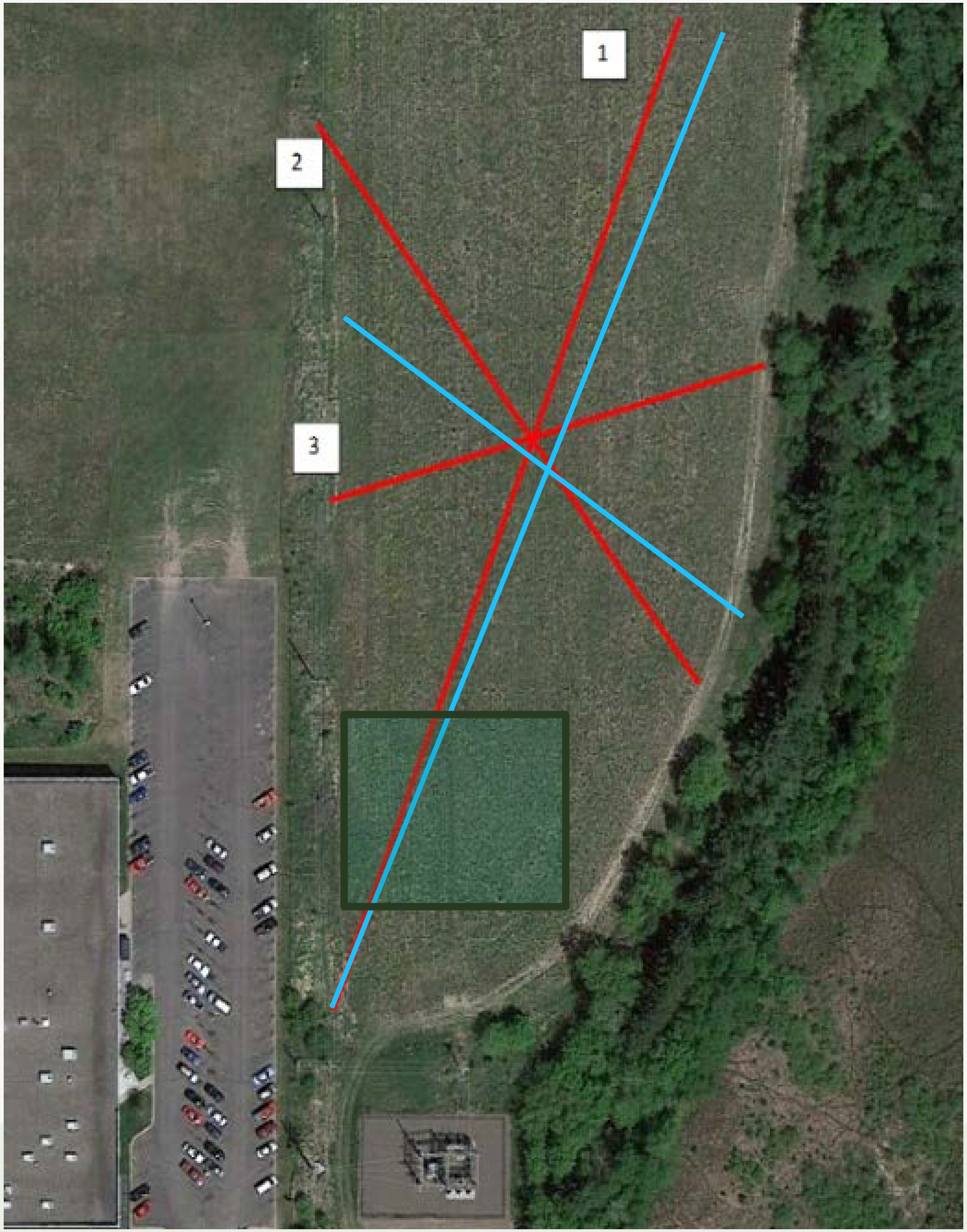
Soil Resistivity Testing Layout





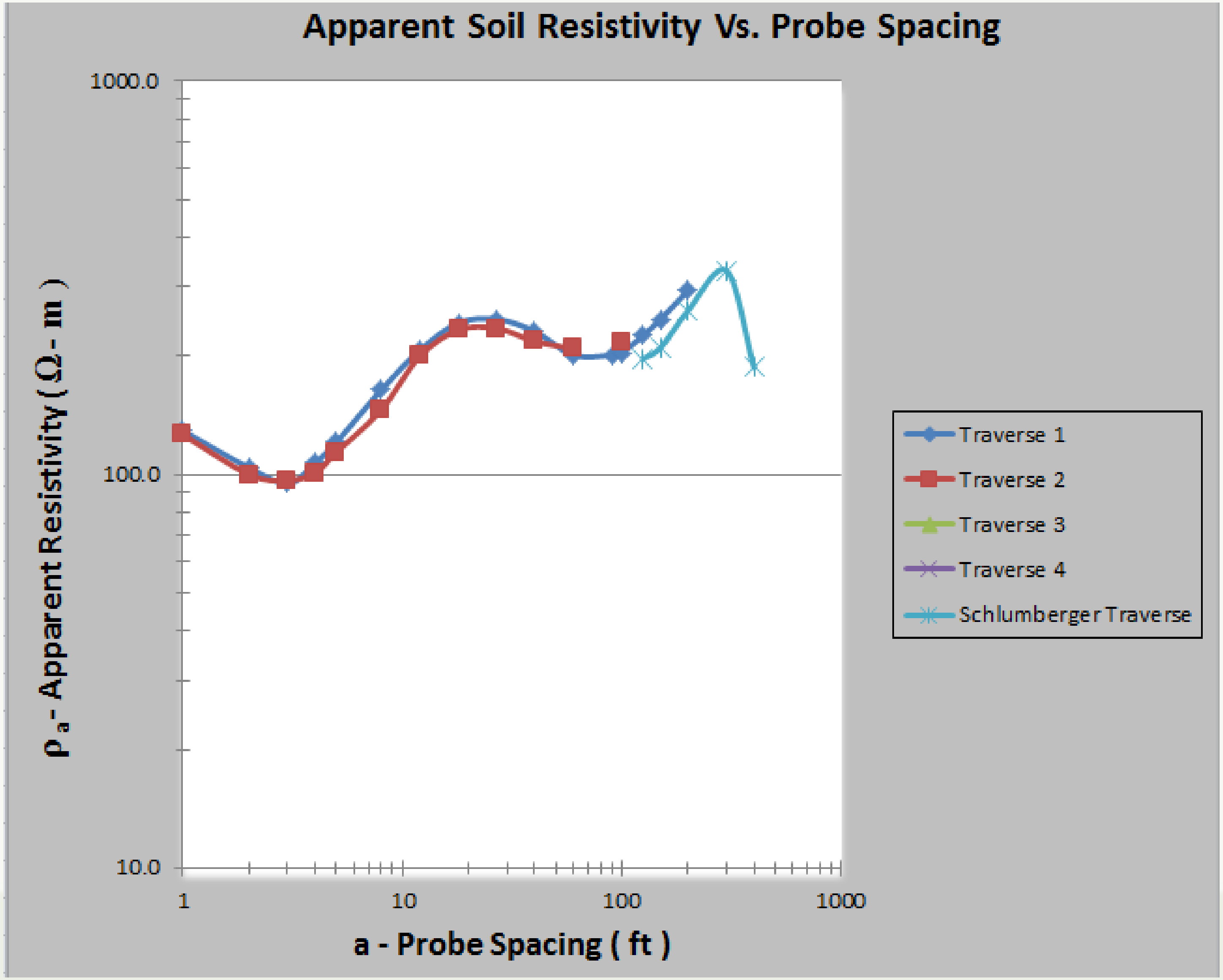
Soil Resistivity Testing Layout

Xcel Energy

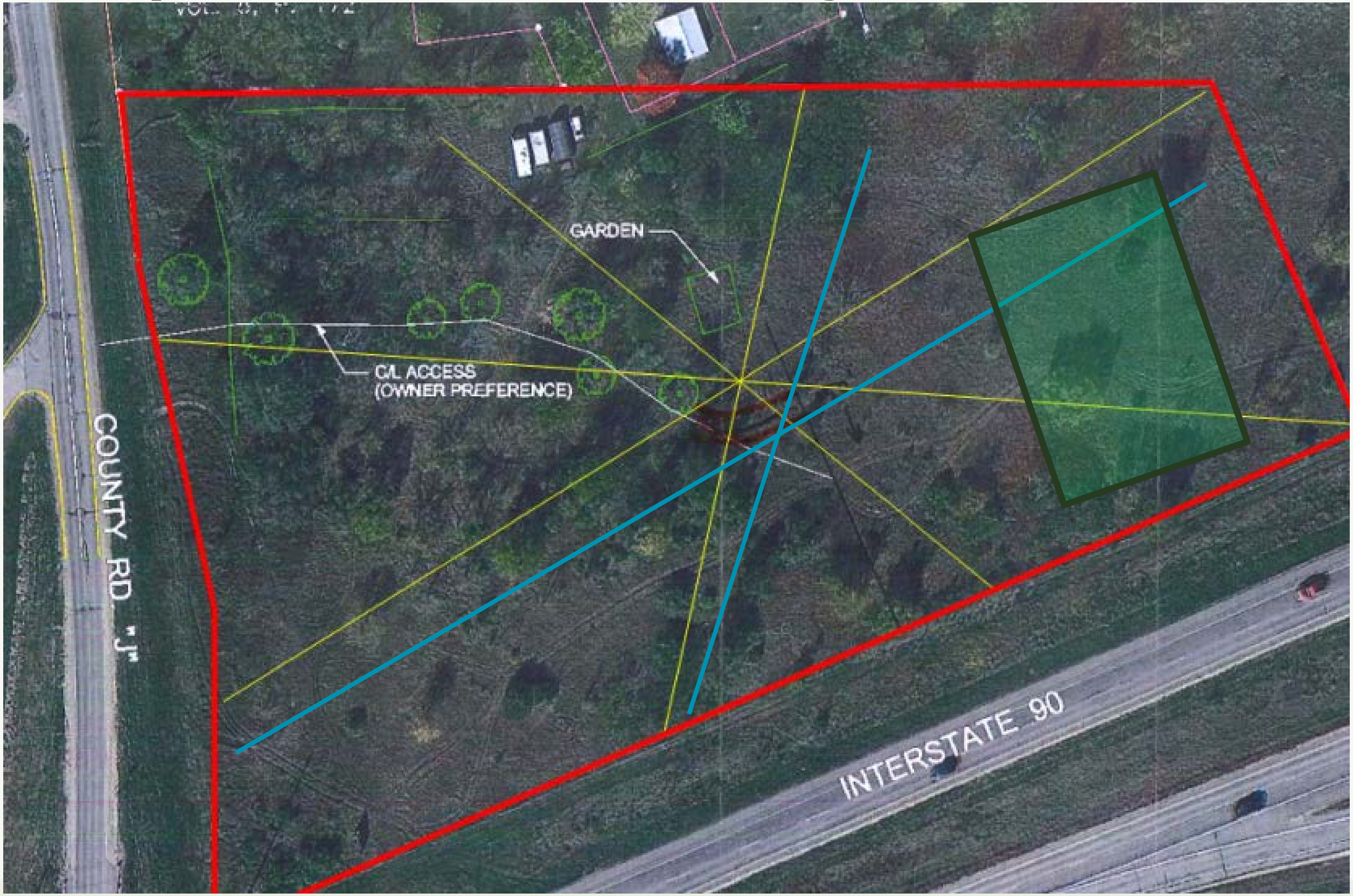


Soil Resistivity Testing Layout

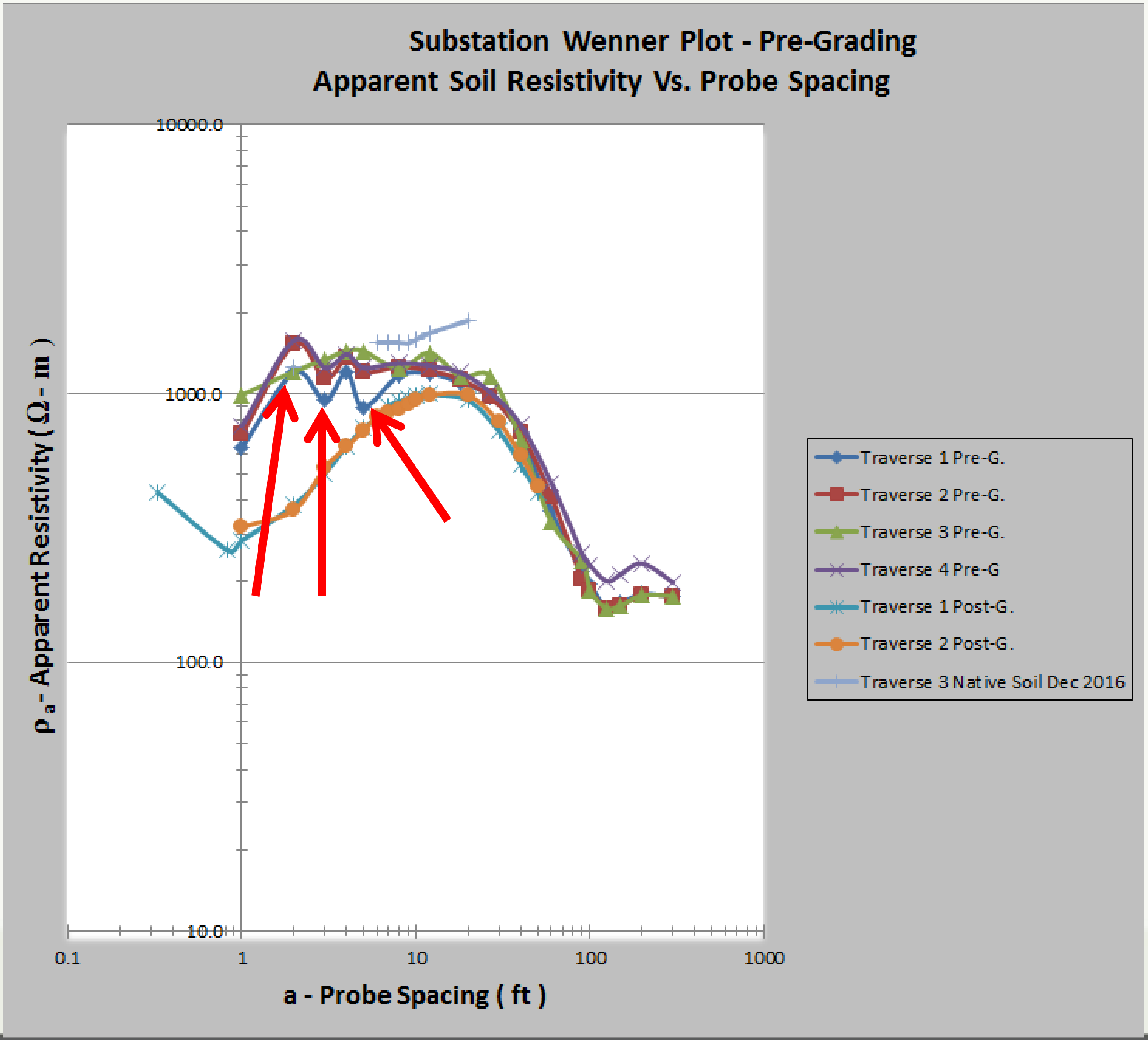
Plot of Soil Resistivity Results



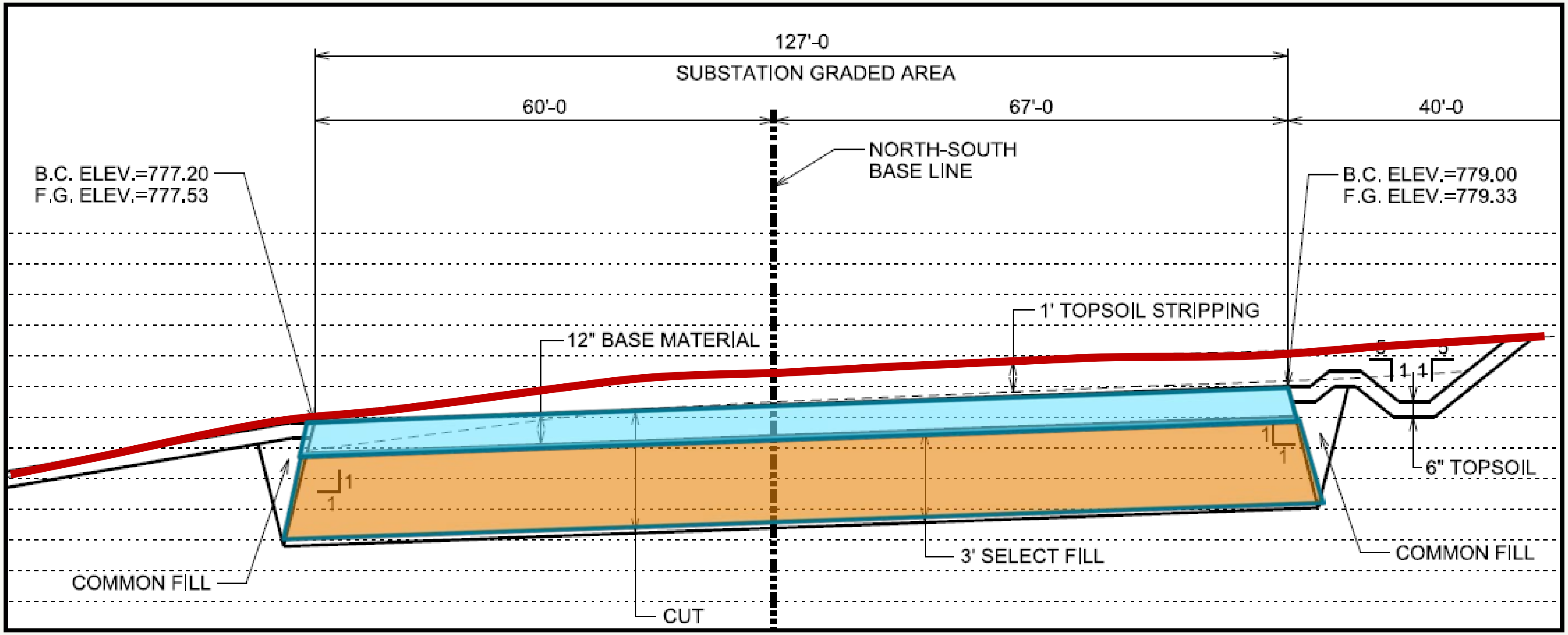
Proposed Soil Resistivity Test Traverses



