A COMPARISON OF TECHNIQUES AND INSTRUMENTATION USED FOR THE MEASUREMENT OF STEP VOLTAGE AND SIMULATED BODY CURRENT

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February 26, 2020

ABSTRACT

This study reviews data from a test conducted in 1987-1988 to resolve questions concerning the making of step potentials and simulated body currents as a means of assessing the safety of a grounding system. The study compares the use of different electrode designs and deployments over a variety of soil types, measuring both step voltages and simulated body currents, and repeating the observations over time for a year and a half.

The installation contact resistance of the testing electrode touching the earth, which is a practical consideration often discounted, turns out to be a major factor in the measurement: it is dominant, and the source of much uncertainty. The design and deployment of testing electrodes exhibit significant shortcomings. The variability in simulated body current measurements gives rise to cautions about their use and interpretation. Step potentials prove to be the easiest and most reliable measurements, although not themselves conclusive. The authors conclude that a good collection of measurements has to include an independent appraisal of both the source voltage and the earth resistivity, the latter including seasonally induced climatic changes.

INTRODUCTION

Step and touch voltage measurements of large and elaborate grounding systems such as power substations are required at times to verify the attainment of the design objectives and to assure safety of operation. The practical aspects of making step potential, touch potential, and simulated body current measurements have received little attention in the past, while researchers have concentrated on issues such as the simulation of line faults, low-voltage current injection testing schemes, the simulation of the human foot, and the use of probabilistic methods to assess risks.

Field testing constitutes an important step for confirming results and obtaining information. The manner in which the data are collected and the type of electrodes used to simulate the human foot can have a significant effect on the data and on the conclusions about safety. Standards ANSI/IEEE Std 80-1986 [1] and IEEE Std 81-1983 [2] provide valuable information in this area. Other literature [3] provides some useful insights into field testing. However, more practical information is often needed by the engineer in designing the test protocol that is at the foundation of the safety assessment. This study investigates the practical questions of what to measure, how and when to make these measurements, and how to interpret the data.

BACKGROUND

This study analyzes the data of a test conducted in 1987-1988 to address these questions [4]. The setting was the extremely low frequency (ELF) transmitting antenna built by U.S. Navy near Clam Lake in Wisconsin [5-8]. The test consisted of using three types of probes to measure step voltages and simulated body currents, once every month for 18 consecutive months, at 12 sites near the ELF antenna ground terminals, where such measurements can be made with relative ease. The grounding electrodes being tested were portions of the ELF antenna ground terminals, which include arrays of long wires buried 1.83 m (6 ft) below ground. The ELF antenna discharges 300 A of 76-Hz current into the ground at each of its ground terminals, and represents a steady signal source for this experiment.

The 12 sites were divided evenly among four soil types: loam, sand, gravel, and bog (standing water). The testing electrodes were of three types: a set of fixed 190-mm-long (7½-in) rods 12.7 mm (½ in) in diameter, installed at the surface of the soil 1 m from each other and left in place undisturbed for the duration of the testing; a set of portable 190-mm-long rods 12.7 mm in diameter, affixed at the end of a 1-m insulating spacer; and a set of portable round metallic disks 80 mm in radius [1,3], similarly affixed at the end of a 1-m insulating spacer. The set of portable rod electrodes and the set of portable disk electrodes were installed temporarily each time the measurements were made, a few feet to the side of, and parallel to, the fixed rod electrodes. A man stood on the temporary electrodes while the measurements were being made to assure good contact with the earth, thus minimizing the contact resistance. The rod electrode was chosen because it appeared to be a good candidate to replace the flat disk that is conventionally used to simulate the human foot. The rod electrode is easier to use in the field and cuts through the surface layer, which is the source of problems when using disk electrodes.

Figure 1 shows the modeling for step potential and body current that is the basis of this study. As usual, shoe resistance and skin resistance (not shown) are assumed to be zero, for a limiting conservative situation, and the body impedance is assumed to be 1,000 Ω. The resistance of the contact points with the earth is divided into two parts: the spreading resistance into the earth under each foot, and the contact resistance at the transition layer between the electrode and the earth. The latter goes to zero under ideal testing conditions, while the testing electrode spreading resistance remains a factor that simulates the spreading resistance under each foot which is assumed to have a surface area equivalent to a disk 80 mm in radius [1,3].

The three electrode types were used to measure both the step voltage and the simulated body current using an high-impedance multimeter, a Fluke 8060A. In the simulated body current measurement, a 1-kΩ resistor was inserted in shunt with the meter to simulate the body resistance. The rod electrodes were chosen to be 190 mm (7½ in) long because this length provides a spreading resistance equivalent to that of a disk 80 mm in radius, as shown in the following calculations [1,9], when the earth conductivity is uniform and the contact resistance is zero. Mutual impedance effects are small when two small electrodes are set one meter from each other, and do not significantly alter this equivalency.

$$R_{disk} = \frac{\rho}{4 \times radius} = \frac{\rho}{4 \times 0.08\, m} = 3.13\rho \qquad (1)$$

$${}_{rod} = \frac{\rho}{2\pi\; length} \left(Ln \frac{4\; length}{radius} - 1 \right) = \frac{\rho}{2\pi\; 0.190 m} \left(Ln \frac{4 \times 0.190 m}{0.00635 m} - 1 \right) = 3.17 \qquad (2)$$

where ρ = resistivity of the earth (Ω·m)

Actual tests using a water pool as the medium have validated this equivalency within a range of 5%.

ANALYSIS

Measurement Comparison

Step voltage and simulated body current measurements were collected at each of the 12 sites, once a month for 18 consecutive months. The time averages of the step voltage and the simulated body current were calculated at each site and for each of the three electrode types: fixed rods, temporary rods, and temporary pads (referred to simply as "fixed," "rod," and "pad," respectively). These averages are listed in Table I and are compared graphically in Figure 2. The sites are grouped according to soil type.

