

HDL-TM-83-6

June 1983

Physical and Computer Modeling of Military Earth
Grounding Practices in a HEMP Environment

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER HDL-TM-83-6	2. GOVT ACCESSION NO. AD-A130141	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Physical and Computer Modeling of Military Earth Grounding Practices in a HEMP Environment		5. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
7. AUTHOR(s) Andrew A. Cuneo, Jr., James J. Loftus Rodney A. Peralta, Electro Magnetic Applications, Inc., Denver, Co		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Harry Diamond Laboratories 2800 Powder Mill Road Adelphi, Maryland 20783		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Communications Engineering Center 1860 Wiehle Avenue Reston, VA 22090		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Ele: 33126K
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE June 1983
		13. NUMBER OF PAGES
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES PRON: WSO-4001WSA9 MIPR: HC1001-9-400		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) HEMP Grounding Electronic systems Hardening Scale modeling Finite-difference transmission-line technique		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Military grounding practices compatible with hardening electronic systems to high-altitude electromagnetic pulse (HEMP) illumination are considered. This study concerns the grounding practices outlined in MIL-STD-188-124, Common Long-Haul/Tactical Communications Systems. Three standard grounding schemes and one new scheme were chosen for study at a 10:1 scale, illuminated by a 59-V/m peak simulated HEMP. There were several significant results: (a) The theoretical technique in general agrees to within a factor of three with the experimental results.		

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20. ABSTRACT (Cont'd)

(b) The type of earth ground system does not appear to be important,

(c) Intracite transients tend to be dominated by electromagnetic coupling to completed conductive loops. When the loop is broken, the transient is characterized by the half-wavelength resonance of the conductor. Grounding paths which do not form part of the loop do not contribute significantly to the transient in the loop.

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1. INTRODUCTION

1.1 Background

In recent years, there has been a resurgence of interest in military grounding practices which are compatible with hardening electronic systems to high-altitude electromagnetic pulse (HEMP) illumination. This study concerns the grounding practices outlined in MIL-STD-188-124, Common Long-Haul/Tactical Communications Systems. Considerable controversy surrounds the topic of grounding practices. None of these practices have been subjected to rigorous HEMP analysis and testing to determine the most effective configuration. To accomplish this goal, 10:1 scale models of three standard grounding schemes and one new scheme (fig. 1 to 4), illuminated by simulated HEMP, were mathematically modeled and tested. The theoretical study used finite-difference transmission-line techniques for scale models of buried and surface conductor configurations. The simulated HEMP tests were performed at the Harry Diamond Laboratories (HDL) Scale-Modeling Facility in the Facility for Research in Electromagnetic Effects (FREME).

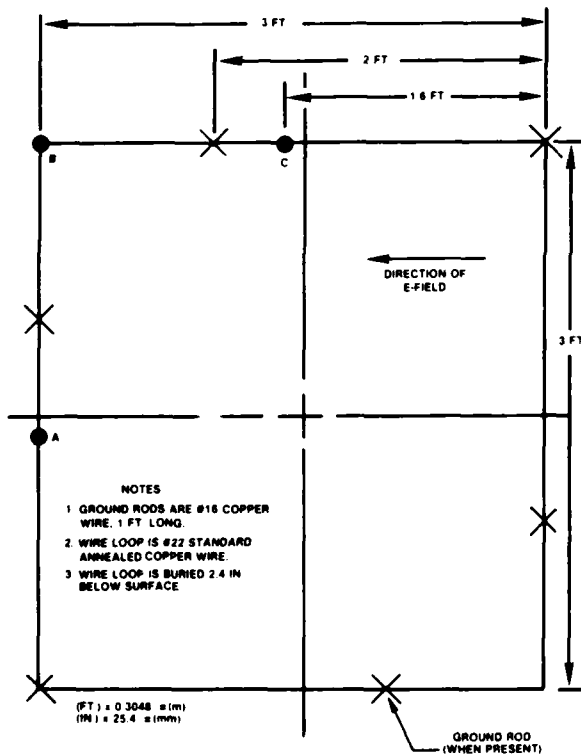


Figure 1. Ground loop model. Positive wire current is counterclockwise.

