The Use of Concrete-Enclosed Reinforcing Rods as Grounding Electrodes

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Abstract—The findings of Ufer that concrete-encased metal objects were effective in providing improved grounding under adverse soil conditions suggests that the reinforcing framework of footings for the columns of structural steel buildings would provide effective grounding function and means. Ensuing tests in high, medium, and low resistivity soils indicate that the grounding capability of such reinforced footings (per unit) is equivalent to that of conventional electrodes under low and medium soil resistivity conditions and superior to them under high soil resistivity conditions. In addition, the much larger number of column footings required for structural reasons does, when used, provide much more effective grounding under all soil conditions than previously used systems. The steel framework of such buildings, if electrically connected at each column base to an inherent grounding electrode, then functions as a very efficient grounding network for system, lightning, and static grounding. Fault grounding should always employ a return conductor following the routing of the faulted conductor. The use of new types of grounding electrodes is becoming obligatory due to the widening unsuitability of water pipe systems for grounding purposes. This unsuitability is due to the use of nonconducting joints in the water piping and to the use of nonconducting piping for the water system.

Introduction

THE FINDINGS of Ufer [1] that metal encased in concrete performs as an effective grounding electrode, constitutes a major breakthrough in grounding technology. This has been recognized to the extent that copper wire embedded in the concrete footings of a structure is now an acceptable alternate to driven rods or pipe electrodes in the soil [2]. This comes as a welcome relief from the condition of ineffective grounding by the use of water pipes due to insulated material or couplings and the antagonism of the proprietors of the water pipes [3]. Wiener [4] has demonstrated that concrete-encased metal rods have very substantial ground current capability, and that the corrosion rate of such rods is lower than that of rods directly in the earth.

There is an untapped reservoir of grounding electrodes now installed or being installed in the concrete footings of structural steel and concrete buildings. This is the reinforcing steel network within each of those footings, made up principally of vertical rods in the pedestals and horizontal rods in the spread footings at their bases. Cross members are utilized for separation and stabilization.

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Aside from large buildings, steel reinforcing rods are installed in the concrete wall footings of smaller structures in many parts of the country. All of these might be considered candidates as grounding electrodes, individually or in groups, for each structure. These rods are known in the trade as reinforcing bars, shortened colloquially to "rebar."

A study of the effectiveness of rebar structures as grounding electrodes was undertaken encompassing industrial locations in the Eastern, Central, and Southern portions of the country, including some locations where the soil resistivity was known to be quite high and conventional grounding methods burdensome.

The principal obstacle to the use of rebar as a grounding electrode is that it is rarely accessible for an electrical connection. Functionally, it is required to be in the higher stress zones of concrete, which are generally near the outer surface. In vertical members such as pedestals, the proximity to the outer surface normally keeps vertical rebars away from contact with the anchor bolts of the steel columns they support, as the latter are conventionally located close to the center of the pedestal as in Fig. 1. The only logical means for connection to the rebar is, therefore, not available for functional reasons. In some instances in this investigation, an anchor bolt was electrically connected to one of the vertical rebars by a short length of bar welded to both. In other cases, a separate copper wire was brazed to the rebar and extended to the outside of the footing pedestal for measurement purposes.

Reinforcing of cast-concrete footings consists of two parts:

1) a mat of horizontal rebar near the bottom of the spread footing;

2) a cage of vertical bars extending from the spread footing upward through the pedestal and positioned by horizontal spacer bar loops at regular intervals. (This cage is normally in the outer portion of the pedestal, serving the same function as the flanges of H beams. These are illustrated in Fig. 1.)

A horizontal "grade" beam, on which to build a masonry wall, is frequently installed between adjacent footings. The horizontal rebars near the bottom of grade beams are fastened to the vertical rebars of the pedestals.

All the rebar elements are held together before concrete pouring only by twisted-steel tie wires. As such, these fastenings would not be considered electrically adequate, and grounding-element design might be based only on the bar to which the electrical grounding connection is made.