The measurements made with the temporary electrodes (i.e., rod or pad) are consistently lower than those made with the fixed electrodes. Specifically, the rod electrode step voltages are an average of 7% lower than the fixed electrode step voltages, and the pad electrode step voltages are 16% lower than the fixed electrode step voltages. For simulated body current measurements, the levels are 22% lower for rod electrodes than for fixed electrodes, and 67% less for pad electrodes. Simulated body current measurements at the gravel sites were extremely low, often ranging at the lower limit of the meter's sensitivity. There was more consistency among step voltage measurements than there was among simulated body current measurements for different electrodes.

The overall pattern with respect to simulated body current versus soil type fits well with expectations. Simulated body currents are relatively higher in bogs; they become smaller as the soil changes to loam, then sand, and finally gravel. Overall, there appears to be less variability in the step voltage data that there is in the simulated body current data. The type of electrode seems to add significantly to simulated body current variability.

Variability by Soil Type and Probe Design

To focus on variability independent of site, each measurement datum was converted to a percentage deviation from the average at the site, using the following equations:

$$\Delta V_n = \frac{V_n - V_{avg}}{V_{avg}} \times 100 \qquad (3)$$

$$\Delta I_n = \frac{I_n - I_{avg}}{I_{avg}} \times 100 \qquad (4)$$

where V_{avg} and I_{avg} are the time averages for each site

These quantities follow a limiting normal distribution with a mean of zero. The standard deviations were calculated for each set of electrodes at each site. The 95% confidence interval is symmetrical about the zero mean and can be characterized by a single absolute number labeled the "one-tail 95% confidence interval" (Figure 3). This index represents the expected overall 95% range of variability of the data on either the negative or positive side of the mean. The calculated one-tail 95% confidence intervals for these data are listed in Table II and are shown in the bar graph of Figure 4.

The expected one-tail 95% confidence interval (variability) in step voltage measurement over soil types and electrode design and deployment seems to be uniform, and in the range of ±30%. The exception is pad electrodes at gravel sites, which produce a variability of around ±110%. Simulated body current measurements, in contrast, show a much higher variability overall. Simulated body current measurements vary by ±165% on average, independent of soil type and electrode design or installation. A minor exception is the fixed electrodes at bog sites, which show a smaller variability.

Measurements of step voltage or simulated body current at gravel sites by means of temporarily installed electrodes are highly variable, and should be considered with some caution. Loamy soil behaves the same way as sandy soil. Bogs, surprisingly, produce considerable variability with temporary electrodes. This may be due to difficulties in installing temporary electrodes when the soil and/or water freeze during the winter months.

Variability over Time

A time analysis shows that the measurement data vary in a periodic fashion over the year, reaching extremes during winter and summer. Figure 5 shows the variability of the step voltage measured with the fixed electrodes at all sites over 18 months. The step voltage peaks during the winter, around January. Figure 6 shows, in a similar fashion, the variability of the simulated body current measured with the fixed electrodes at all sites over 18 months. The dispersion of the simulated body current data in Figure 6 is much greater than the dispersion of the step voltage data in Figure 5, in agreement with the variability comparison of Figure 4. Some of the overall data variability in Figure 5 can be measured as a seasonal effect. A sinusoid fitted to the step voltage data of Figure 5 yields the following equation:

$$\frac{V}{V_{avg}} = 1 + 0.08 \times \sin\left(\frac{2\pi}{365} \times (Day + 41)\right) \tag{5}$$

Day = Sequential day of the year counted from January 1

The simulated body current measurements of Figure 6 show a seasonal effect also, with a peak in spring-summer and a bottoming out in winter. However, a larger portion of this variability appears to be random. In the extreme case of pad-measured simulated body currents, shown in Figure 7, the randomness of this variability is so great that the seasonal effect is hardly discernible.

Impedance

Figure 1 shows that the simulated body current depends on the source voltage and on the combined spreading/contact resistance of the electrodes that simulate the human feet. These quantities are related to the step voltage by Ohms law. Furthermore, the step voltage varies so much less than the simulated body current that it can be assumed to be constant. It follows, then, that the variability in simulated body current must be inversely related to a similar variability in the spreading/contact resistance. Empirical observations about simulated body current bottoming out in winter confirm this inverse relationship, since the ground is cold and most likely frozen in winter, causing the spreading resistance to peak.

The spreading and contact resistances of the two feet in series, Figure 1, cannot be separated in this type of testing, and are calculated as a unit from step voltage and simulated body current measurements. One kΩ is subtracted from the ratio V/I to adjust for the body resistance that was inserted for the simulated body current measurement. The spreading/contact resistances thus calculated are for both testing electrodes in series; the results are shown in Table III, together with the expected 95% confidence intervals (high and low). The log-transform was used to normalize the data. The spreading/contact resistance of a single testing electrode can be derived by taking the data in Table III, and dividing by two.

The extreme variability in spreading/contact resistance is a reflection of the great variability in simulated body current measurements. Figure 8 compares the time-averaged spreading/contact resistance for the various electrode designs over the 12 sites. The fixed electrodes provide the lowest spreading/contact resistances, and electrodes installed temporarily yield consistently higher spreading/contact resistances. The use of temporary electrodes seems to include an additional quantity that we shall refer to here as the "installation contact resistance." It is as if the contact resistance itself consisted of two parts: (1) a nominal contact resistance under ideal conditions that reflects the discontinuities in the interface layer due to the graininess of the soil, and (2) an additional installation contact resistance due to extraneous factors. There is no other difference in testing that can explain the systematic differences between the rod electrodes installed permanently and the rod electrodes installed temporarily. In the case of the pads there is possibly another factor, discussed below.

An estimate of the installation contact resistance is obtained by subtracting the calculated spreading/contact resistance of the fixed electrodes from the calculated spreading/contact resistance of the temporarily installed rods and pads. These differences are listed in Table III and are shown in Figure 9. The installation contact resistance appears to be of the same order of magnitude as the spreading/contact resistance itself, but often higher. The installation contact resistance is greatest for gravel sites, and least for bog sites (an expected result), and it is greater for pad electrodes than for rod electrodes.

Field observations seem to confirm these results. Any temporary installation produces a contact area between the electrode and the earth that is less than what is achieved by a similar electrode installed permanently. Pushing a rod into the ground, especially hard ground, often produces a tapered hole; this causes the rod to be in true contact with the earth only at its tip. There are similar problems with the installation of temporary pads in winter, on frozen and hard ground, and during mid-summer, when the ground is typically dry and covered by dead or dry vegetation.