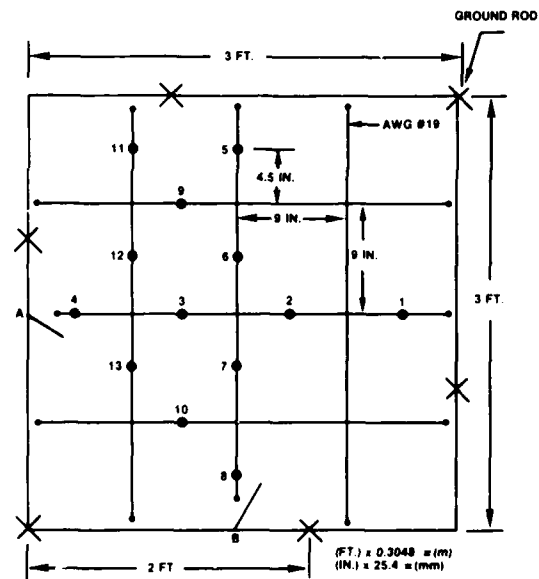


Figure 2. Rebar model, occasionally connected to counterpoise (ground loop) at A or B. Direction of E-field as in figure 1.

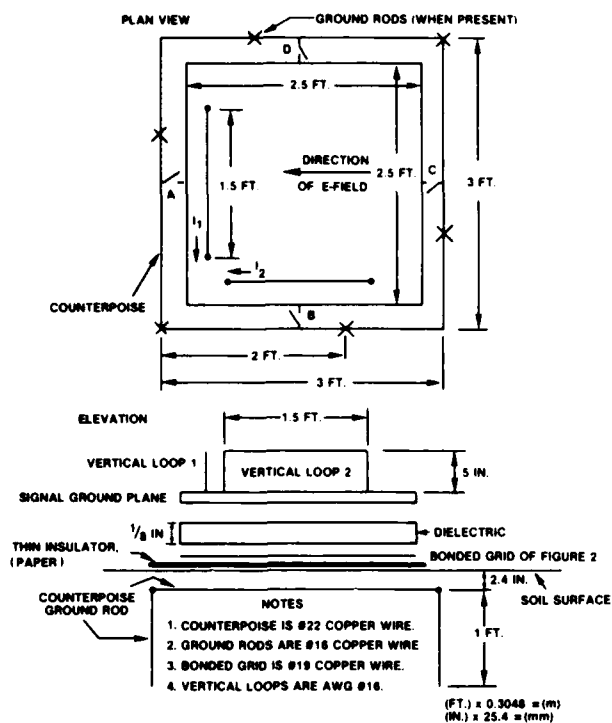


Figure 3. Signal ground plane with earth counterpoise system.

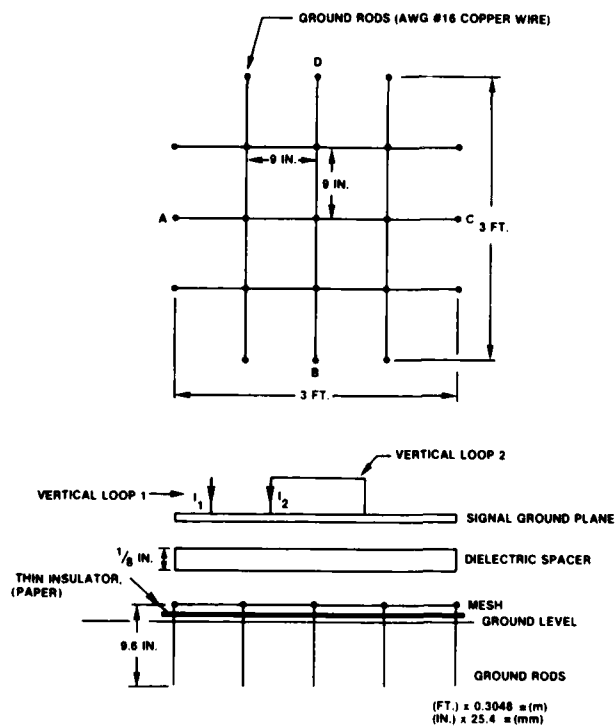


Figure 4. Model for new earth ground system.