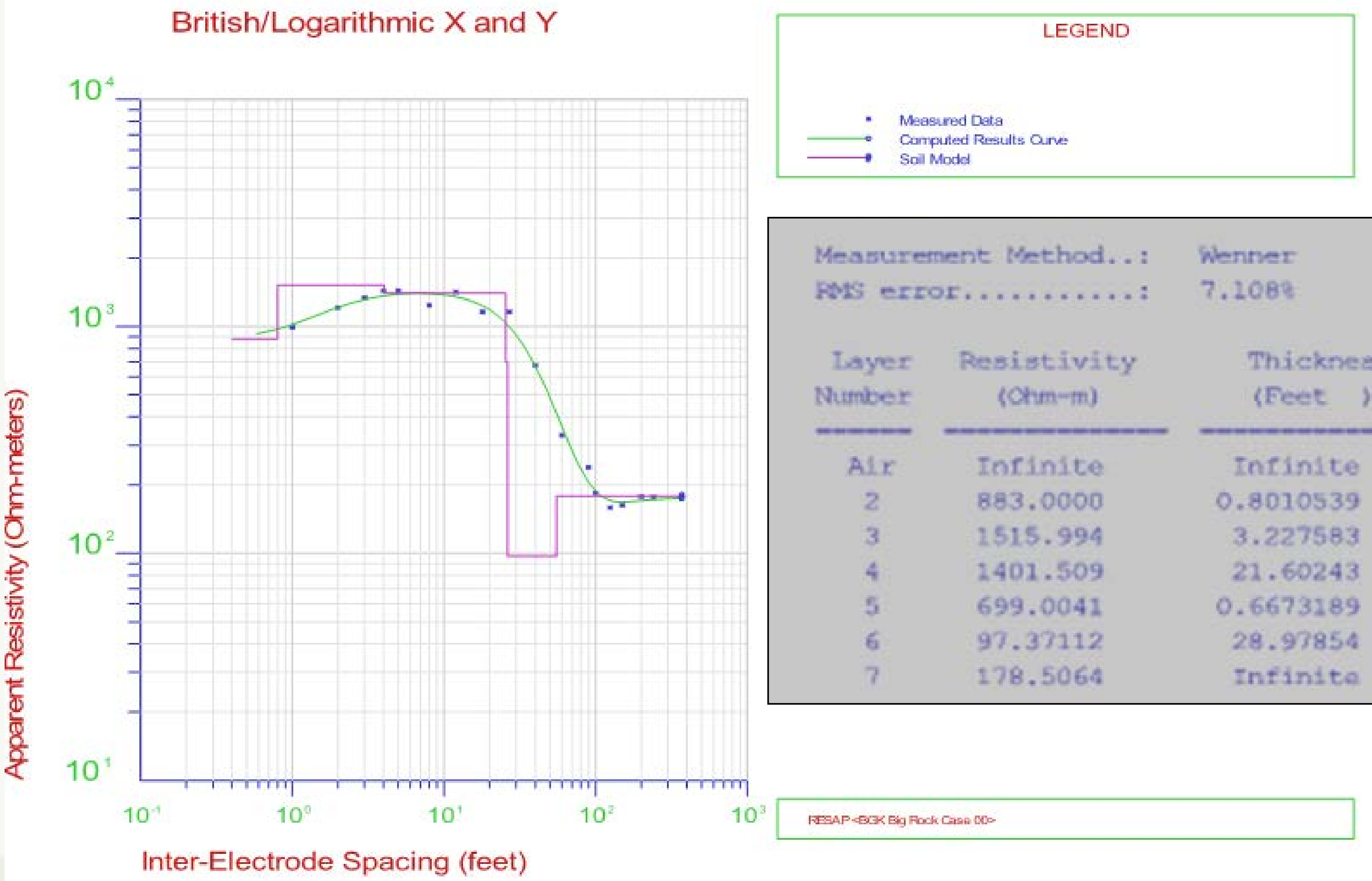
Wenner Data Comparison Pre-& Post-Grading



Substation Grading Section Drawing



Wenner vs. Schlumberger Soil Models

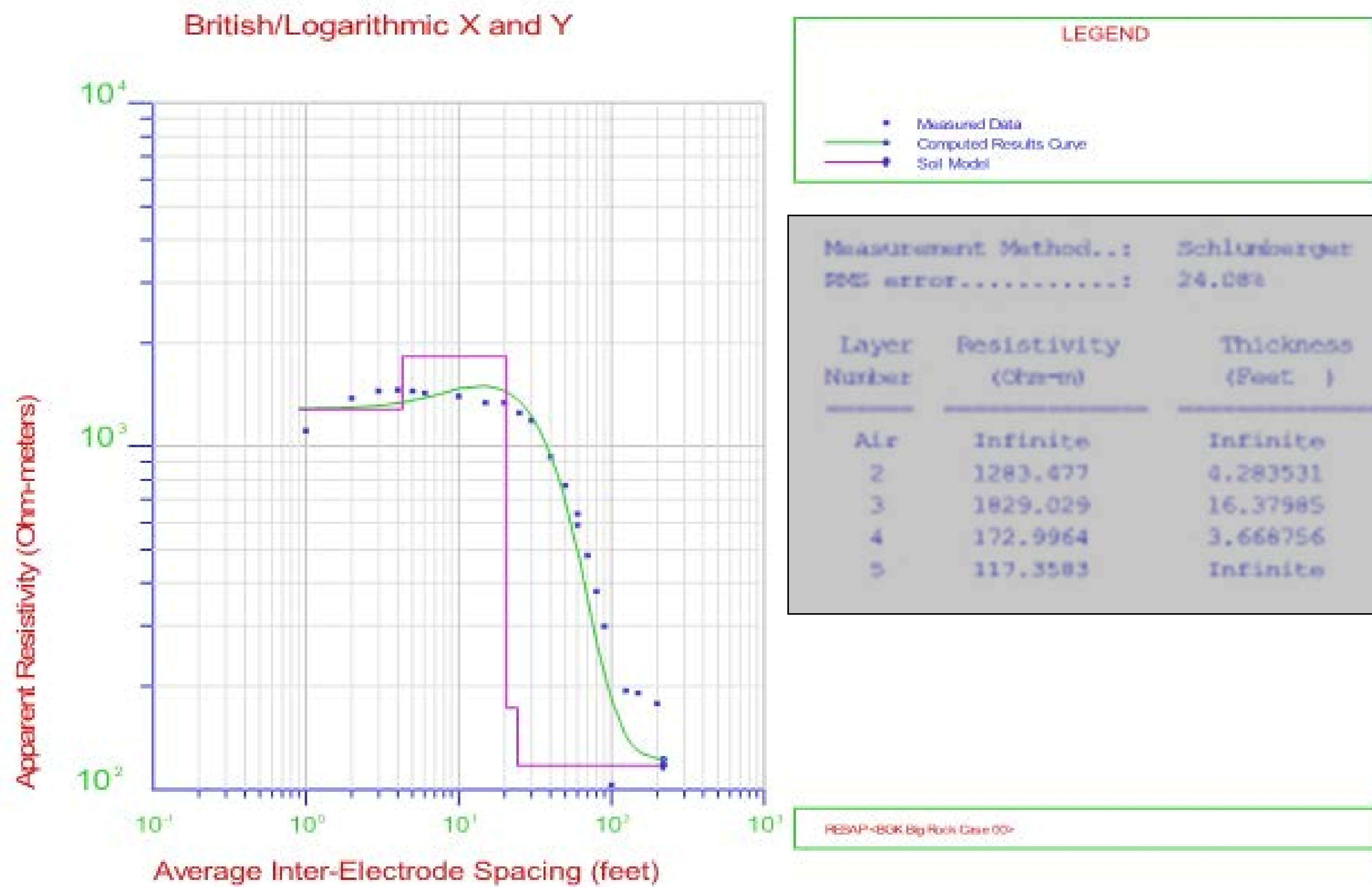


Measurement Method..: Wenner

RMS error...........: 7.108%

Layer Number	Resistivity (Ohm-m)	Thickness (Feet)
Air	Infinite	Infinite
2	883.0000	0.8010539
3	1515.994	3.227583
4	1401.509	21.60243
5	699.0041	0.6673189
6	97.37112	28.97854
7	178.5064	Infinite

Wenner vs. Schlumberger Soil Models



Measurement Method..: Schlumberger
RMS error...........: 24.08%

Layer Number	Resistivity (Ohm-m)	Thickness (Feet)
Air	Infinite	Infinite
2	1283.477	4.283531
3	1829.029	16.37985
4	172.9964	3.668756
5	117.3583	Infinite

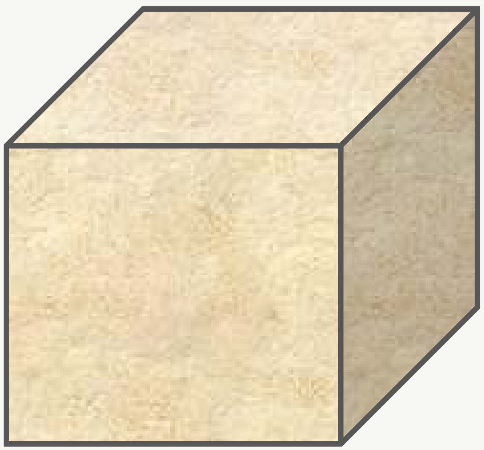
RESAP <BGK Big Rock Case 00>

Soil Resistivity Test Documentation

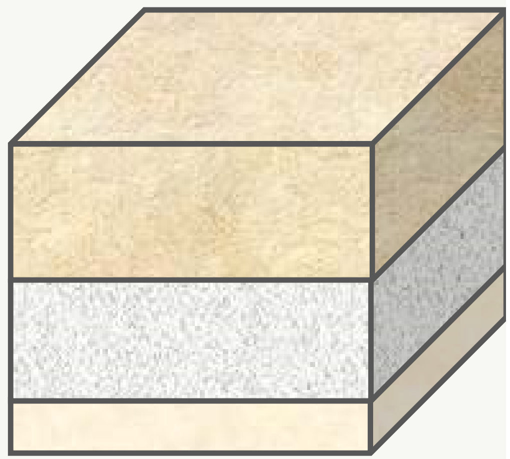
- Test equipment model number
- Test lead resistance (measured)
- Ambient Temperature when test was taken
- Date of test
- Standard test result form
- Resistivity & Resistance measurements at various pin spacing
- Notes