Soil Resistivity Stratification

The difference in the calculated spreading/contact resistance between pads and fixed electrodes includes another subtle factor besides the installation contact resistance. The stratification of the earth resistivity due to soil moisture content variations with depth and over time. The pad and rod electrodes (installed permanently or temporarily) respond differently to this factor because of the difference in their physical shape.

The spreading/contact resistance of the pad depends heavily on the very top layer of the earth, the top 25 to 50 mm (1 to 2 in). In this experiment, this layer would contain organic matter, including small living organisms. This layer also experiences a drastic variation in soil moisture, going from water saturation during rainfalls to extreme dryness during droughts. The spreading/contact resistance of the rod electrode, on the other hand, is highly dependent on the soil resistivity near its tip, 190 mm (7½ in) below the surface, and is minimally affected by the surface type and conditions.

The spatial and time variations of moisture content in the first 0.3 m (1 ft) of the soil are obviously important for this type of testing, but the field testing did not address these variables. The table on soil resistivity variations due to soil moisture variations in Reference 9 indicates that the soil resistivity would increase typically by 440% for top soil and 290% for sandy soil, for a drop in moisture content from 20% to 10%. The effects on spreading/contact resistance in our case would be moderated by the fact that only a gradual change in moisture content with respect to depth takes place in the zone of influence of the spreading resistance. On the other hand, the first six lines of Table III, which deal with similar type soils, loam and sand, indicate that the calculated spreading/contact resistance of pads is 800% higher than the calculated spreading/contact resistance of fixed rod electrodes. This suggests that the stratification factor in soil resistivity is a moderate factor. The bulk of the difference measured between pads and fixed electrodes can still be attributed to the installation contact resistance.

DISCUSSION

Permanently installed electrodes are obviously the best choice for providing the most reliable data. However, they require much more care and cost more to install and operate, especially because of the time and precautions needed for proper aging of the electrode in the ground, which is the most assured way of eliminating or minimizing the installation contact resistance. They are most suitable when time measurements are required and few locations are involved in the study. Temporary electrodes are easier to use, and are cost-effective when many measurements have to be made over a vast grounding grid or when many ground locations are involved.

The rod electrode is more effective than the disk in measuring simulated body current because it produces data with less variability. We should note, however, that the rod electrode will produce relatively higher measurements than the pad when the ground electrode system being tested is buried at shallow depths, as it is often the case with power line ground rods. The rod electrode reaches out to higher-potential points close to the grounding electrode, while the pad electrode, which remains on the surface, does not; however, the pad electrode more closely simulates a human foot resting on the ground. Thus the rod electrode provides less variable data, but is likely to distort the picture if it comes too close to the grounding electrode under test or if there is a substantial stratification effect in soil resistivity, as mentioned above. The rod electrode also has other disadvantages: it cannot be used on hard surfaces such as bituminous pavements, concrete surfaces, or frozen ground. On any type of hard surface, it has to be installed in a permanent fashion.

The installation contact resistance is a problem to watch out for, because it is as large as the spreading/contact resistance of the testing electrode and is much more variable. It may bias the measurements and lead to a less conservative conclusion. The installation contact resistance reaches extreme highs in magnitude and variability with pads used on gravel. It contributes significantly to the variability of simulated body currents. This is supported by other researchers who have used steel-wool or conductive rubber pads to minimize the installation contact resistance [3].

Not even step voltage measurements are immune to this problem. Installation contact resistance in the megohm range affects the measurement of many high-impedance voltmeters and explains the previous observations of consistently lower step voltage readings with temporarily installed electrodes.

Time analysis indicates that there is a seasonal effect that could be taken into account. The yearly cycling of the step voltage is clearly discernible in voltage measurements. However, in dealing with simulated body current measurements, the seasonal effect is swamped by other variabilities and becomes less relevant. A clear conclusion for simulated body current measurements is that simulated body currents drop off drastically in the winter at northern latitudes, and that they depend almost exclusively on rainfall and soil moisture during the rest of the year.

The last question is what to measure. Clearly, the one-time, random measurement of simulated body current provides a very uncertain result. Repeated measurements over time provide a better picture in providing both a time profile and a sizable statistical sample to support more reliable conclusions. Worst-case simulated body current measurements provide another approach, reliable if precautions are taken to ensure worst-case conditions. Worst-case measurements should be made in the summer right after a rainstorm, when both soil temperature and moisture are the highest, yielding the highest level of soil conductivity. Rather than having to wait for a rainstorm, flooding the area on a summer day to simulate the effects of a rainstorm may constitute an acceptable alternative. The next best alternative would be to make the measurements right after a substantial rainfall during the wet season, when storm activity may be more frequent and more predictable. Soil conductivity variations between summer and spring and between summer and fall are more extreme and more significant in response to moisture variations than in response to temperature changes. In either case, the wait involves delays and costs that in some cases are not affordable or justifiable. Furthermore, this approach may yield unacceptably conservative results. The consideration of such extreme circumstances is commensurate with risk analyses and other probabilistic methodologies [10, 11].

Pad electrodes should be utilized in these simulated body current testings, and should be installed carefully to minimize the installation contact resistance. Wet soil, sought for a worst-case simulated body current measurement scenario, also helps to eliminate or minimize the installation contact resistance. Rod electrodes with a similar spreading resistance can be used instead, as long as the soil can be penetrated and has a reasonably uniform resistivity, and the testing electrode length is small compared to the burial depth of the grounding electrode being tested (i.e., 20% or less).