1.2 Objectives

The objectives of the study of grounding practices are to determine the

- (a) EMP response of an earth ground system,
- (b) effectiveness of ground rods,
- (c) effects of an earth ground system on coupling to facility equipment, and
- (d) effectiveness of a signal ground plane.

Three of the most commonly used grounding systems and one new type have been selected for study. They possess one or more characteristics of all systems. It is desirable to ascertain the relative merits of grounding schemes of varying levels of sophistication. A longer term goal is to develop and test theoretical modeling techniques for grounding practices. A successful theory provides an alternative to extensive testing to empirically determine EMP hardening practices.

2. ANALYTICAL AND EXPERIMENTAL APPROACH

2.1 Experiments

The coupling source is a plane wave 50-kV/m double exponential HEMP threat scaled to 59 V/m in the tests and the model. The physical scale is approximately 10:1. The resulting current is measured at each of the test points. The four experiments are summarized in the following paragraphs.

Experiment 1: ground loop only.--In the first experiment, the test object is a simple square loop, as shown in figure 1. Current on the loop at points A, B, and C is measured with and without the ground stakes. The objective here is to investigate the effects of ground rods and provide a basis of theoretical and experimental comparisons for the simplest geometry.

Experiment 2: ground loop plus coarse rebar structure.--The second experimental configuration is shown in figure 2. This configuration is the same as in experiment 1, except that a bonded grid mesh is within the loop as shown. This grid lies on the soil surface. The grid may or may not be connected to the ground ring at points A and/or B. In this experiment, the ground rods are always connected and in place. The measured currents consist of wire currents at test points 1 through 12. In this experiment, the wire mesh represents a facility ground mesh, and the intent is to determine how connection to the earth ground system affects the current distribution on the mesh.

Experiment 3: response of signal ground plane with counterpoise earth ground system.--The configuration for this experiment is given in figure 3. This has the same earth ground configuration as figure 2. In the present case, the facility and signal ground systems consist of the bonded grid (fig. 2), which lies on top of the soil, the 1/8-in.-thick dielectric spacer, and then the metal ground plane on top. The metal plane has two loops on it, as

shown. Currents I_1 and I_2 are measured in this experiment. The signal ground plane is connected to the bonded grid (the facility ground) at only one place at a time, either A or B. For each of these cases, the current is measured for the bonded grid connected to the earth ground subsystem at points A only; B only; A and B; A, B, and C; and A, B, C, and D. The objective is to determine how the connection of the facility and signal ground planes affects coupling to facility equipment.

Experiment 4: response of signal ground plane with new earth ground system.---The configuration for this experiment is shown in figure 4. This configuration is the same as that of figure 3, except that the facility earth electrode system is different. The signal ground plane with the two loops is the same in both figures.

In the present case, instead of using a counterpoise, the earth electrode subsystem used numerous ground rods attached to a mesh identical to the one in figure 2. This facility ground may be connected to the signal ground points A, B, C, or D. Currents I_1 and I_2 are measured for connections made at A; B; A and B; A, B, and C; and A, B, C, and D. The objective here is the same as that of experiment 3, except with a different earth ground system.

2.2 Analytical Technique

Electro Magnetic Applications, Inc., of Denver, CO, was contracted to perform the calculations. The goal is to model the time-domain current in a grounding system which results from illumination by a HEMP. This first requires modeling a generalized EMP in free space striking a plane interface with a medium of frequency dependent σ , ϵ , and μ . Two computer codes, 1TOP and 1DEEP, were developed for the surface reflection and refraction, respectively. Both codes require a Fourier transform capability and must be able to solve the standard plane wave Fresnel equations. With an input of the original wave, $\sigma(\omega)$, $\epsilon(\omega)$, and $\mu(\omega)$ --the pulse shapes at the burial depth and on the surface--are obtained.

In the second part of the analysis, the loop and rebar structures were modeled by use of a time-domain buried cable code, NEDBC. This code was modified for a ground loop by setting the potentials of the end-points equal. Nonlinearities were neglected. Furthermore, the rebar intersections are treated using Kirchoff's laws, otherwise neglecting the mutual interactions of wires.