Soil Resistivity Modelling

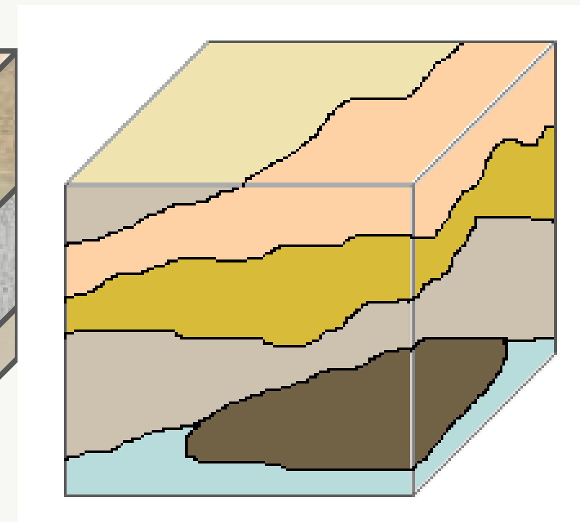
- Soil Basics



Homogeneous

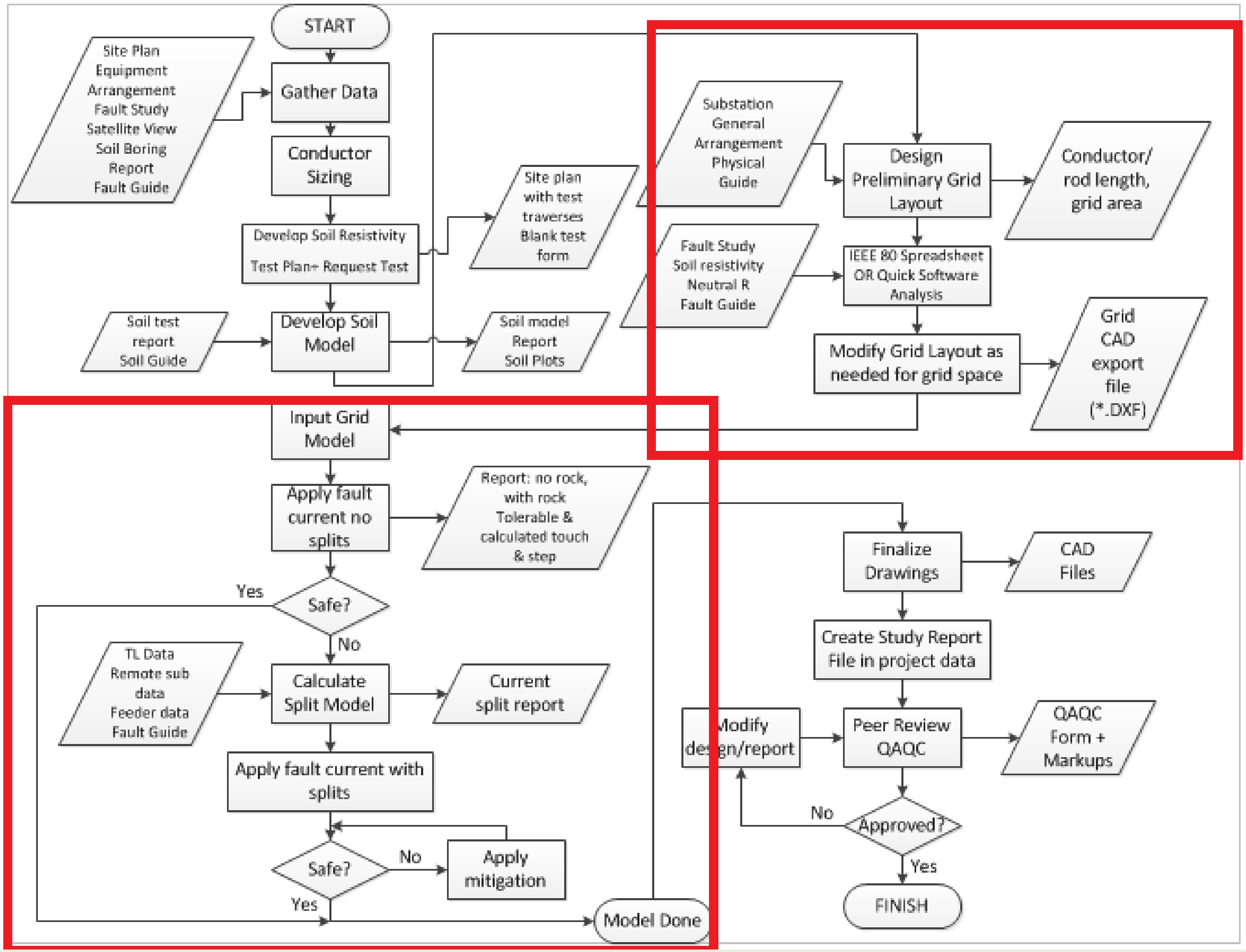


Multi - Layered



Actual soil

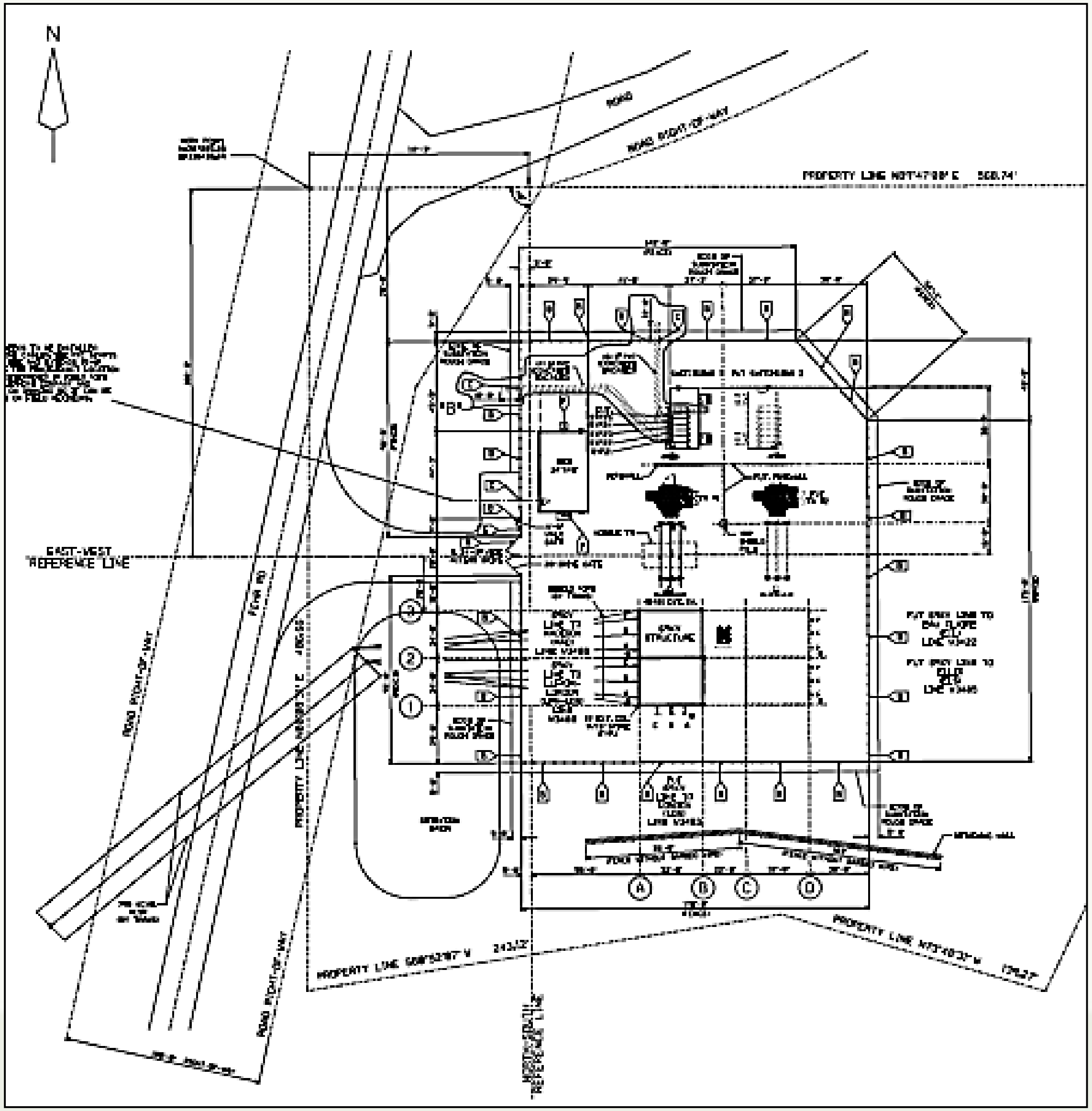
Ground Grid Design & Modeling



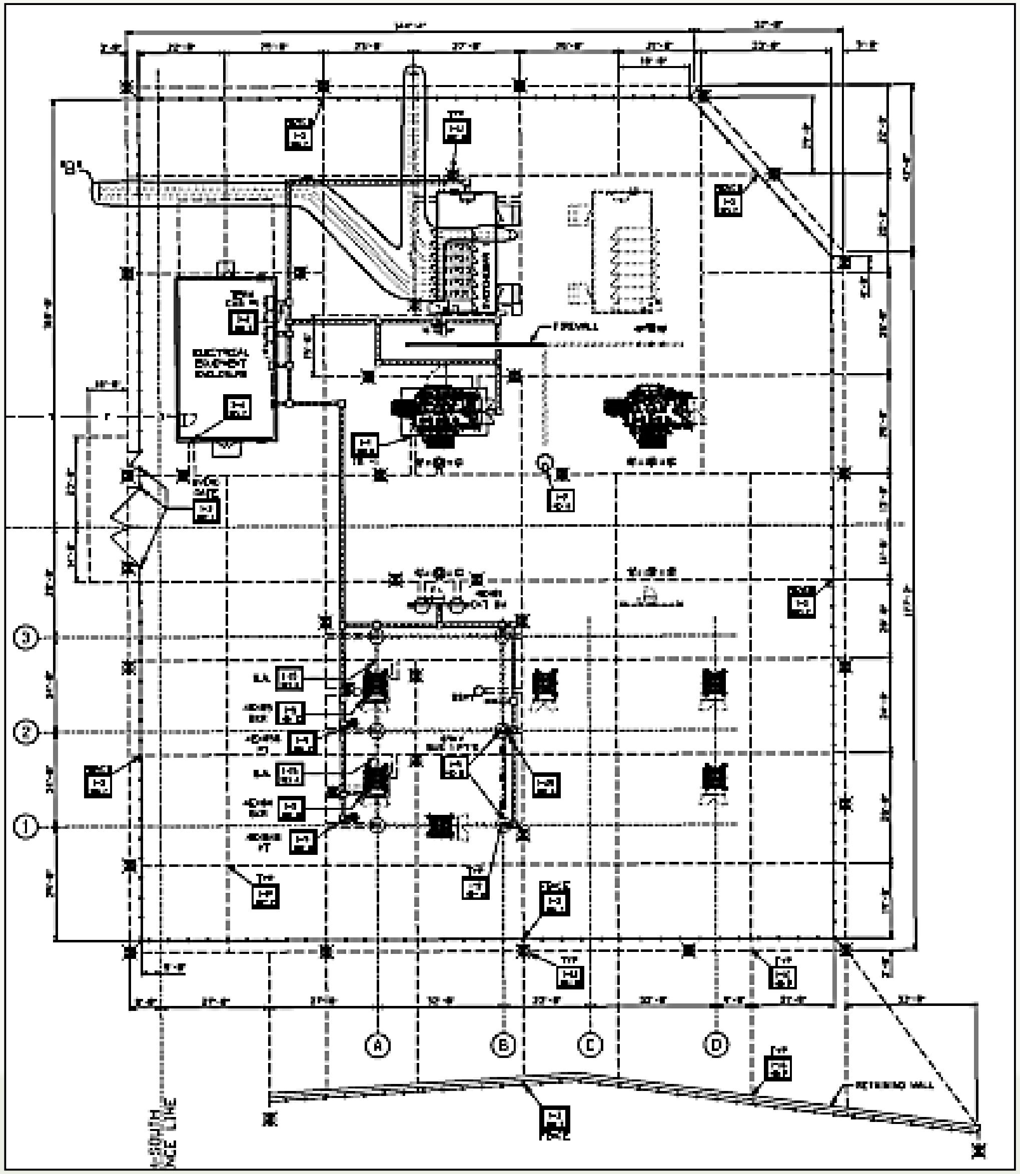
Design & Modeling Substation Ground Grid

- Ground grid layout
- Fault current system analysis & location
- Split factor modeling
- Safety analysis
  - V_{touch}, V_{step}
  - GPR plots
  - Safety & Summary Reports

General Substation Layout



General Ground Grid Layout

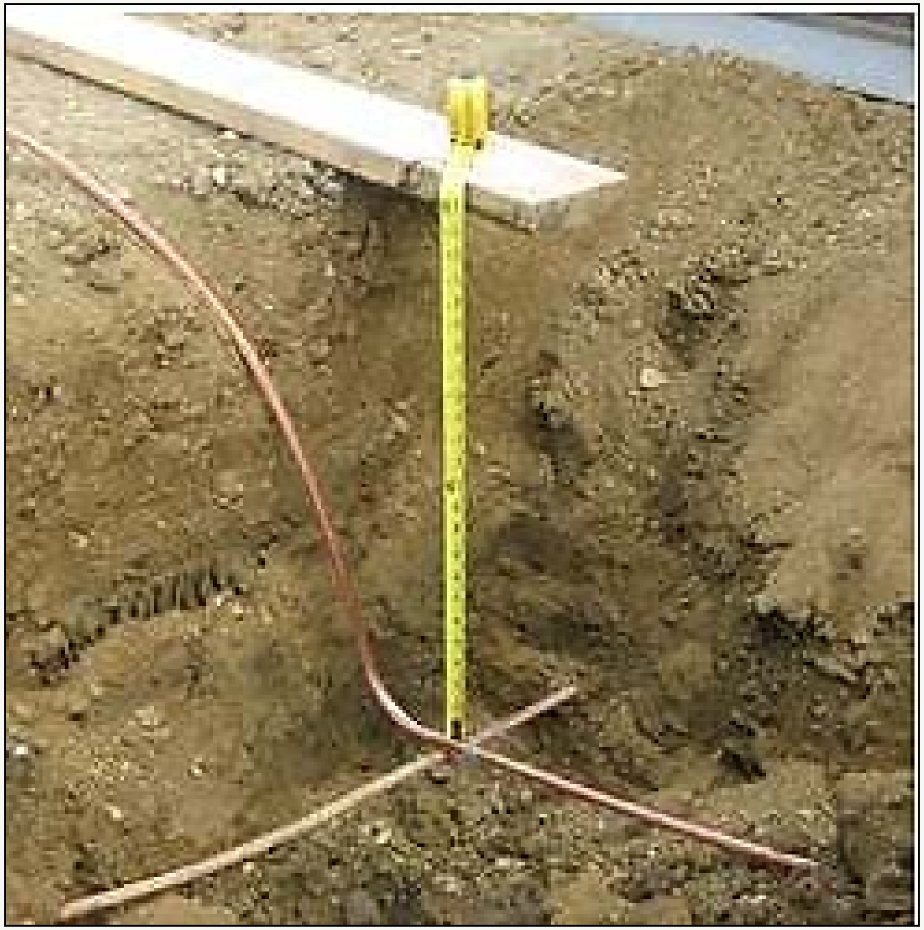


General Ground Grid Layout

1. Grid area – Loop 3’ outside fence
2. Main components – adjacent grid lines
3. Complete grid spacing
4. Gate(s) grading ring
5. Grading runs - UG facilities
6. Rods
7. Bond all structures & equipment

General Ground Grid Layout

General Ground Grid Layout



Ground Rod Application Guideline

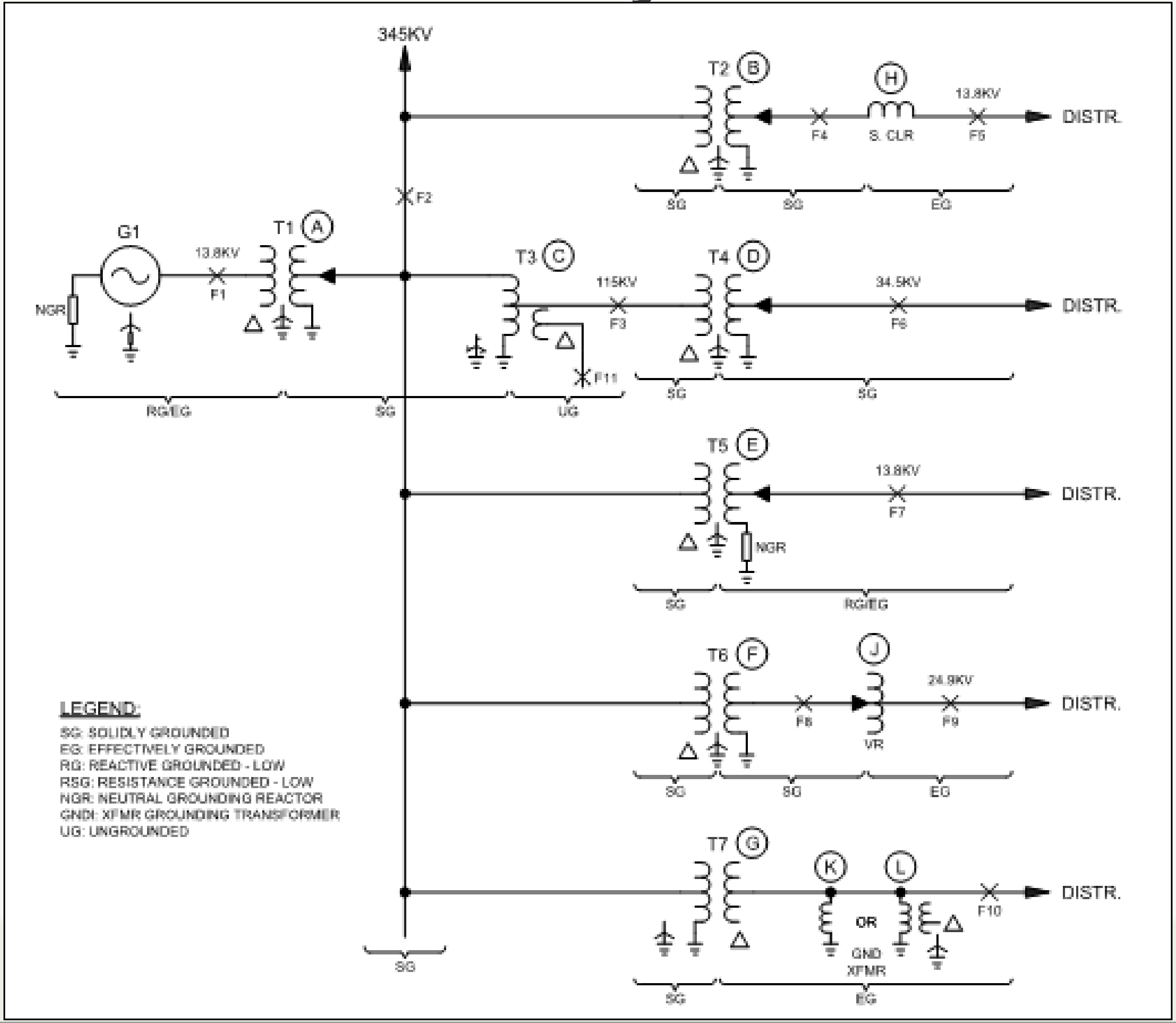
- UL listed
- Length, diameter
- Spacing
- Perimeter
- Equipment
- Open spaces


Coffee Break

Fault Current Analysis

1. Short circuit study
    1. LLG, SLG, fault duration, X/R
    2. Design margin
2. Identify ground sources
    1. Transformer connections
    2. # of T-lines & feeders
    3. Grounding transformers
    4. Generator Step-Up TR connections