Step voltage measurements provide a good starting point because they are the least affected by soil type and electrode design, and they can be made at any time with the most reliability. Such measurements are clearly to be preferred if the safety criterion is based solely on voltage thresholds. Worst-case simulated body currents can be estimated from step voltage measurements and independently derived soil information such as earth resistivity, moisture, and temperature measurements. Climatological information for the area of interest (such as that available from the National Oceanic and Atmospheric Administration, the National Weather Service, and other sources) can help in assessing the worst case for soil conductivity. There is an uncertainty to simulated body current estimates using this approach, but there is also uncertainty in measuring simulated body currents and establishing worst-case conditions, while testing costs escalate considerably. **CONCLUSIONS**

This study finds that testing electrode designs have shortcomings that the investigator should be aware of when analyzing the data. The flat disk electrode seems a good and simple model for the human foot, but it has serious limitations in current measurements because of the combination of spreading and installation contact resistance. The rod electrode is a "niche application." Other types of electrode designs should therefore be experimented with: 50- to 100-mm (2- to 4-in) rigid disks, pads with 25- to 50-mm (1- to 2-in) fangs, self-conforming pads, and other types of conductive footwear.

The "installation contact resistance" is a major problem. It is a circumstantial factor difficult to eliminate systematically. It is also intimately associated with the spreading/contact resistance, and one cannot differentiate between them. It is ordinarily taken to be part of the phenomenon being measured, when it is mostly an artifact of the measurement process. Efforts to factor out this quantity should include an independent assessment of earth conductivity by some other method.

Simulated body current measurements have many caveats, but are still desirable. They have particular significance within a worst-case scenario when testing in these conditions is practical and affordable. Step voltage measurements are relatively easy to make by comparison. Step voltage measurements can be done with high confidence with any type of testing electrode and on almost any soil type (with some reservations on gravel). However, the step voltage information has to be combined with separate earth conductivity measurement data and other information on seasonal ground resistivity variations to arrive at a final assessment [1].

In the end, the engineer has to be aware that the safety of a grounding electrode system depends not only on the observable step voltages, but also on the soil type and the soil conditions, which vary considerably over the year, and that the type of data collected and equipment used can affect the results.

ACKNOWLEDGMENTS

The authors express their appreciation to the Department of the Navy, which provided the opportunity to obtain the data presented in this analysis, and to Messrs. J. R. Gauger, R. G. Drexler, and W. Lancaster, who were responsible for setting up the test and collecting the data.

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Table I. Time averaged measurements.

Site No.	Soil Type	I pad	I rod	I fixed	V pad	V rod	V fixed
		(Ma)	(mA)	(mA)	(V)	(V)	(V)
12	Loam	0.25	0.46	0.43	5.48	5.52	5.88
1	Loam	0.25	0.78	0.87	4.10	4.17	4.41
7	Loam	0.11	0.41	0.42	3.45	3.69	4.02
8	Sand	0.10	0.19	0.21	6.11	6.26	6.48
9	Sand	0.15	0.32	0.38	4.00	3.98	4.24
5	Sand	0.07	0.82	1.18	3.55	3.57	3.85
2	Gravel	0.001	0.01	0.02	2.72	4.93	5.73
11	Gravel	0.02	0.28	0.38	1.71	2.30	2.36
4	Gravel	0.001	0.08	0.19	1.02	1.85	2.02
6	Bog	1.15	1.49	2.13	3.37	3.34	3.64
10	Bog	0.86	1.23	1.50	2.22	1.96	2.29
3	Bog	0.17	0.22	0.26	0.51	0.50	0.53

I = simulated body current, V = step voltage

Table II. The one-tail 95% confidence interval of the measurement deviation from the site time-average.

Site No.	Soil Type	I pad	I rod	I fixed	V pad	V rod	V fixed
		(%)	(%)	(%)	(%)	(%)	(%)
1	Loam	254	109	93	24	35	12
7	Loam	259	97	68	47	20	19
12	Loam	168	101	90	33	29	19
5	Sand	224	109	93	16	23	18
8	Sand	176	100	85	14	13	17
9	Sand	210	111	86	13	15	15
2	Gravel	425	219	172	122	40	12
4	Gravel	369	193	123	126	25	22
11	Gravel	723	245	205	89	18	8
3	Bog	154	88	49	25	35	24
6	Bog	146	108	11	14	26	19
10	Bog	155	92	28	22	58	11

I = simulated body current, V = step voltage

Table III. Average spreading resistance by site, the related 95% confidence interval (low, high), and the installation contact resistance.

Site No.	Soil Type	Rf-low	Rf	Rf-high	Rr-low	Rr	Rr-high	Rp-low	Rp	Rp-high	Rr-Rf	Rp-Rf
											Contact Resistance	
		kΩ	kΩ	kΩ	kΩ	kΩ	kΩ	kΩ	kΩ	kΩ	kΩ	kΩ
12	Loam	3.61	14.5	58.4	0.66	20.8	655	1.23	66.8	3634	6.29	52.3
7	Loam	3.29	9.05	24.9	0.25	17.6	1223	0.63	90.1	12841	8.52	81.0
1	Loam	0.68	5.07	38.0	0.15	7.64	392	0.73	64.5	5703	2.57	59.4
8	Sand	11.7	32.9	92.3	3.09	51.3	850	2.66	158	9449	18.4	125
9	Sand	3.84	11.2	32.8	0.59	18.4	577	2.01	68.9	2360	7.21	57.7
5	Sand	0.36	2.60	18.8	0.09	7.70	691	3.24	149	6892	5.10	146
2	Gravel	37.1	407	4482	66.7	1061	16889	157	4175	110704	653	3767
4	Gravel	0.86	15.7	287	0.94	73.9	5811	261	2585	25530	58.2	2570
11	Gravel	0.19	17.6	1680	0.23	40.4	7089	33.2	972	28521	22.7	955
3	Bog	0.27	0.98	3.56	0.01	2.75	614	0.01	9.99	10328	1.78	9.01
6	Bog	0.40	0.69	1.19	0.01	3.29	1274	0.01	9.69	6644	2.60	9.00
10	Bog	0.23	0.51	1.15	0.00	2.70	2914	0.01	7.85	12075	2.18	7.34