The methods for calculating wire resistances (R) per unit length, capacitances (C) per unit length, inductances (L) per unit length, conductances (G) per unit length, currents (I), and voltages (V) are discussed in the following paragraphs.

The methods involve the solution of the transverse electromagnetic (TEM) transmission-line equations

$$\frac{\partial I}{\partial X} = - \frac{\partial (CV)}{\partial t} - GV \quad , \quad (1)$$

$$\frac{\partial V}{\partial X} = V_S - \frac{\partial (LI)}{\partial t} - IR \quad , \quad (2)$$

where V_S is the voltage source which arises from the tangential incident electric field. The transmission-line parameters are defined as follows:

$$C = \frac{2 \pi \epsilon}{\ln \left(\frac{r_w + \delta}{r_w} \right)} \quad , \quad (3)$$

where

r_w = radius of wire and

$$\delta = \text{skin depth in earth} = 0.794 \left(\frac{2t}{\mu \sigma} \right)^{1/2} \quad , \quad (4)$$

with the assumption

$$\frac{\pi}{2} = \omega t \quad .$$

Also,

$$L = \frac{\mu}{2\pi} \ln \left(\frac{r_w + \delta}{r_w} \right) = \frac{\mu \epsilon}{C} = \frac{1}{v_p^2 C} \quad (5)$$

(coaxial inductance), where v_p is the propagation velocity of the medium and

$$G = \frac{\sigma}{\epsilon} C \quad . \quad (6)$$

Ground rods are included as a perturbation to G at the appropriate spatial location. Resistances were obtained from standard formulas,¹ with the result that for a 1-ft ground rod the resistance is 70 Ω for a soil conductivity of 0.05 mho/m. The relative dielectric constant used in the calculation was 3.5, although the dielectric constant does not significantly affect the results.

¹E. D. Sunde, *Earth Conduction Effects in Transmission Systems*, Dover Publications, Inc., New York (1968).

For the mesh above the earth, surface cable code techniques were used. The parameters are the same as those used for the buried cable analysis, except that the capacitance is halved and the inductance is doubled.²

2.3 Excitation Used and Relationship to HEMP Threat

Electromagnetic scale modeling³ of grounding systems for experimentally determining external coupling features requires the generation and measurement of radiated pulses closely resembling the critical characteristics of a HEMP. For the scale-modeling facility, HDL has developed a simulator consisting of a resistively tapered dipole antenna driven by a nanosecond pulser. This results in a simulated HEMP, shown in figure 5, with a 59-V/m peak and a 0.78-ns rise time at the test object location. The distortion region between 47 and 100 ns is due to late time behavior of the antenna and error introduced due to the integration of the measured signal (using a B sensor) buried in the noise. To compare the model values to the full-scale HEMP threat values, the following formula is used:

$$I = \left(\frac{50 \text{ kV/m}}{59 \text{ V/m}} \right) (10)(I') ,$$

where

I' = "1/10 model" current

and

I = full-scale HEMP data.

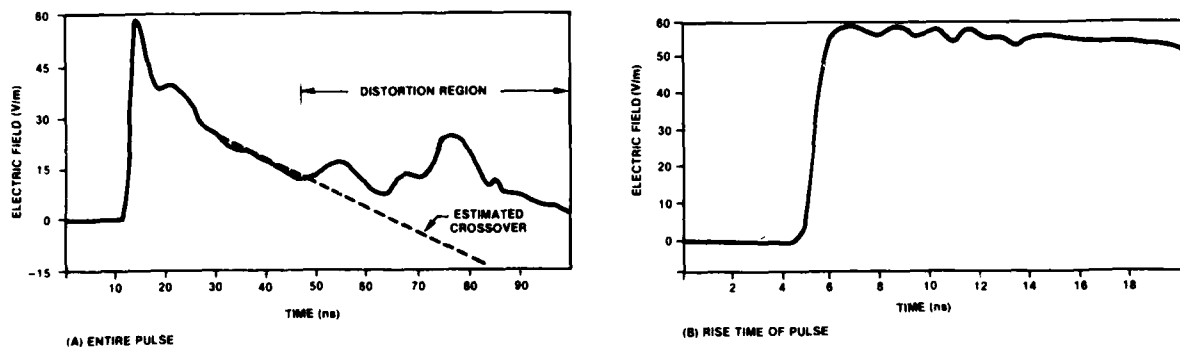


Figure 5. Incident simulated HEMP electric field.