Fault Current Analysis



Xcel Energy

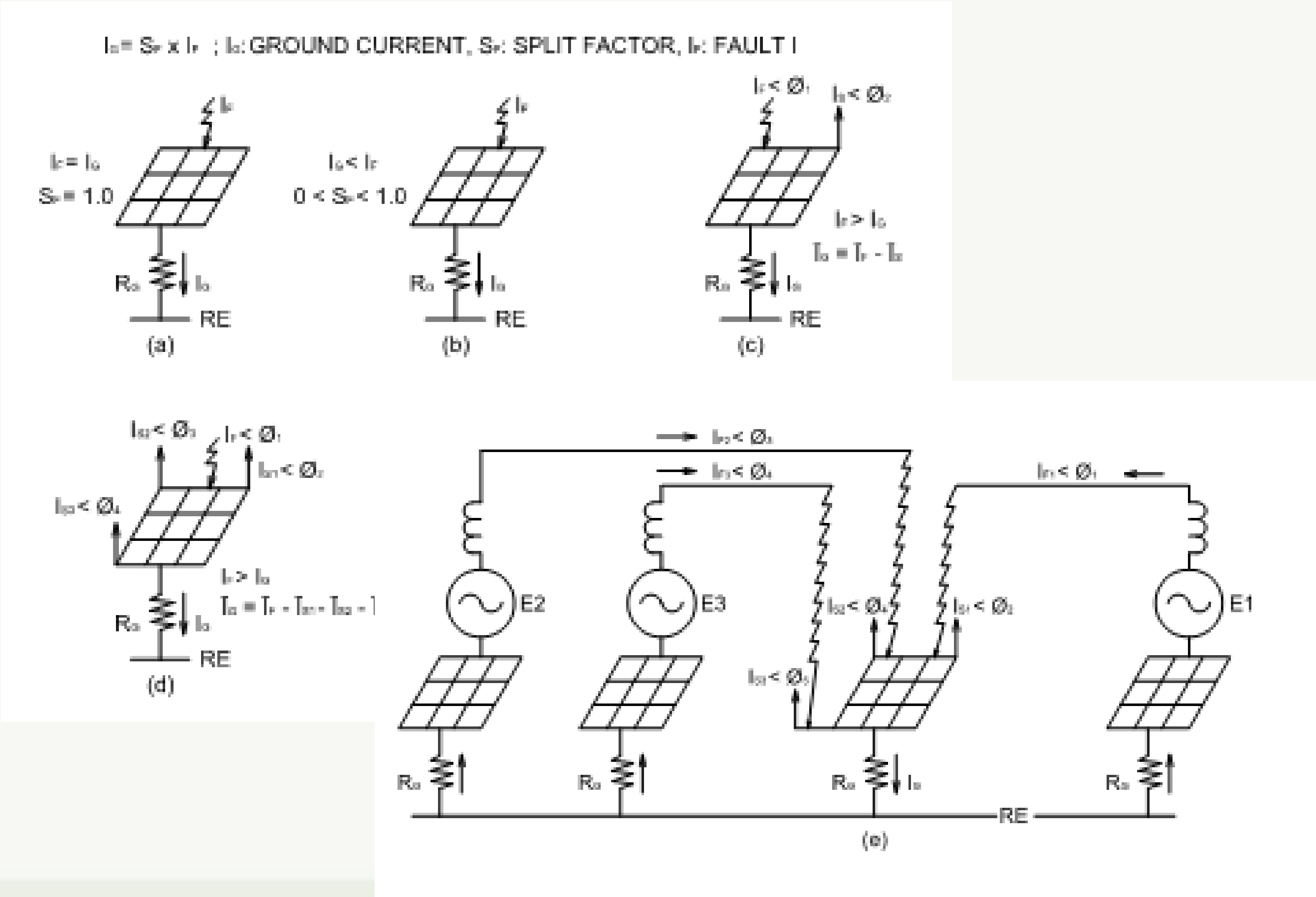
Split Factor Analysis

- $S_f = I_g / (3I_0)$
- TL shield wire & feeder neutral currents
- Grid vs. OHSW /neutral currents
- “Hand” (IEEE 80 Annex C) vs. Software calculation

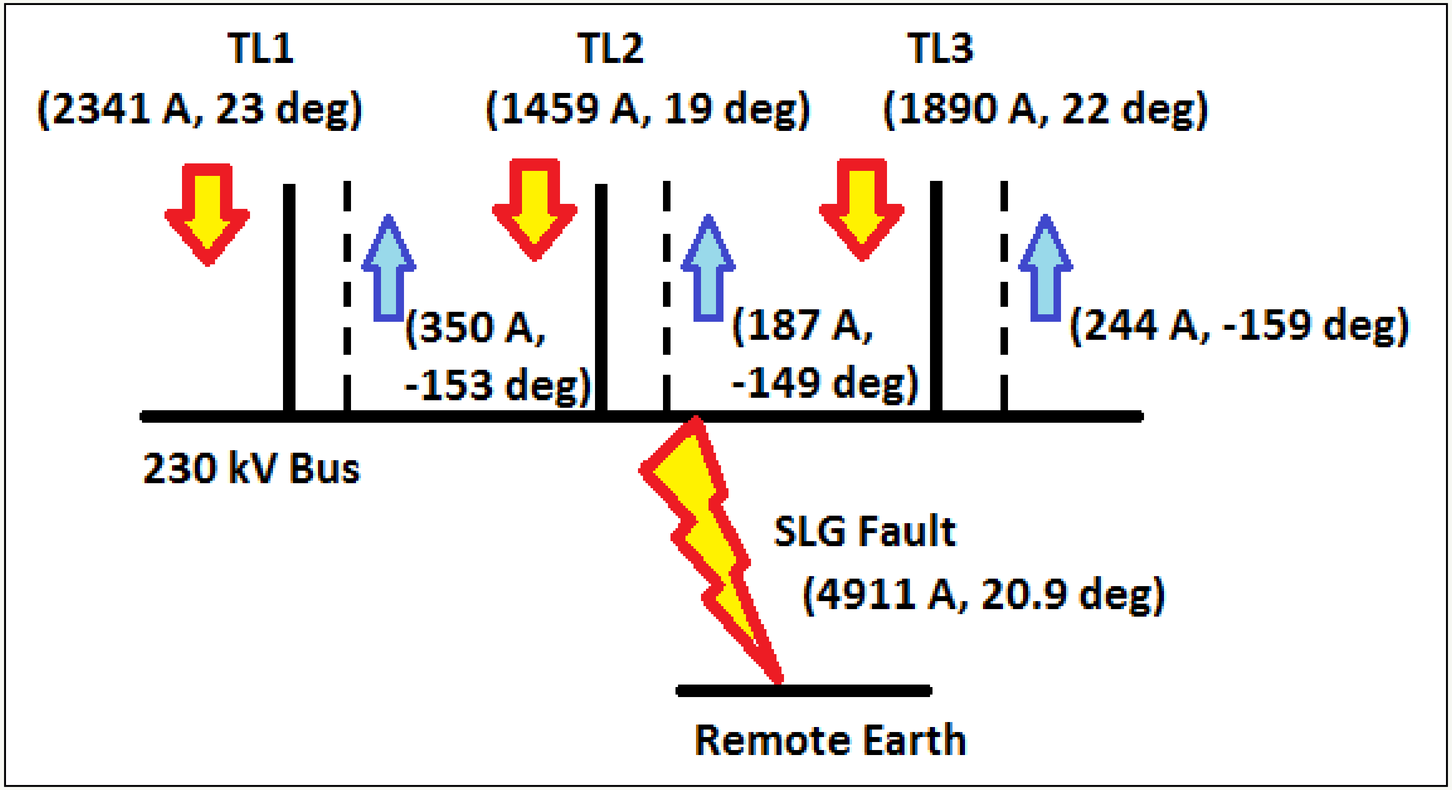
115 kV Triple Circuit with Two Shield Wires

115 kV Double Circuit Line with Two Shields

Split Factor Analysis



Split Network One-Line



Injected current ($3I_0$): 5687.8 A, 21.6°

Current in shields: 779.3 A, -153.9°

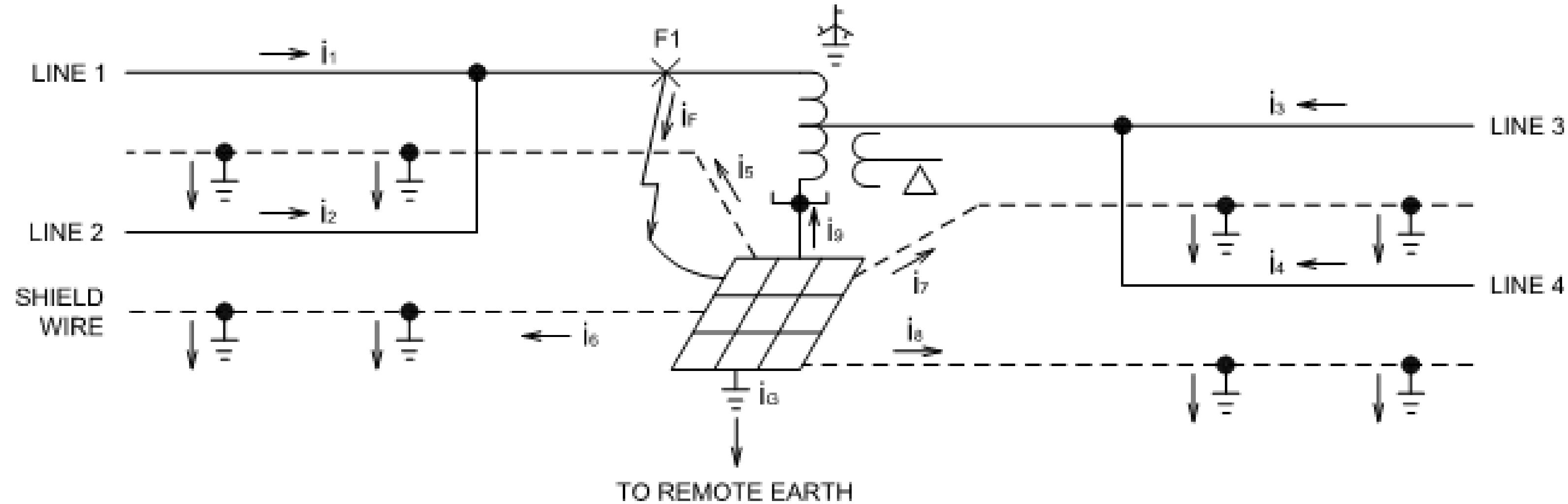
Earth current: 4911 A, 20.9°

Split factor: S_f = 4911/5687.8 = 86% into remote earth

Example 1 - Fault Analysis

A) TRANSMISSION SUBSTATION:

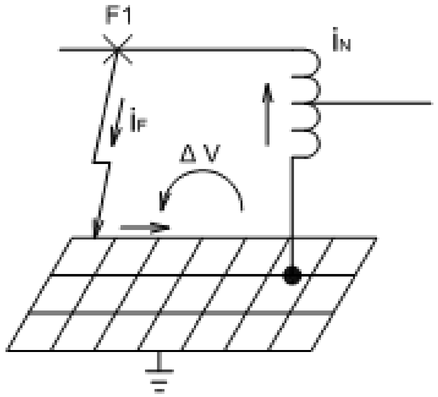
A.1) SLG FAULT @ HVSIDE. (0) SEG. CURRENT. CLOSE FAULT. 345KV, 115KV. 115KV MESHED. ALL OH LINES.



$i_G = i_1 + i_2 + i_3 + i_4 - i_9 - i_5 - i_6 - i_7 - i_8$

- $i_1 + i_2 + i_3 + i_4$: I_0 CONTRIBUTION FROM LINES
- i_9: AUTO XFMR NEUTRAL I_0
- $i_5 - i_6 - i_7 - i_8$: CURRENT SPLIT TO SHIELD WIRES

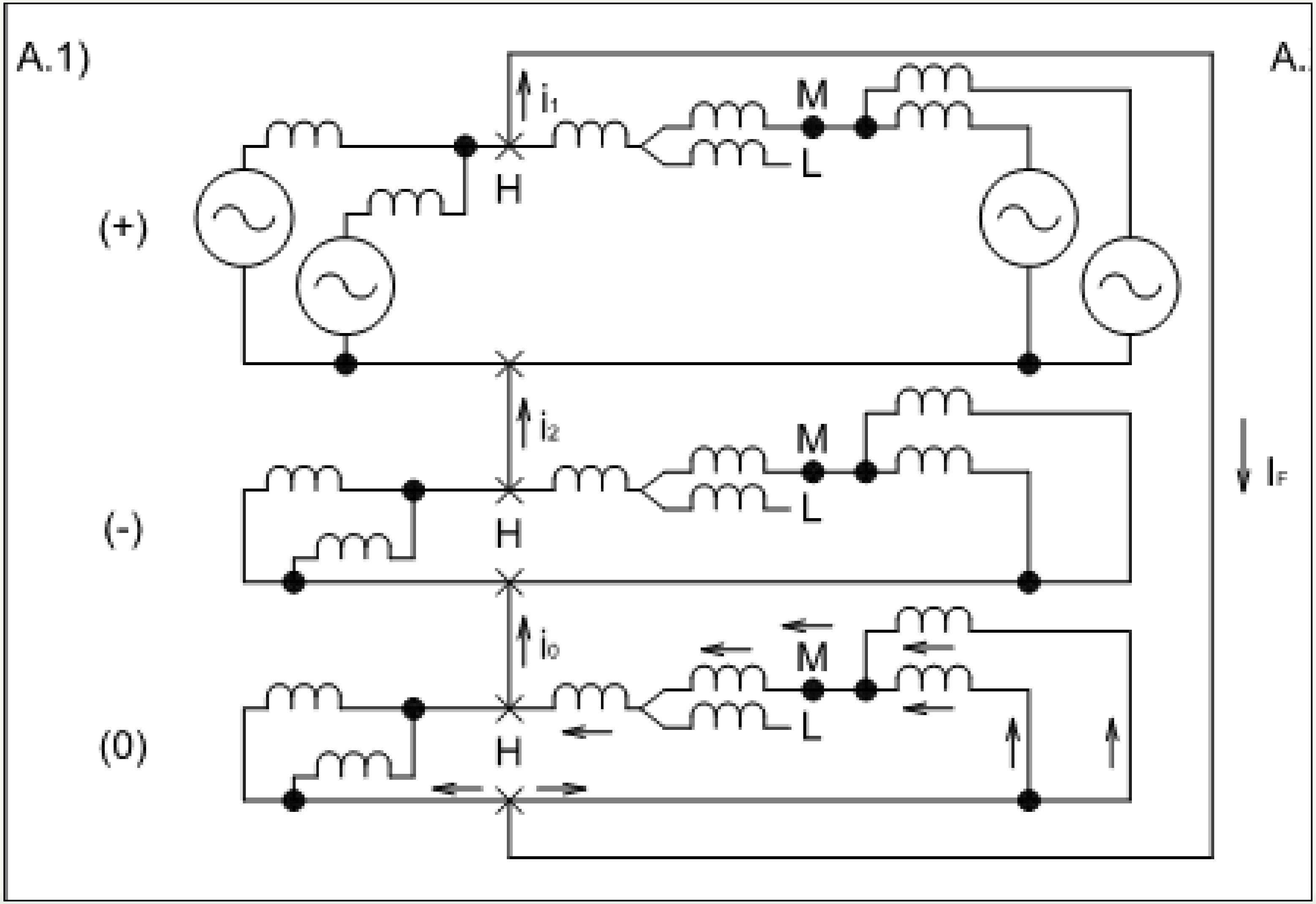
USE i_G FOR FAULT CURRENT FOR GROUNDING STUDY



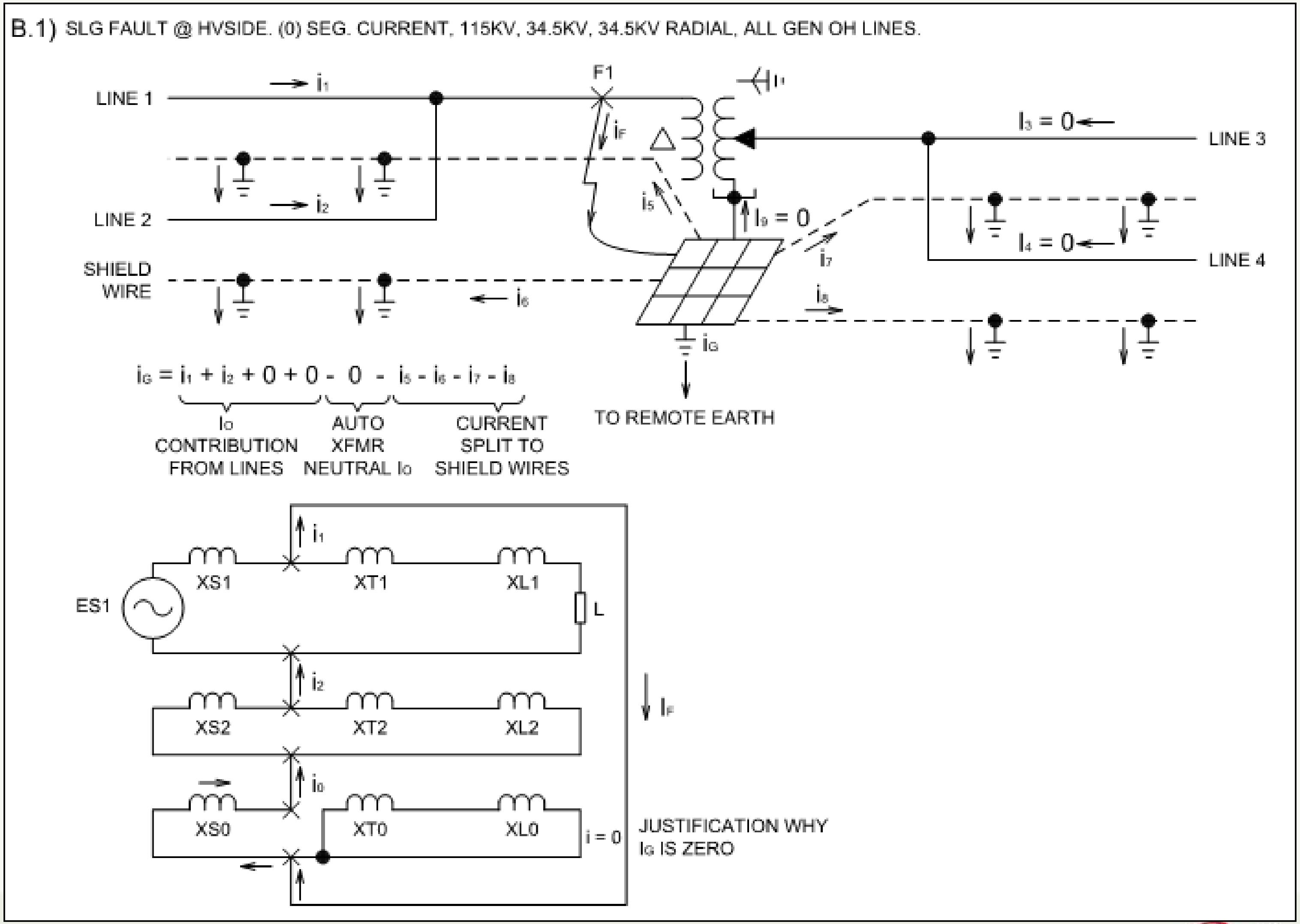
NOTE: IF SUBSTATION IS LARGE THEN THERE IS GPD DIFFERENCES DUE TO THE NEUTRAL - F1 CIRCULATING CURRENT LOOP. THIS COULD POSE DANGEROUS CONDITIONS TO PEOPLE.