f = fixed electrode, r = rod electrode, p = pad electrode

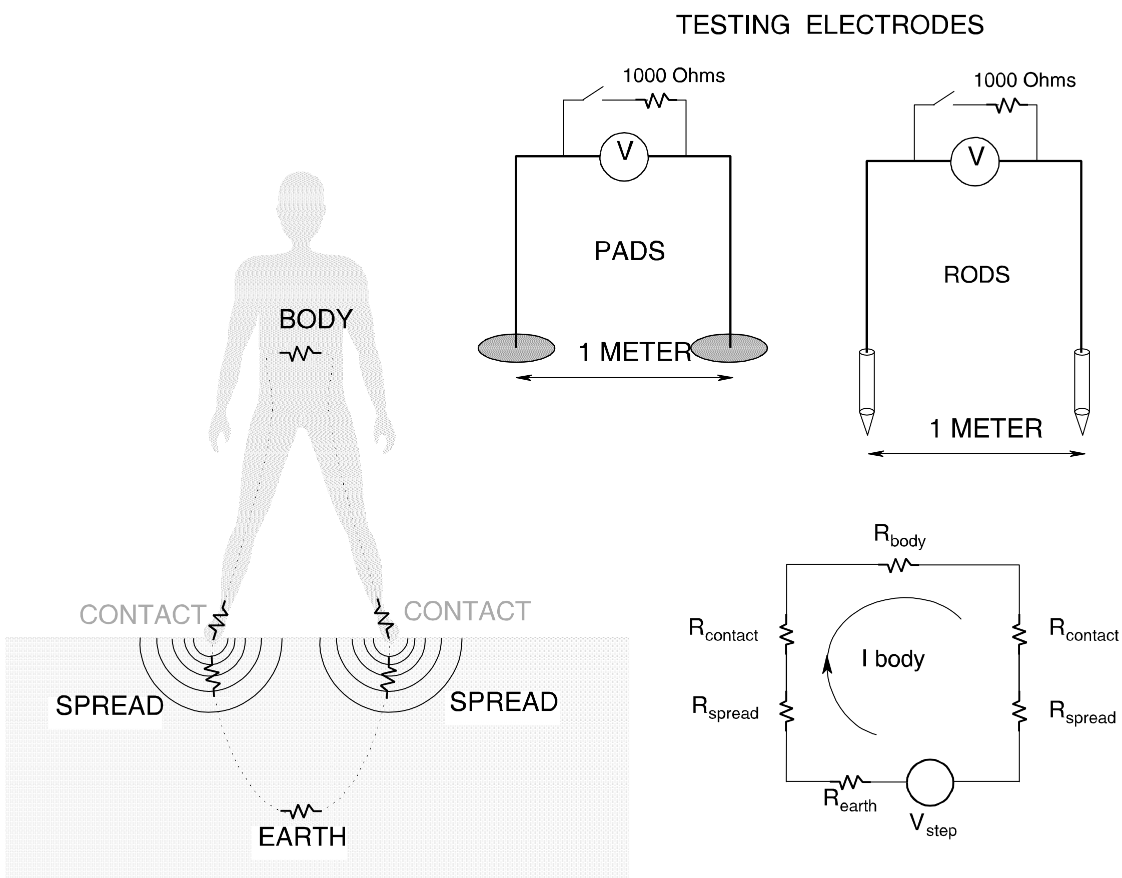

Figure 1. Model for step voltage and simulated body current measurements.

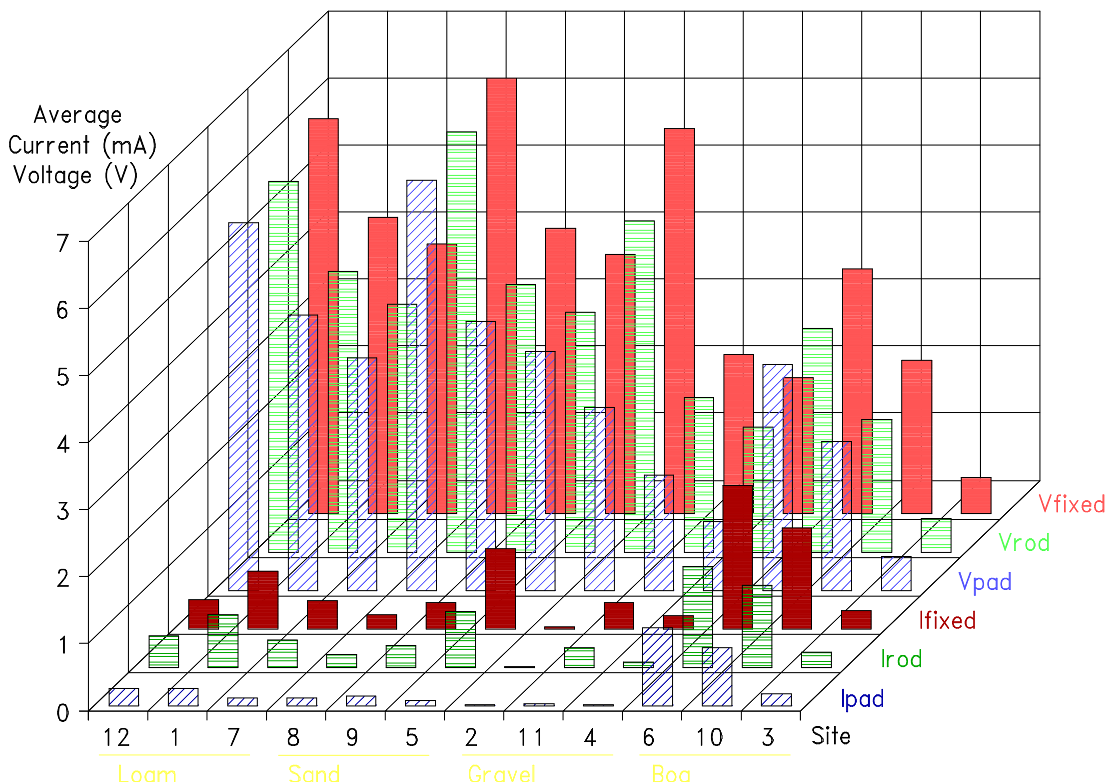

Figure 2. Comparison of time-averaged measurements.