²R. A. Perala and R. B. Cook, *The Effects of Dielectric and Soil Nonlinearities on the EMP Response of Cables Lying on the Surface of the Earth*, Electromagnetic Applications, Inc., Denver, CO, EMA-79-P-3 (January 1979).

³G. Sinclair, *Theory of Models of Electromagnetic Systems*, Proceedings of IRE (November 1948), 1364-1370.

Techniques for measuring the amplitude of the scaled-down HEMP waveforms have been developed by HDL at the Scale-Modeling Facility.⁴

2.4 Test Setup

The HDL Scale-Modeling Facility occupies a large structure at the North Annex of Fort Belvoir, VA. The structure, which is known as the FREME, is approximately 46 x 30 m, with the highest point of the roof 15 m above the floor. The modeling is carried out in an 18- x 24-m* box containing chemically treated sand.⁵ For this effort, the depth of the sand was built up to accommodate the ground rods.

The scaled-down grounding systems, shown in figures 1 to 4, are embedded in or placed on the chemically treated sand. A 40-ft[†] long resistively tapered dipole antenna is suspended 2.5 m above the sand over the model. This antenna is driven by the nanosecond pulser. Time-domain sampling techniques are used to observe the response of the scaled-down ground systems to the scaled-down HEMP. Tektronix CT-1 current probes are attached to particular test points for each test. The recording instrumentation consists of a digital processing oscilloscope controlled by a Tektronix WP1221 Signal Processing System. The measurement points are identified in figures 1 through 4.

3. RESULTS OF EXPERIMENTS

3.1 Results of Experiment 1

Typical predicted and measured waveforms for experiment 1 are compared in figure 6. Table 1 summarizes a comparison of peak values.

It is noted that peak values are predicted within a factor of 2 to 3. The pulse shapes agree quite well, although the predicted pulses are much wider than those measured.

The data support the following conclusions:

(a) The mathematical model predicts peak values within a factor of 3.

⁴Andrew A. Cuneo, Jr., and James J. Loftus, *Measurement of Scaled-Down High Altitude Electromagnetic Pulse (HEMP) Waveforms*, Harry Diamond Laboratories, HDL-TM-81-6 (March 1981).

⁵Andrew A. Cuneo, Jr., and James J. Loftus, *Scale Modeling for the Patriot Electromagnetic Pulse Test*, Harry Diamond Laboratories, HDL-TM-81-16 (May 1981).

* (in.) x 25.4 = (mm).

† (ft) x 0.3048 = (m).

(b) The mathematical model predicts at least as large or larger effects of the ground rods as was measured, but in all areas the effects of the ground rods appear to be practically insignificant.

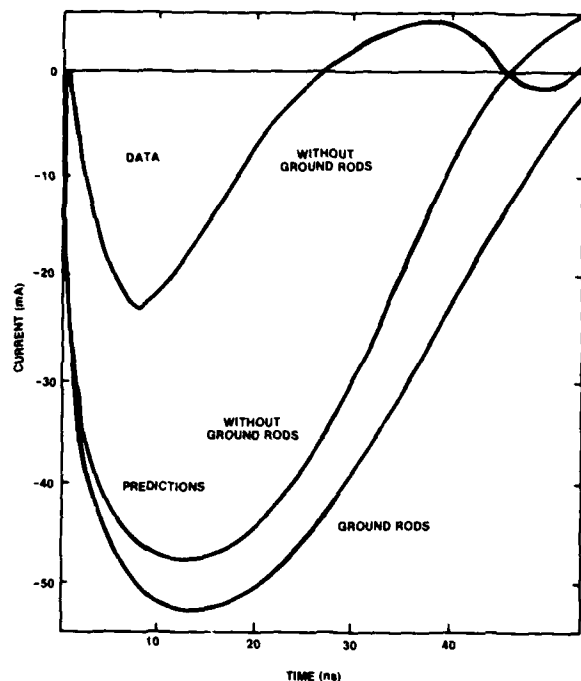


Figure 6. Experiment 1: predictions and data at point B.