NOTE: IF 115KV IS RADIAL THEN i3 = i4 = 0 IF THERE ARE NO SOURCES OF GENERATION THERE OR MESHED NETWORK.

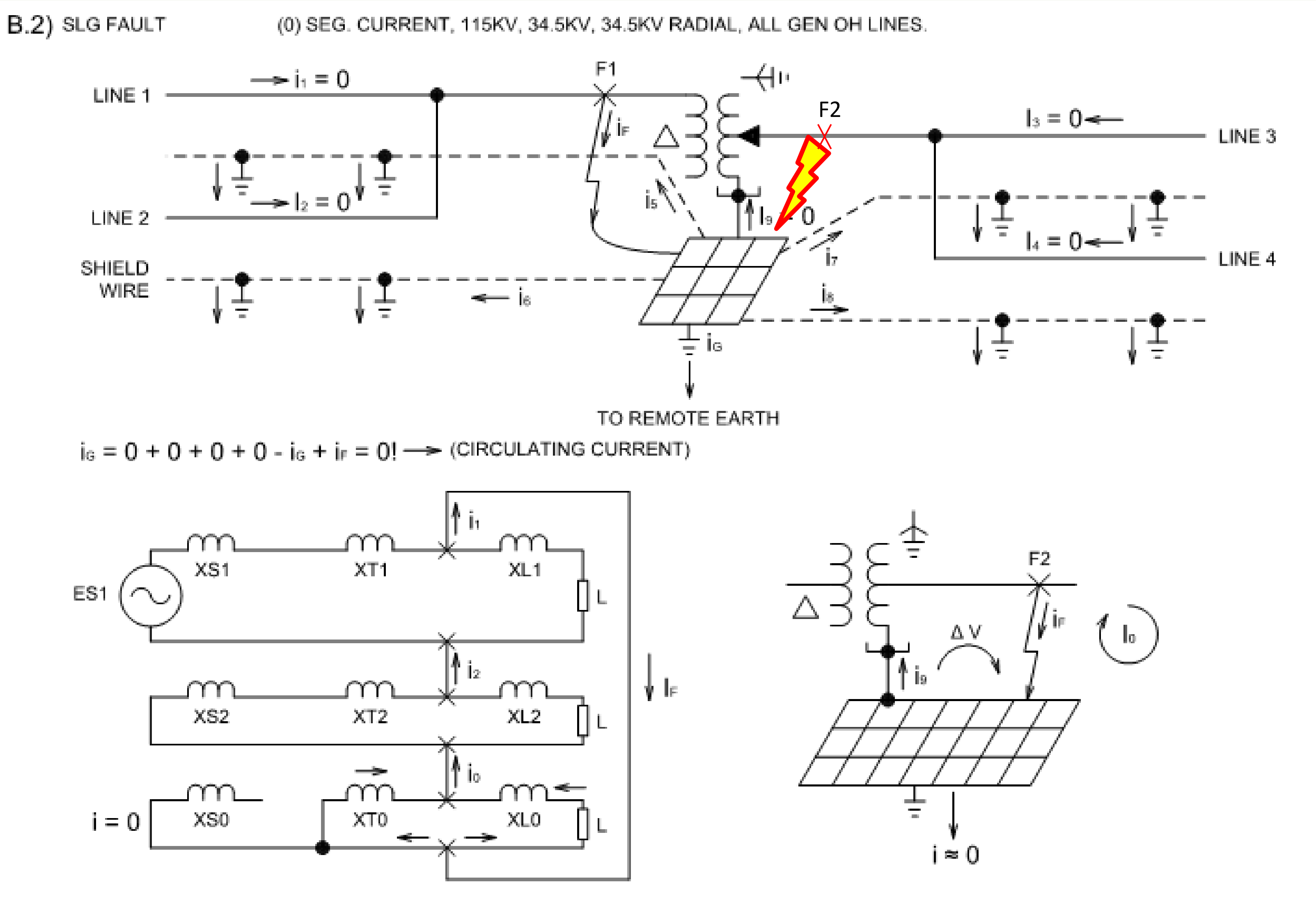
Example 1 - Symmetrical Comp. Analysis



Example 2-Fault Current Analysis



Example 3-Fault Current Analysis



Safety Analysis - Touch

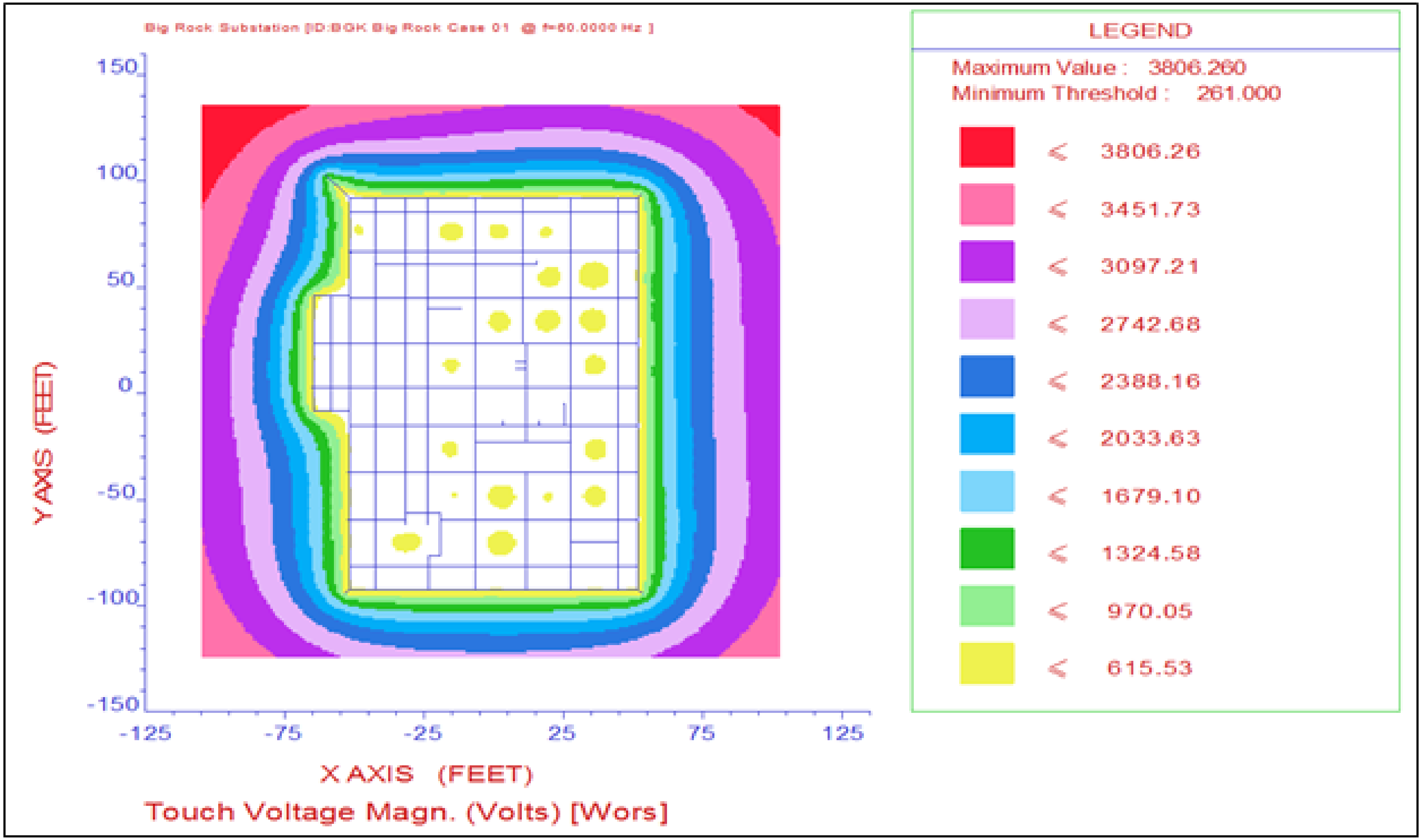
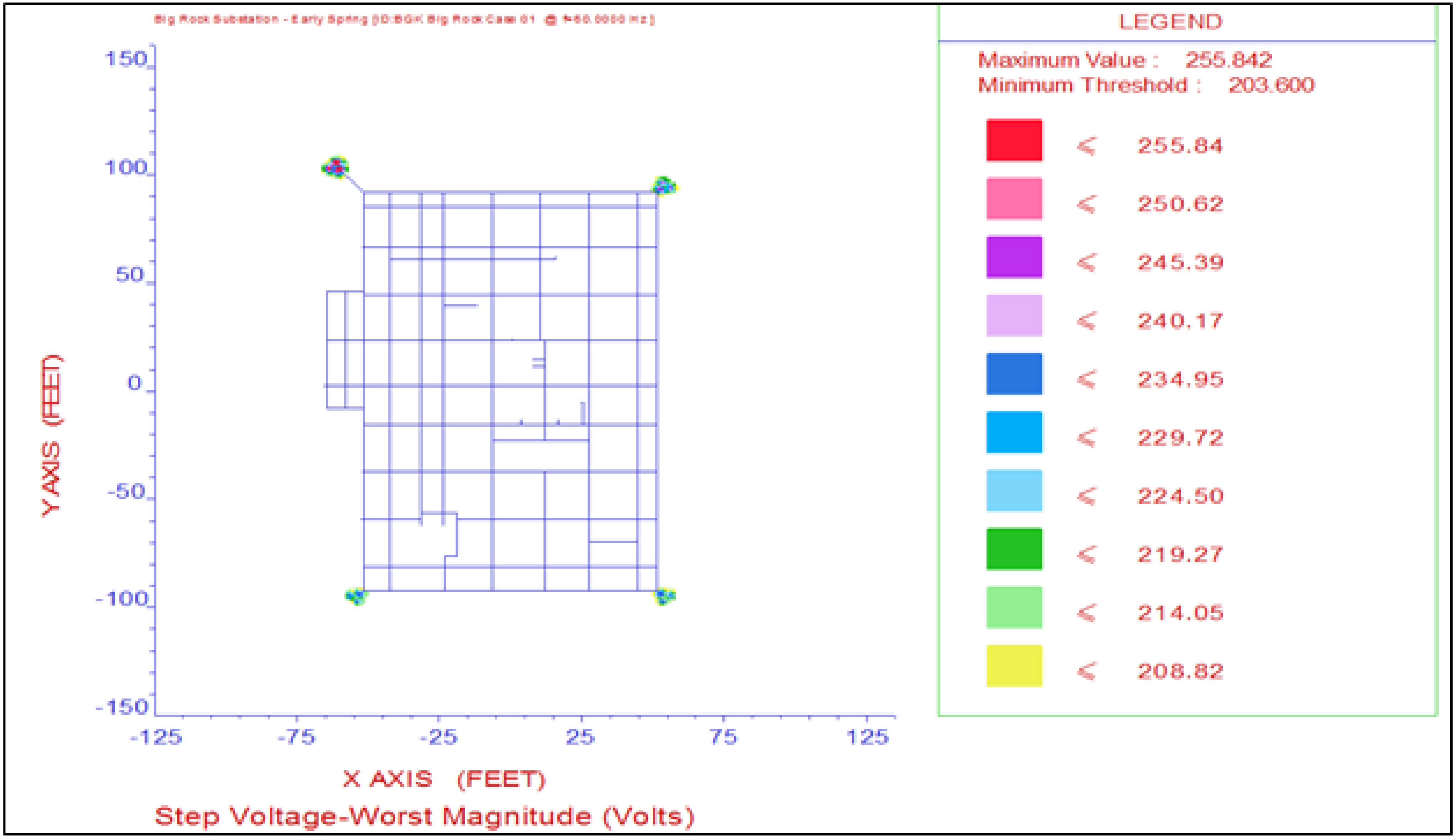


Figure 1: Touch Potential, no rock, 400 ms, 2950 A, summer

Safety Analysis - Step



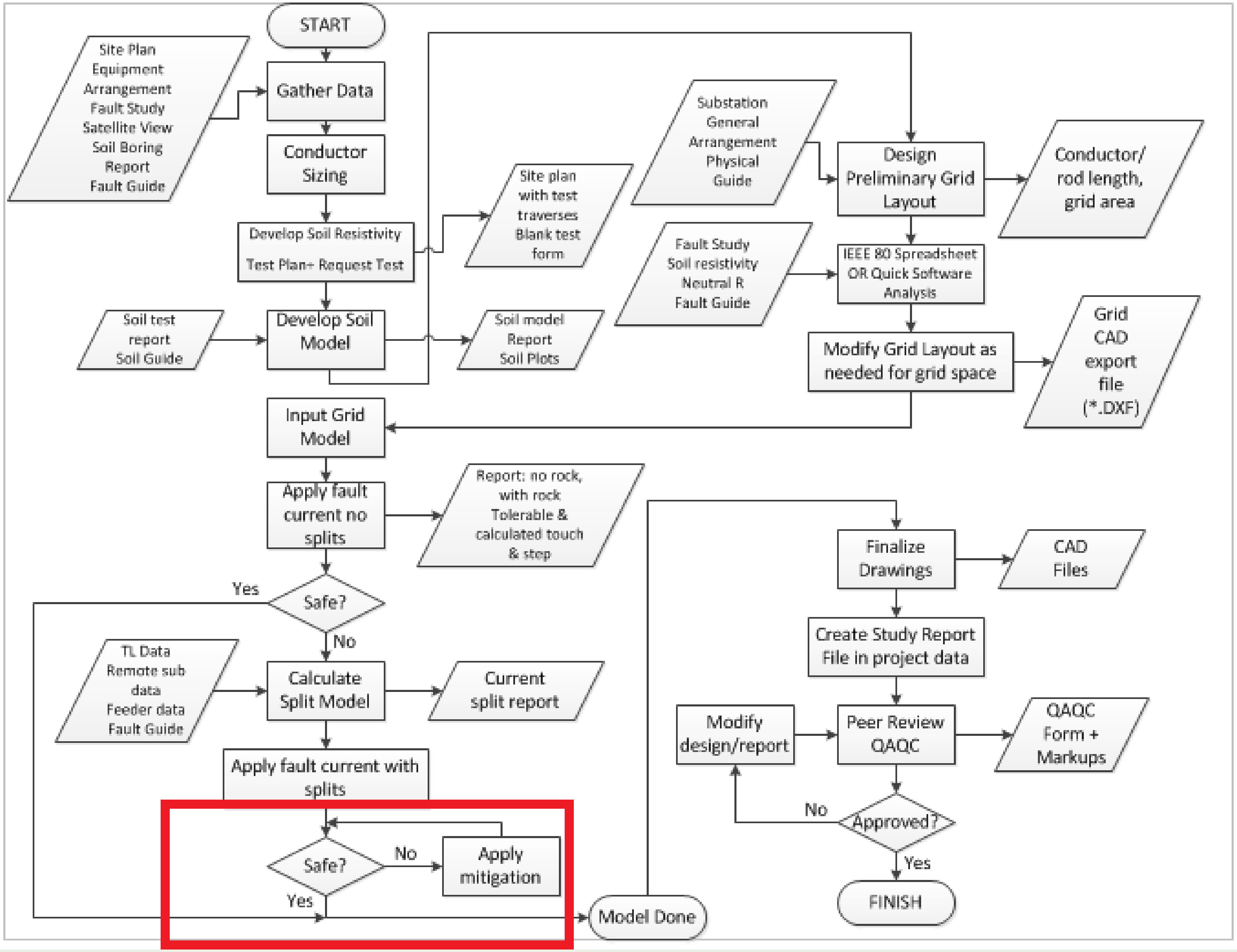
Parametric Safety Analysis

Table 5: Touch & step potential per fault current and rock resistivity, summer, post-grade