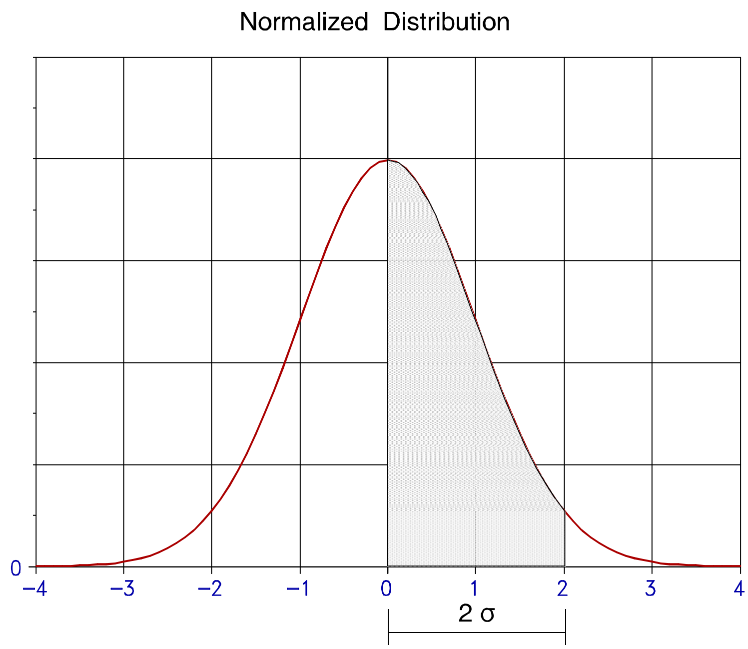

Figure 3. Upper tail (shaded) of the 95% confidence interval.

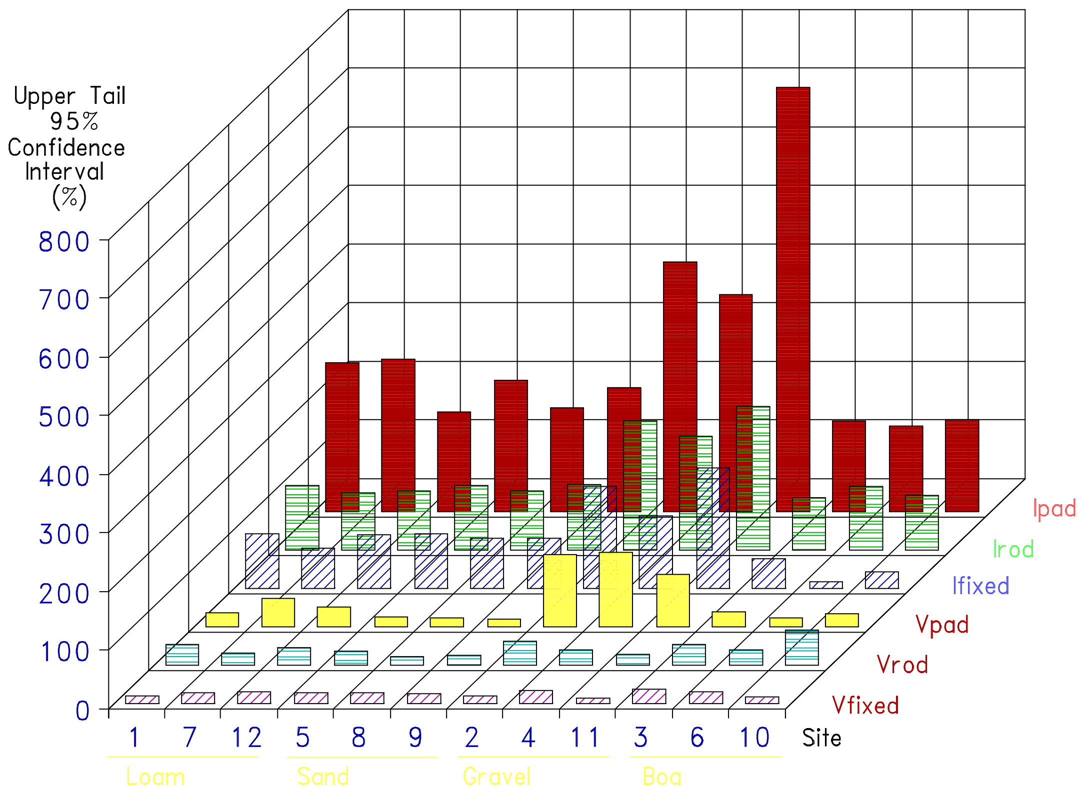

Figure 4. Comparison of data variability.