TABLE 1. SUMMARY OF COMPARISON OF PREDICTED AND MEASURED PEAK VALUES FOR EXPERIMENT 1

Test point	Peak amplitude (mA)			
	With ground rods		Without ground rods	
	Predicted	Test	Predicted	Test
A	5	8	3	9
B	53	24	48	22
C	84	41	72	38

3.2 Results of Experiment 2

Overlays of typical measured and predicted responses for experiment 2 are shown in figure 7. Table 2 summarizes a comparison of peak values. The predictions of principal responses agree quite well with measurements in peak amplitude, but again the predicted waveshapes are broader than those measured. The model predicts nonprincipal responses to be zero by symmetry. The measured values then indicate how well the experiment is laid out. This appears to have been well done, because of the small values indicated. The data support the following conclusions:

(a) Principal predictions in general agree with measurements to within 33 percent.

(b) For the principal responses, in general, only an insignificant effect caused by the different connections is noted. It therefore does not seem to make a great deal of difference where, if, or how many times the ground systems are connected together.

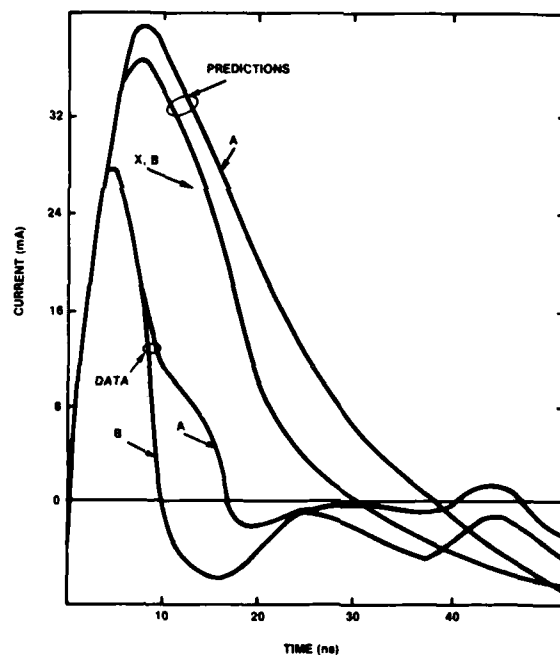


Figure 7. Experiment 2: predictions and data for wire current at point 2 (A--connected to counterpoise at A, B--connected at B, X--not connected to counterpoise).

TABLE 2. PEAK VALUE OF MEASURED AND PREDICTED CURRENT (mA) RESPONSES FOR EXPERIMENT 2

Test point	A open, B open		A closed, B open		A open, B closed		A closed, B closed	
	Experiment	Model	Experiment	Model	Experiment	Model	Experiment	Model
1	15	18	15	18	15	18	15	-
2	28	37	28	39	28	37	28	-
3	27	35	29	45	27	35	29	-
4	14	14	35	51	14	14	36	-
5	1	0	2	2	1	0	2	-
6	2	0	2	11	1	1	2	-
7	1	0	3	10	2	1	7	-
8	1	0	2	1	5	6	19	-
9	29	36	29	37	29	36	29	-
10	30	36	30	37	30	36	30	-
11	13	10	11	9	13	10	11	-
12	3	-	12	-	2	-	12	-
13	7	1	12	24	7	1	12	-

3.3 Results of Experiments 3 and 4

Comparisons of predicted and measured results are shown in figures 8 through 10. Figures 8 and 9 show overlays of I_2 . The peak values agree within a factor of two, and the general waveforms are of similar shape. The principal difference is that the predictions (which were obtained by simply allowing the current to be the ratio of the magnetic flux to the loop inductance), did not include the resonances which do appear in the data. Figure 10 shows the response I_2 without a metal ground plane;* that is, the ends of the wires are simply inserted into the sand. It is noted that the peak response is about the same, but the shape of the waveform is changed by the soil (see app A). The responses of I_1 are predicted to be zero by symmetry.