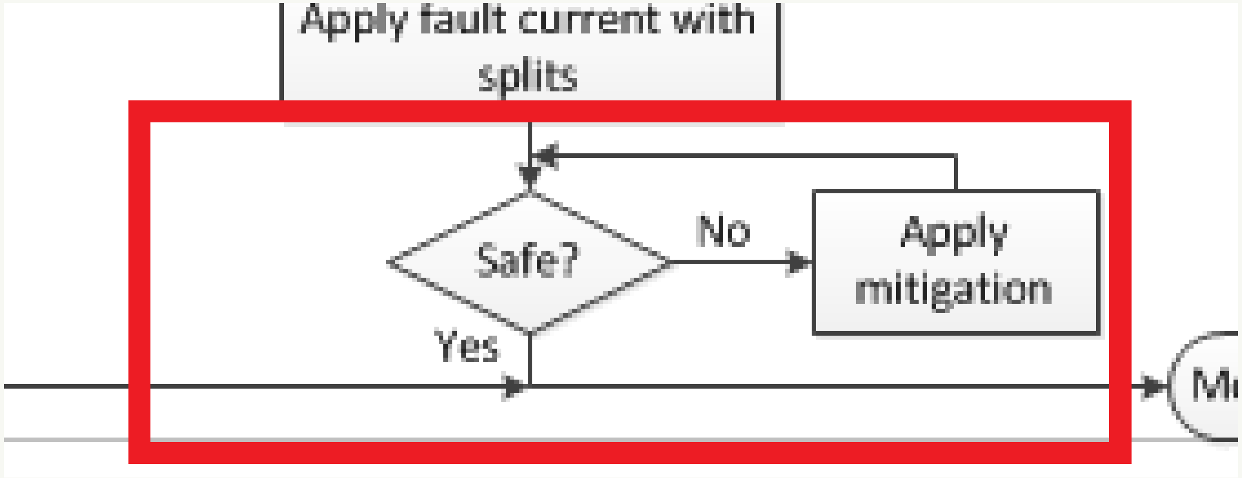
I_{EARTH} (A)	No Surface Rock (283 Ω-m)	4" Surface Rock 300 Ω-m	4" Surface Rock 450 Ω-m	4" Surface Rock 600 Ω-m	4" Surface Rock 1500 Ω-m
2950	UT, US(1)	UT, SS	UT, SS	UT, ST (2900), SS	ST (4500), SS
2800	UT, US(1)	UT, SS	UT, SS	ST, SS	ST, SS
2700	UT, US(1)	UT, SS	UT, SS	ST, SS	ST, SS
2600	UT, US(1)	UT, SS	ST, SS	ST, SS	ST, SS
2500	UT, US(1)	UT, SS	ST, SS	ST, SS	ST, SS
2400	UT, SS	UT, SS	ST, SS	ST, SS	ST, SS
2350	ST, SS	ST, SS	ST, SS	ST, SS	ST, SS

Legend: Unsafe Touch (UT), Safe Touch (ST), Unsafe Step (US), Safe Step (SS)

Safety Analysis - Mitigation



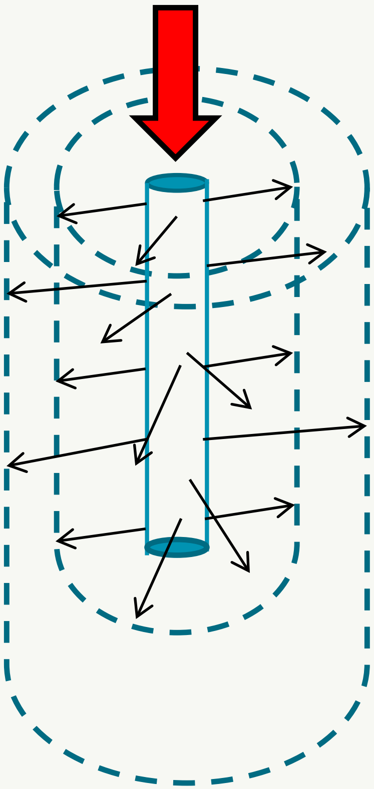
Safety Analysis - Mitigation

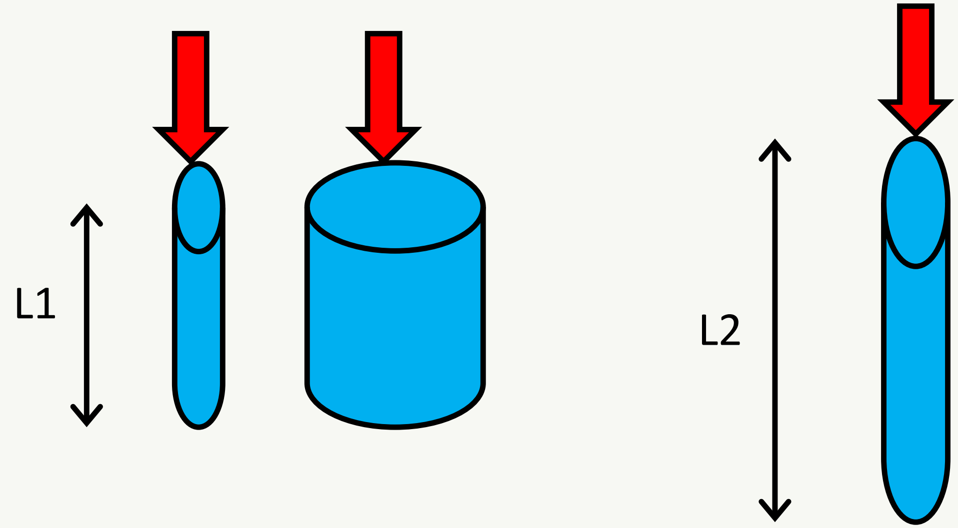


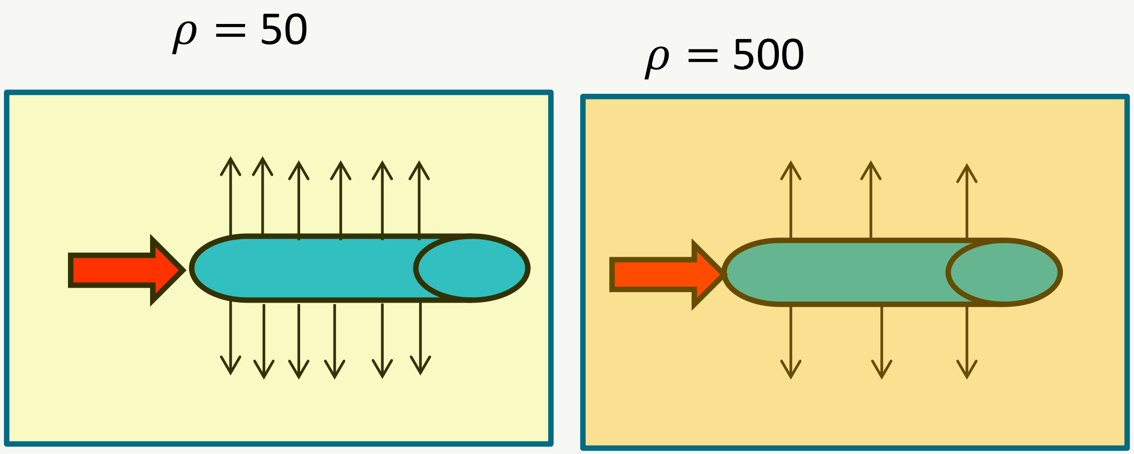
Mitigation Options

- Reduce clearing time
- Add conductor
- Add rods / extend rod length
- Ground wells
- Increase area
- Surface rock
- Satellite grid
- Soil enhancement
- Bond adjacent grids

Leakage Current







Testing

- Fall of Potential, IEEE 81-2012

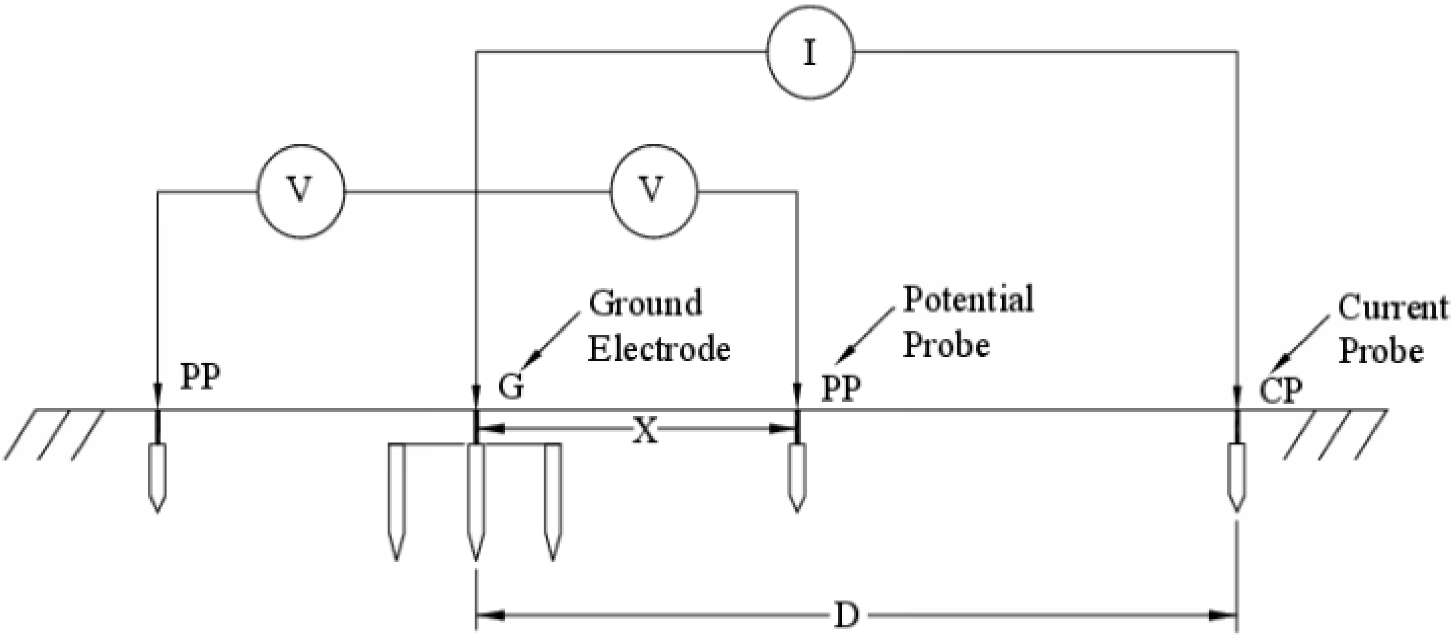
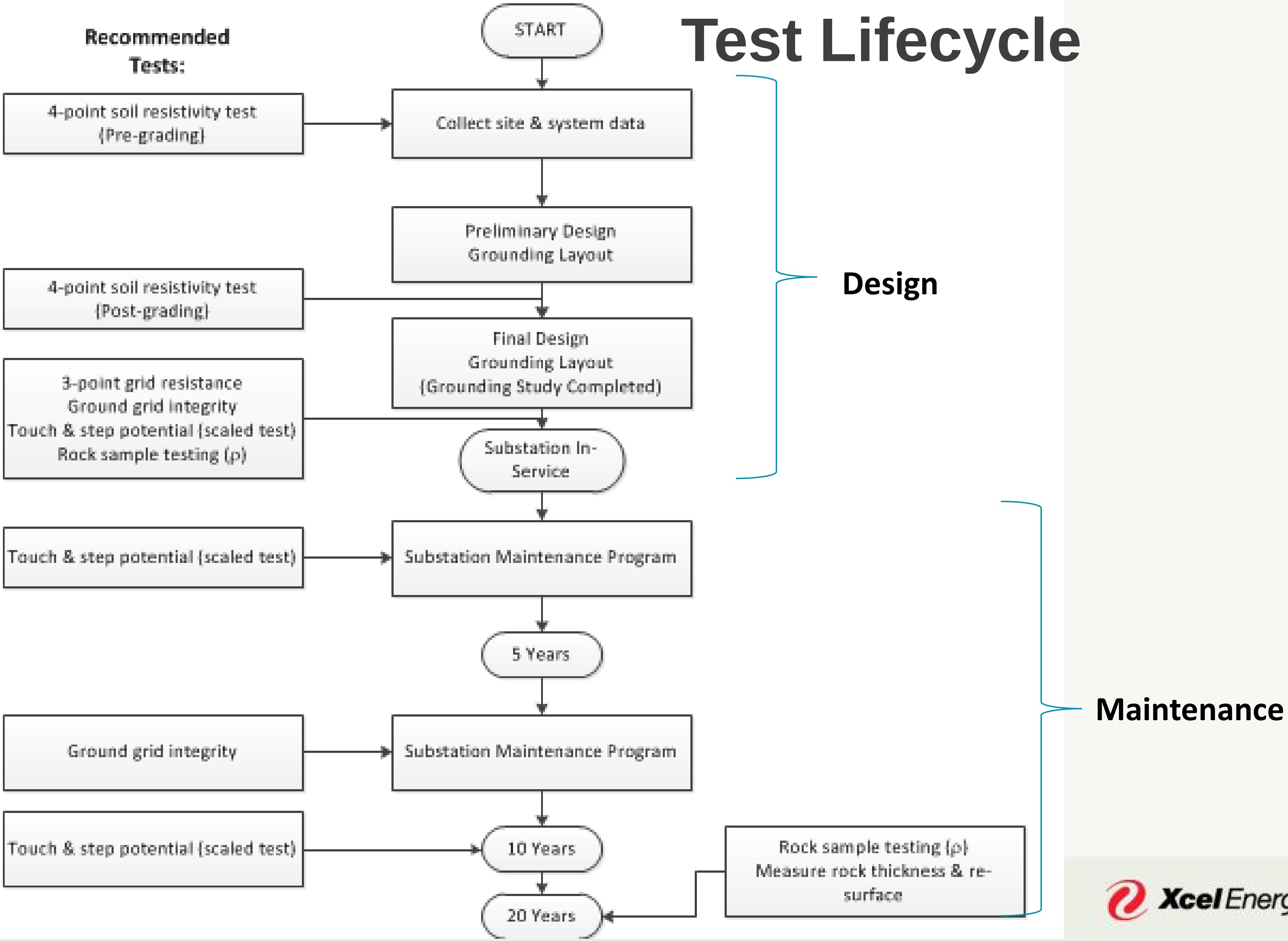