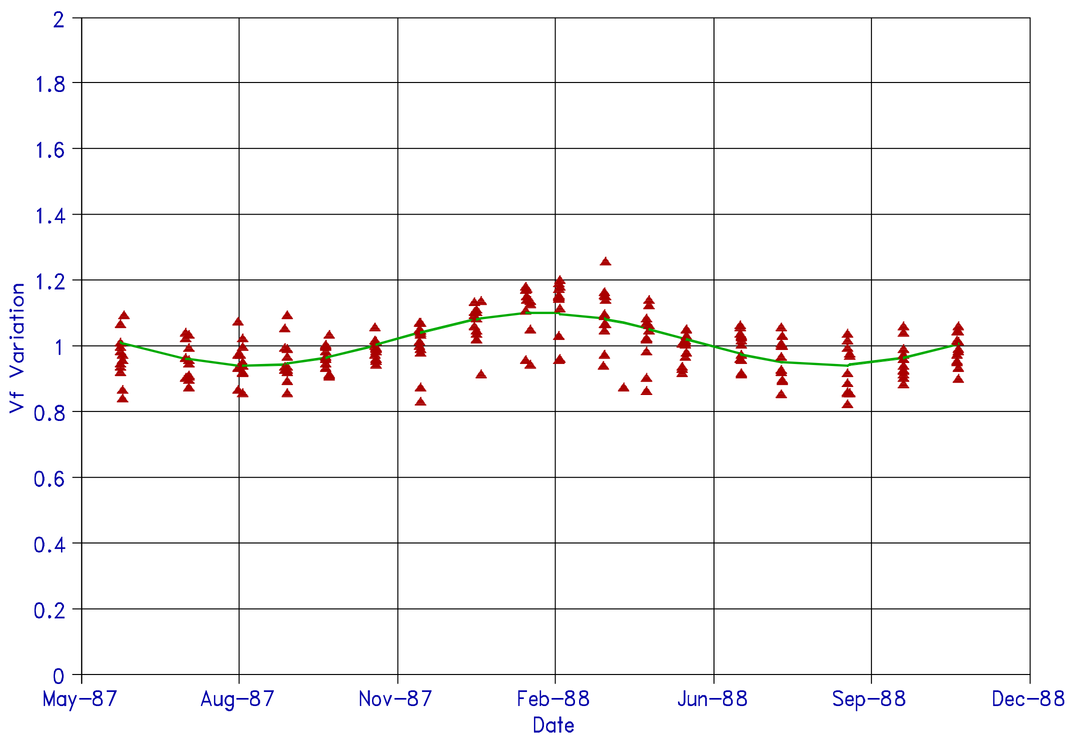

Figure 5. Fixed-electrode voltage data variation for all 12 sites and over 18 months, with the fitted sinusoid.

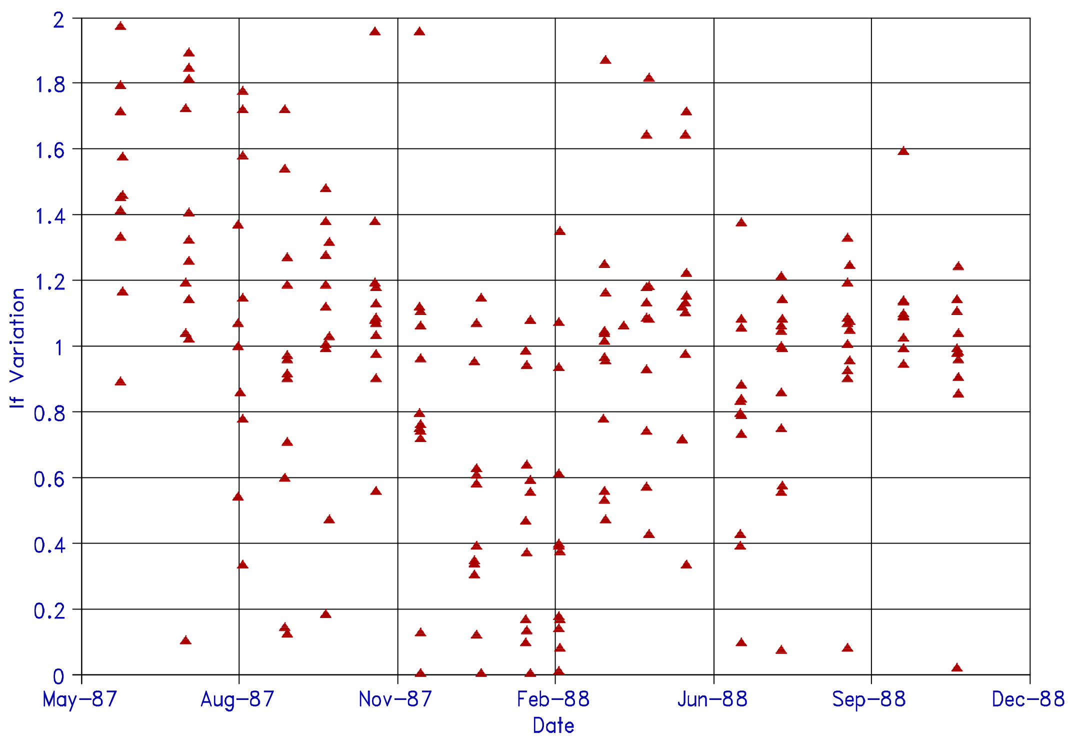

Figure 6. Fixed-electrode current data variation for all 12 sites and over 18 months.

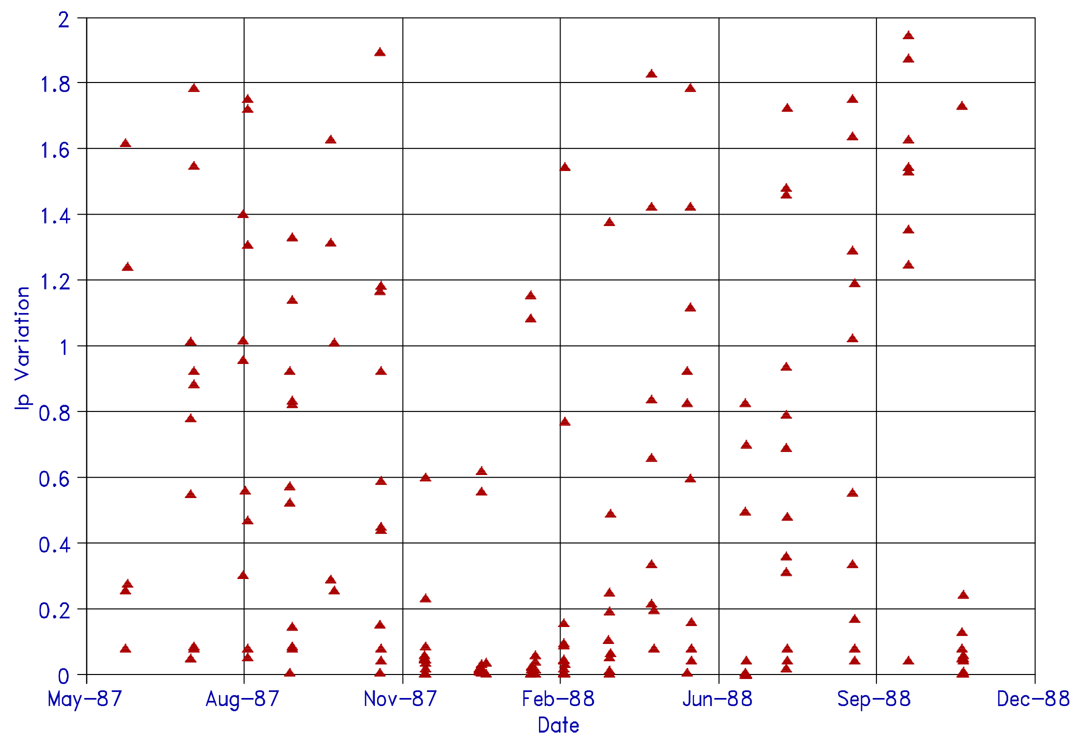

Figure 7. Pad-electrode data variation for all 12 sites and over 18 months.