The data support several conclusions:

(a) Results from experiments 3 and 4 agree within experimental error; hence, there appears to be no significant difference caused by the type of earth ground system used.

(b) Whether or not, how often, or where the signal ground plane is connected to the earth ground system does not appear to make any significant difference in the response of overhead cables in a facility. The cable response appears to be independent of the ground connections, as long as there is a signal ground plane present to complete the loop.

* I_2 is measured at the wire/sand interface.

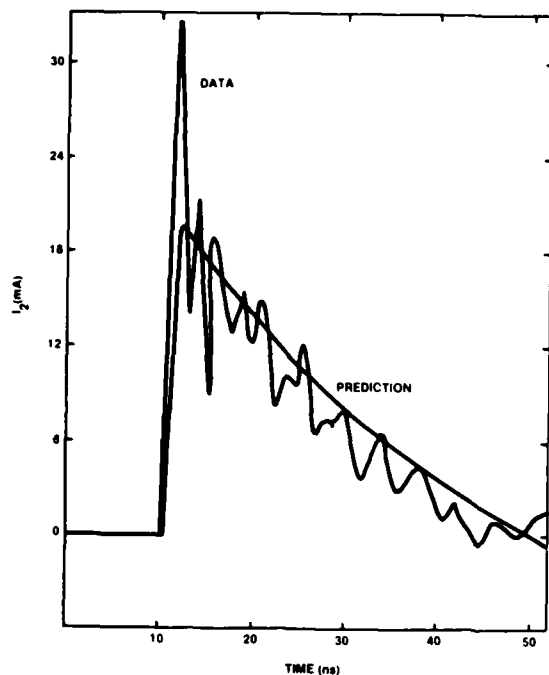


Figure 8. Experiment 3: predictions and data for vertical loop current I_2 at Scale Modeling Facility. Data taken with signal ground connected to bonded grid at B and grid connected to earth ground at A and B.

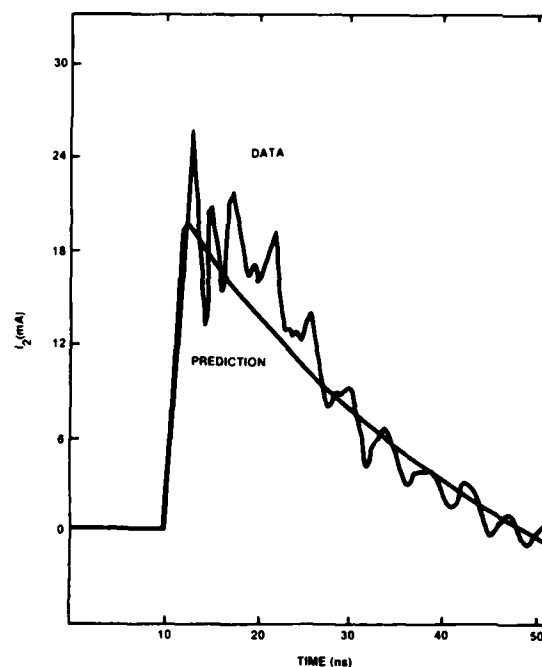


Figure 9. Experiment 4: predictions and data for vertical loop current I_2 with bonded grid connected to earth ground at A.