Figure 6—Illustration of fall-of-potential method

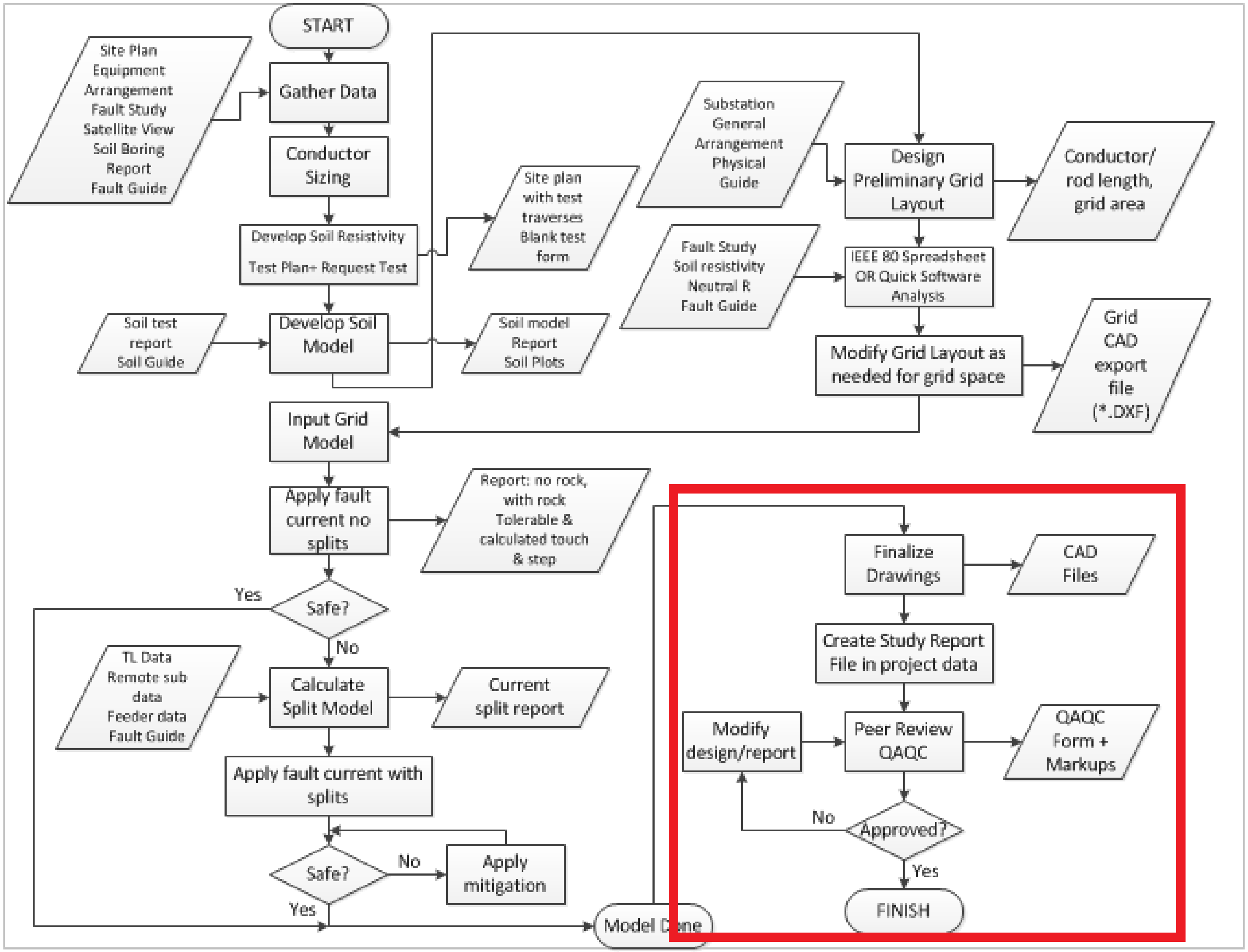
Source: IEEE 81-2012

Testing – 3 Pin Method (Grid Resistance)

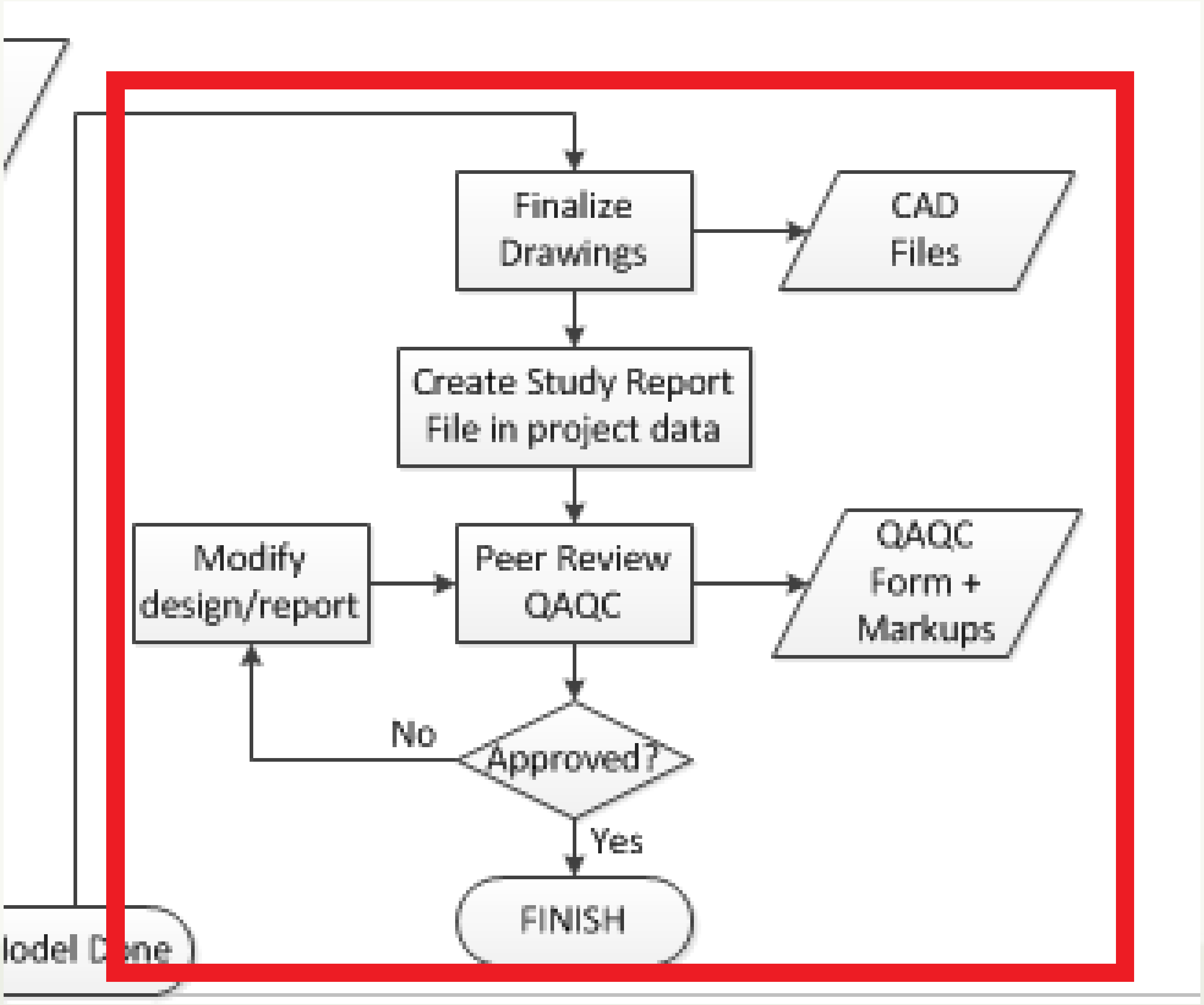
Test Lifecycle



Grounding Study Report



Grounding Study Report

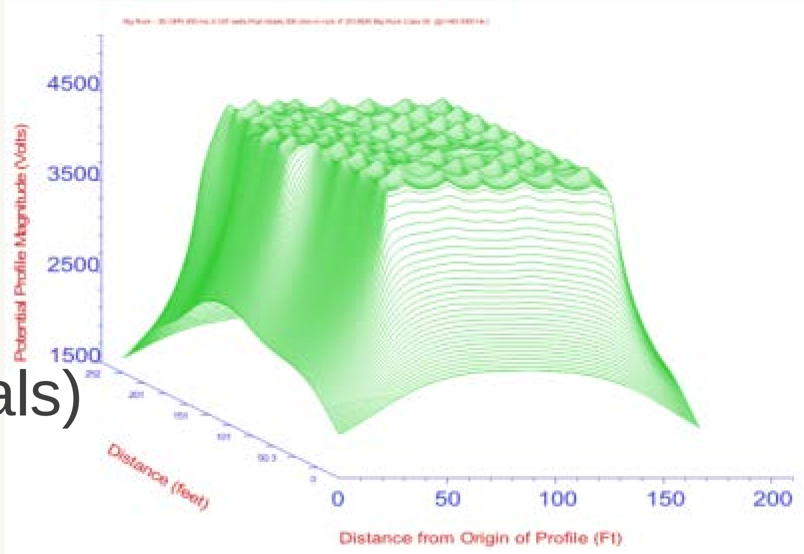


Grounding Study Report

Safety Analysis Report Data

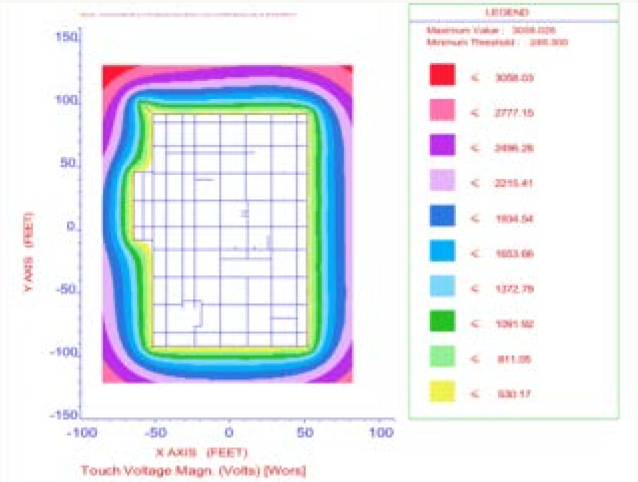
- Soil boring report
- Soil resistivity test report
- Fault study report, current magnitude, duration, safety margin, X/R
- Rock, soil resistivity models
- Body weight – IEEE 80 formulas
- Simulations different conditions
- Split Factor – calculation method, assumptions
- Photos
- Drawings
- Protection data

Ground Grid Report

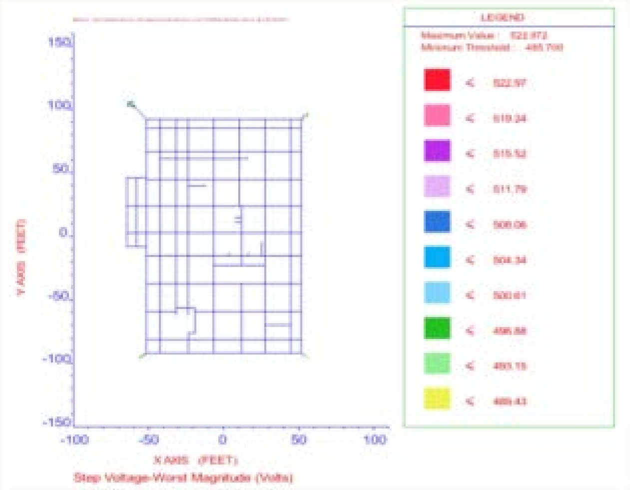


- Design variables
- Soil model data
- Safety analysis(touch-step potentials)
- Simulation files
- Simulation log

Touch Potentials Substation



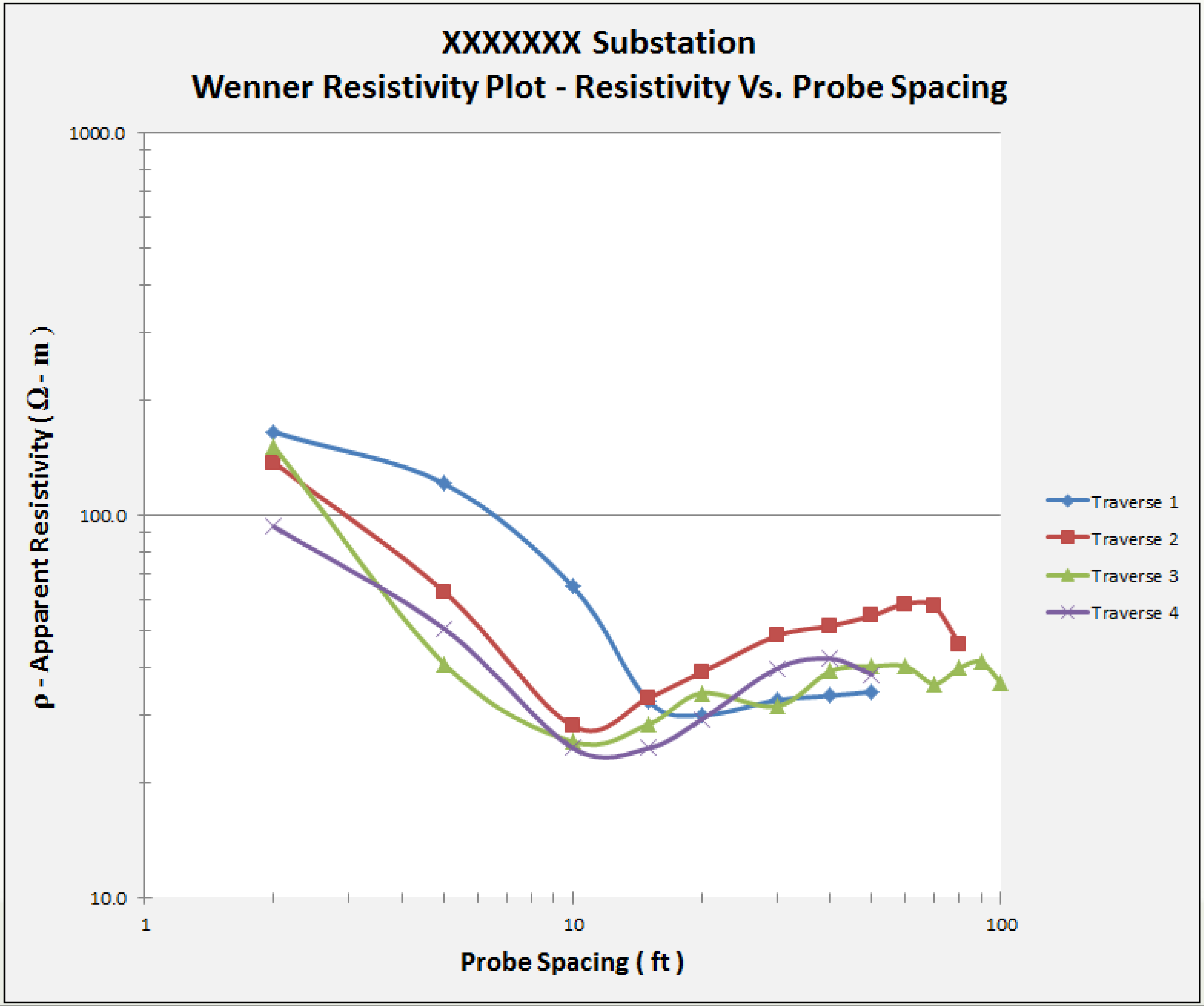
Step Potentials Substation



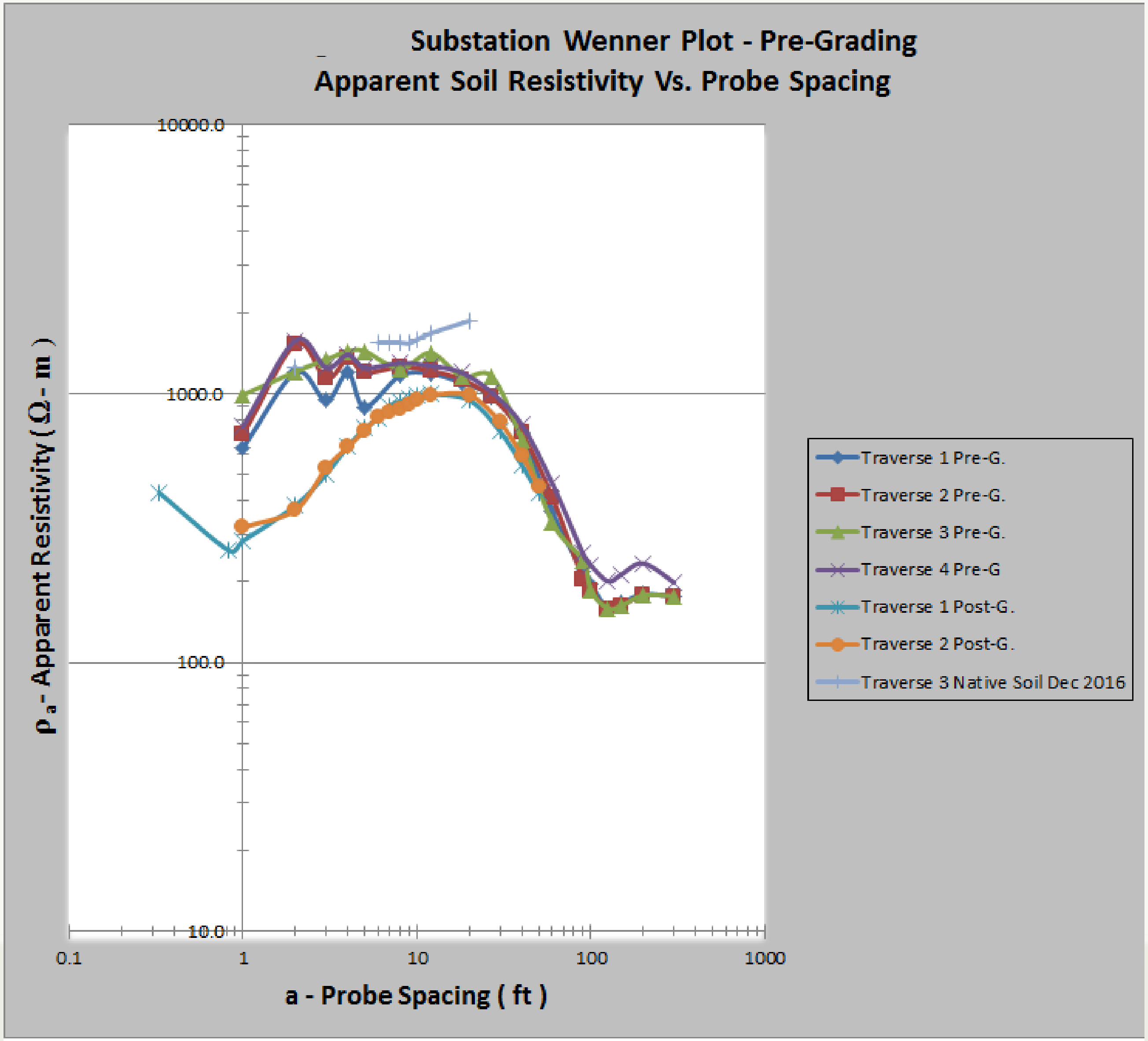
Grounding Design Variables

- Soil model variables (variance test results) Pre- & Post-grade
  - Approximation method used of raw data, error, discard data
  - Impact of fill material
  - Limited test data