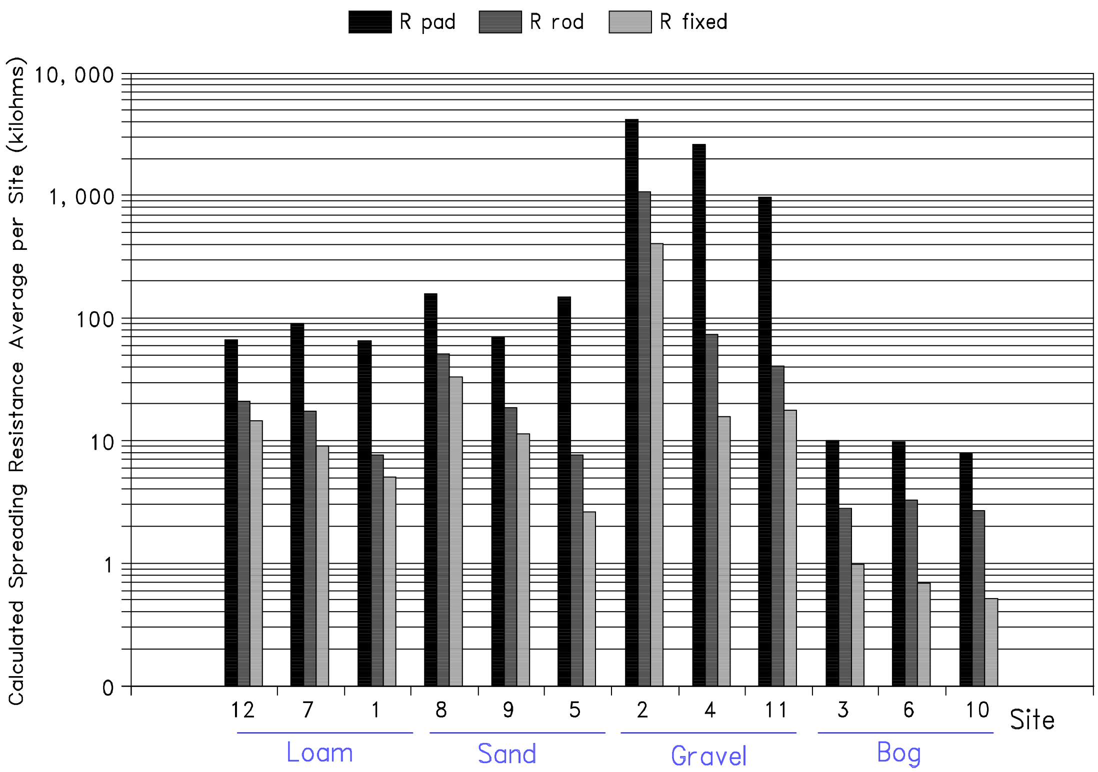

Figure 8. Comparison of spreading resistance for various probe designs and deployments.

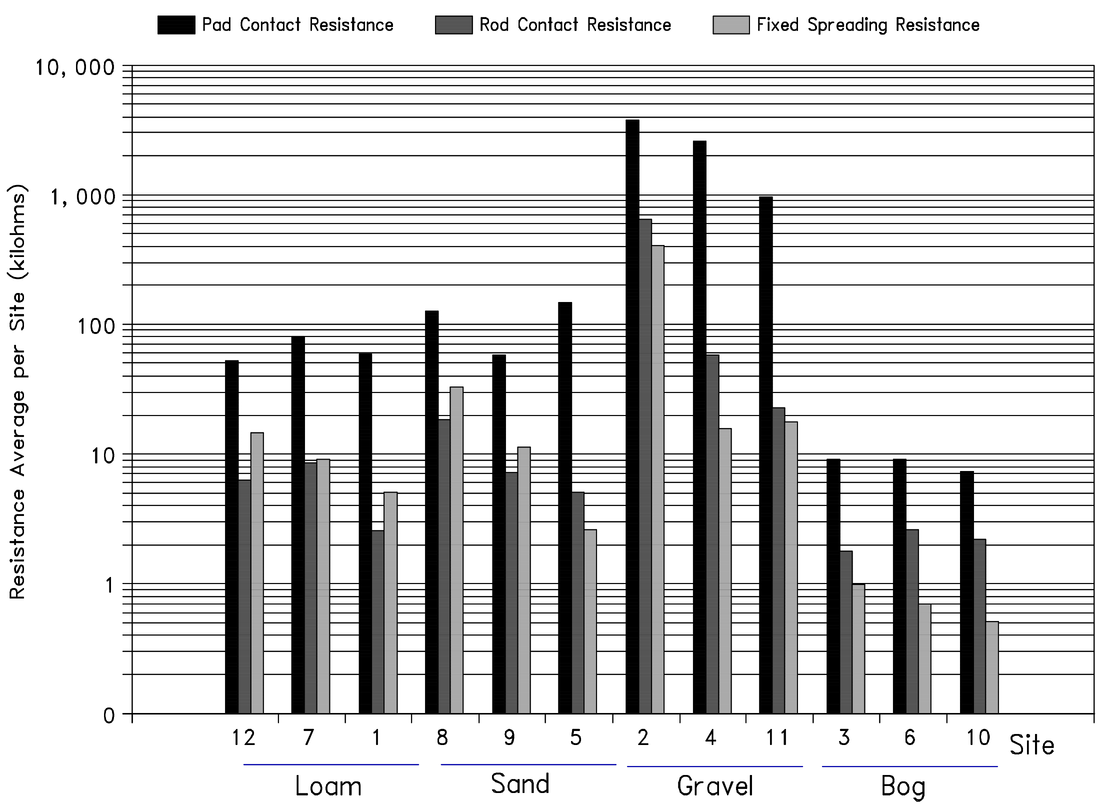

Figure 90. Comparison of installation contact resistance to fixed-electrode spreading resistance.