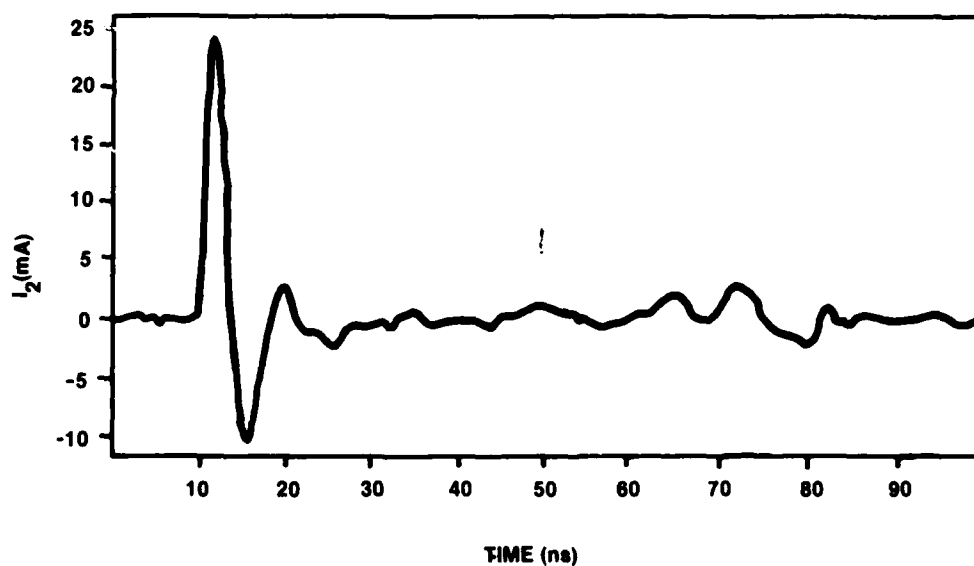


Figure 10. Current I_2 from experiment 3 (without metal ground plane).

4. SUMMARY OF RESULTS

The major conclusions resulting from this study are summarized as follows:

- (a) The type of earth ground system does not appear to be important.
- (b) Location of connections (and whether or not connections are made) of the signal ground plane to the earth ground system does not appear to be important.
- (c) The earth ground system can increase currents on a coarse grid signal ground structure when they are connected together.
- (d) The earth ground system does not increase the response of test loops on a continuous metal ground plane when the plane and earth ground system are connected together.
- (e) Currents on the order of hundreds of amperes are induced on the earth ground system by HEMP (Example: $84 \text{ mA} \times [(50,000 \text{ V/m})/(59 \text{ V/m})] \times 10 = 712 \text{ A}$).
- (f) Adding ground rods made little difference in the response.

A second useful result is the consistently close agreement between the relatively simple theoretical model and the test results. This suggests that the model should prove useful for future studies when extensive testing is not possible.

The basic results of this study show that the choice of the earth ground system and how it connects to the signal ground plane do not affect the free-field EMP response of intrafacility cables. The choice of grounding system can be based on other considerations.

One item, not yet taken into account, needs to be mentioned. Most facilities have long lines which can inject a large current into the facility. The effect of the different ground systems under these conditions has not yet been addressed, and it is a worthwhile subject for future research. However, it is not expected that the choice of the earth ground system will be significant here either, although the way in which the EMP cable currents are "bled off" by spark gaps, etc., is expected to be significant.

APPENDIX A.--CALCULATION OF WIRE RESONANCE

The wire resonance is estimated below.

The total electrical length of the wire is

$$\begin{aligned} [1.5 + 5/12 + 5/12 + 2(6/12 + 6/12)] \text{ ft} &= 4.33 \text{ ft} , \\ &= 1.32 \text{ m} . \end{aligned}$$

Computing the half-wave resonant frequency,

$$\begin{aligned} \ell &= \lambda/2 , \\ \lambda &= 2\ell = 2(1.32) = 2.64 \text{ m} , \\ f &= \frac{3 \times 10^8 \text{ m/s}}{2.64} = 1.14 \times 10^8 , \\ f &= 0.114 \times 10^9 \text{ Hz} , \end{aligned}$$

and

$$f = 0.114 \text{ GHz} .$$

from the data $f = 0.125 \text{ GHz}$.

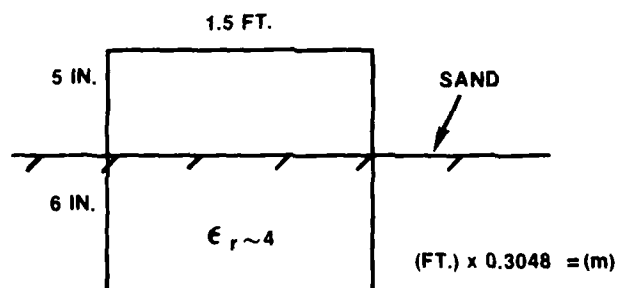


Figure A-1. Calculation of wire resonance (resonance is estimated).

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