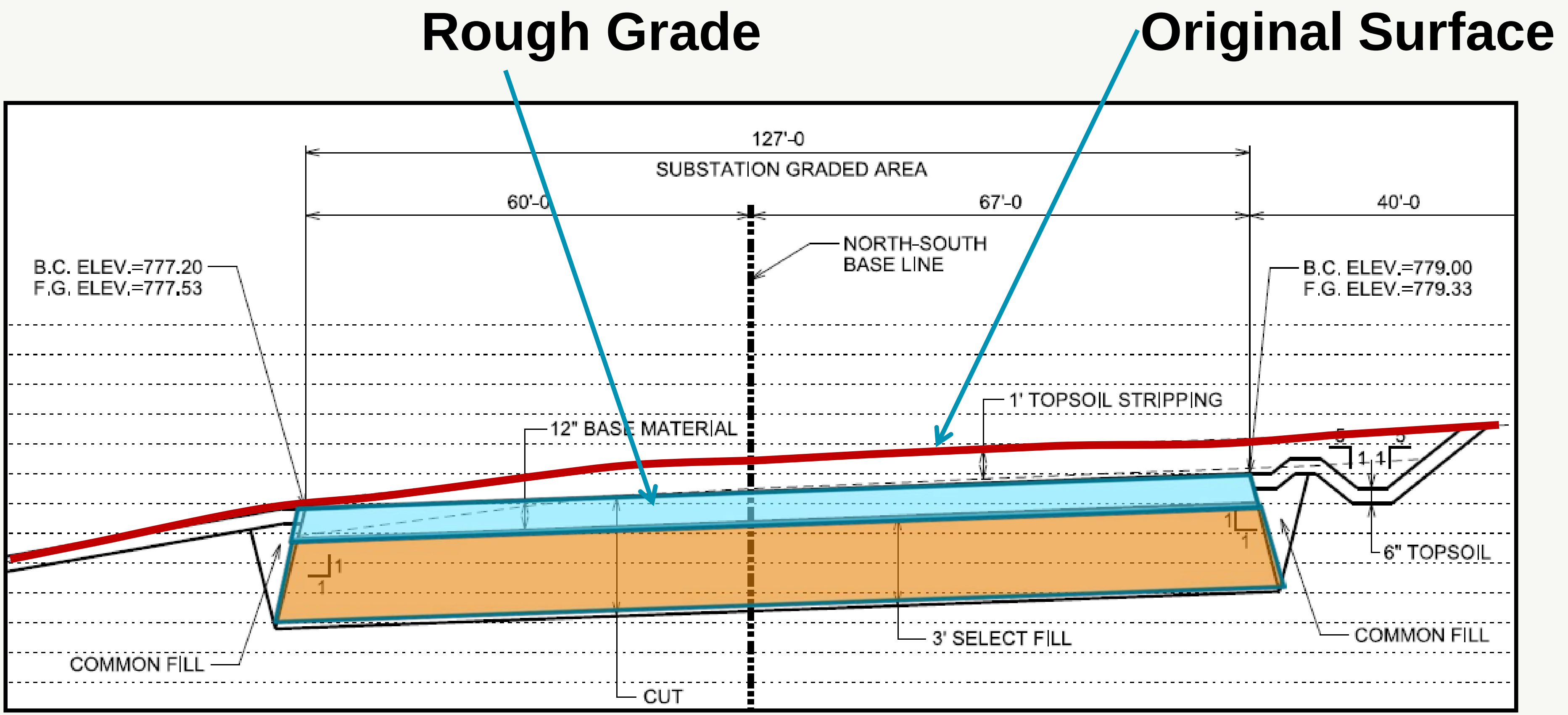
Grounding Design Variables



Grounding Design Variables



Substation Grading Section Drawing



Grounding Design Variables

- **Seasonal modelling of soils**
  - Drought, flood, **winter**, summer, early spring-late fall
  - Map frost depth
  - Multiplication factor discussion
  - Table with various soil resistivities
  - Mitigation options

Spring Conditions

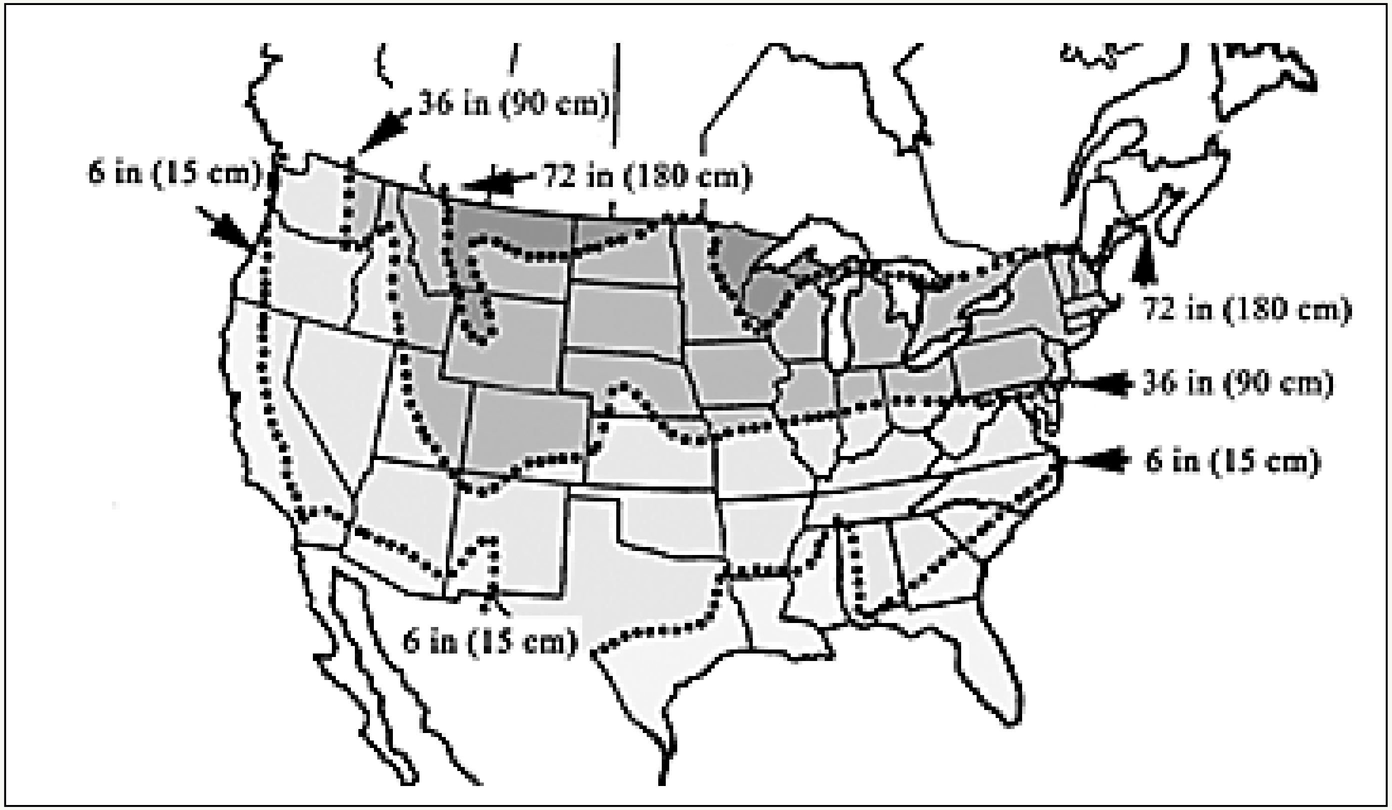

2014 03 10


2014 03 10

Fall Conditions

Winter Conditions

Map Frost Depths



Grounding Design Variables

- Crushed rock resistivity
  - Last developments - IEEE 81 Task Force
  - Testing
  - Examples of values
  - Maintenance
  - Foreign materials (wind erosion, contamination, snow, salt spray, vehicle mud & traffic, etc.)

Surface Rock Resistivity

Examples for assumption of crushed rock value (rock not tested)

Pre-grading top soil resistivity (Ω-m)	Post-grading top soil resistivity (Ω-m)	Use 1.0 - 1.5 - 2.0x highest soil resistivity + 2000 Ω-m (if applicable)
800	400	800-1200-1600-2000
150	600	600-900-1200-2000
1200	800	1200-1800-2000
100	200	200-300-400-2000
30	50	50-100-150-2000

Surface Rock Resistivity

Touch & step potential per fault current and rock resistivity, summer, post-grade

Legend: Unsafe Touch (UT), Safe Touch (ST), Unsafe Step (US), Safe Step (SS)

I_{EARTH} (A)	No Surface Rock (283 Ω-m)	4” Surface Rock 300 Ω-m	4” Surface Rock 450 Ω-m	4” Surface Rock 600 Ω-m	4” Surface Rock 1500 Ω-m
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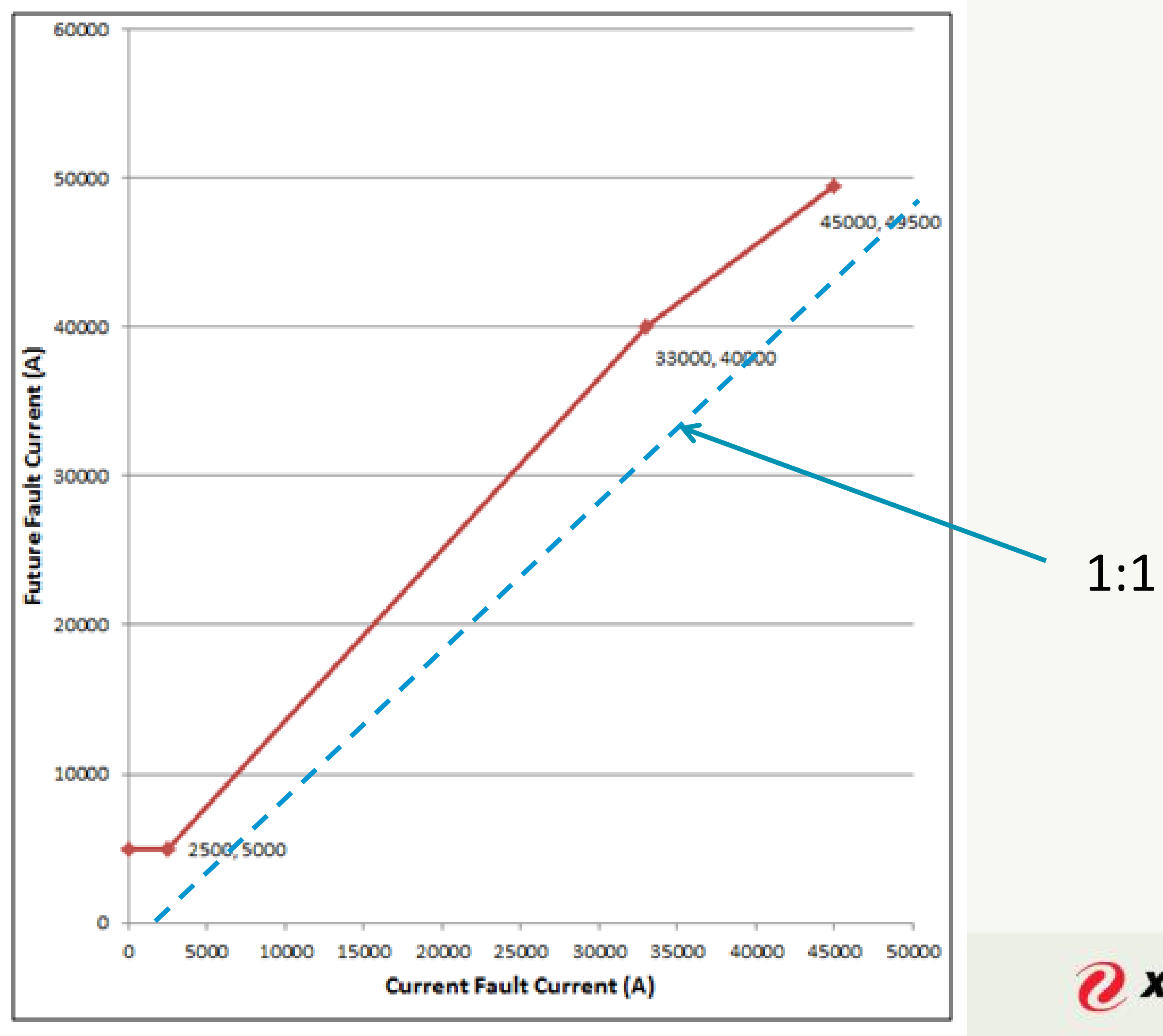
2800	UT, US(1)	UT, SS	UT, SS	ST, SS	ST, SS
2700	UT, US(1)	UT, SS	UT, SS	ST, SS	ST, SS
2600	UT, US(1)	UT, SS	ST, SS	ST, SS	ST, SS
2500	UT, US(1)	UT, SS	ST, SS	ST, SS	ST, SS
2400	UT, SS	UT, SS	ST, SS	ST, SS	ST, SS
2350	ST, SS	ST, SS	ST, SS	ST, SS	ST, SS

Fault Current Design Margin



Grounding Design Variables

- Fault clearing time
  - Short circuit curve
  - Explain examples of contingencies from protection perspective:
    - BF, no BF
    - Reclosing
    - Functional teleprotection vs. failed, stepped distance

Grounding Design Variables

Summary of variables & how their combined application affect design and develop consistency:

- Rock resistivity = 3000 Ω-m
- Fault current = 30 kA * 1.05 (design margin) = 31.5 kA
- Good soil - resistivity estimated = 100 Ω-m (uniform)
- 12 lines - Neutral Imp =0.19 Ω - SF= 15% flowing into grid
- HV lines with comms. so fault duration calculated = 10 cyc
- X/R low – no TR in sub only HV switching station - X/R = 2.0

Grounding Design Variables

Summary of variables & how their combined application affect design and develop consistency:

- Rock resistivity = surface soil resistivity layer = 355 Ω-m
- Fault current = 30 kA * 1.20 (design margin) = 36 kA
- Soil resistivity test results = 8 layer model
- Line model (12 lines) results Current SF = 42% flowing into grid
- HV lines with loss of comm. Fault duration calculated = 20 cycles (Zone 2 clearing)
- X/R calculated = 8.2 (round up to 10 for safety margin)

Conclusions & Recommendations

- Define acceptable ranges for design variables
- What assumptions are acceptable
- Do not focus on only one design variable
- Obtain accurate field data
- Document success and shortcomings

Questions?

Thank You!