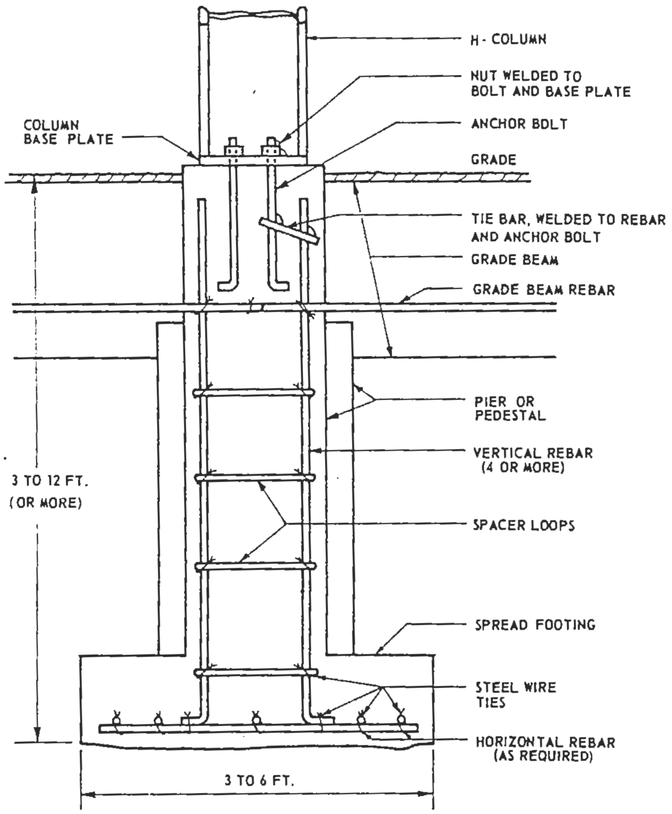


Fig. 1. Typical spread footing for steel column.

At the same time, it has been found that these wire ties are surprisingly effective electrical connections. The grade beams were found highly effective in joining footings, to the extent that at one site where grade beams were installed, fractional ohm values were obtained at each footing so interconnected. One might think that the ties would fail under fault conditions. However, it should be remembered that there are a large number of these junctions (no. 8 or larger steel wire) effectively in parallel, cinched tightly together to support heavy rebar structures before and during the pouring of the concrete. They are also embedded in the concrete so corrosion is not a factor.

The tables and graphs of Appendix III are based on all four vertical rebars in a footing pedestal being effective primary electrodes, even though only one is directly welded to the electrical system.

Effectively, the surrounding of a metallic bar with concrete in the earth constitutes immersion of the bar in a reasonably uniform medium of about 3000 Ω·cm. This medium then is immersed in the earth, the resistivity of which varies widely from a minimum of about 500 Ω·cm to over 500 000 Ω·cm. The comparison of the surface area of the rod and the outer surface area of the concrete, in conjunction with the resistivities of the materials, then controls the net ground circuit resistance (see Appendix I).

Earth resistivity, exclusive of metallic mineral content, is primarily a function of the electrolytic content of the soil. This, in turn, depends on the content of the of enough water to keep these in solution. The granular nature of the soil affects the "holding power" for water, and the nature of the electrolytic path. Temperature affects the resistivity of the electrolyte, decreasing it as the temperature rises [5], [6]. (Frozen, it has very high resistivity.)

Water alone, without soluble electrolytic material in the soil, does not enhance ground conductivity. For instance, in central Florida, where the annual rainfall is very high, soil resistivity is unusually high, even when the soil is saturated. The quantity of rainfall plus high porosity tends to leach out the natural electrolytic material in the soil, leaving it a poor conductor. The same condition accounts for much of the poor conductivity of sandy, gravelly soils in the mountainous areas where rainfall rates tend to be high.

The effectiveness of concrete as a uniform resistivity "ground" is due to its inherent alkaline composition and hygroscopic nature. This combination encompasses the two requirements of conductivity for electrolytes, moisture and ionic mobility. The dense nature inhibits leaching. Concrete in the earth tends to draw moisture from the soil and keep its own water content high, a condition which accounts for its consistent, low resistivity, even under the desert conditions described by Ufer [1].

The advantage of having a ready-made grounding electrode at each column footing is that these footings are spaced about 20 feet apart throughout the building area. The use of multiple electrodes is widely resorted to where single electrodes are not adequate, generally at increased cost. But with column footings, multiple electrodes are automatically available, and at little or no cost. In areas of good soil conductivity, where a single grounding electrode is adequate, only one need be used. Where more electrodes are required, they are readily available.

The principal cost of making electrical connection to the rebar is that of connecting an anchor bolt to the rebar, usually by welding a short piece of rebar between the two. Even without this connection, a typical footing resistance utilizing contact only with the anchor bolts is about 50 ohms, which in itself yields a very tolerably low ground resistance when say 20 columns are involved.

It is possible that this low inherent resistance to ground at each column footing is responsible for the present lack of damage to these footings when a building is struck by lightning. Lightning is a steep-fronted impulse current wave; such waves divide at each junction of structural steel and proceed along all available paths. Some columns may be equipped with external grounding electrodes (rods) for lightning protection; the balance of the columns in each building are not. When a surge reaches the bottom end of an "unequipped" column, a completely insulating or open circuit would cause a doubling of the surge voltage, and bursting damage would be likely. Where the bottom end is a concrete footing, with anchor bolts only connected to the column, the typical resistance of 50 ohms per column is evidently tolerably low, and the surge is

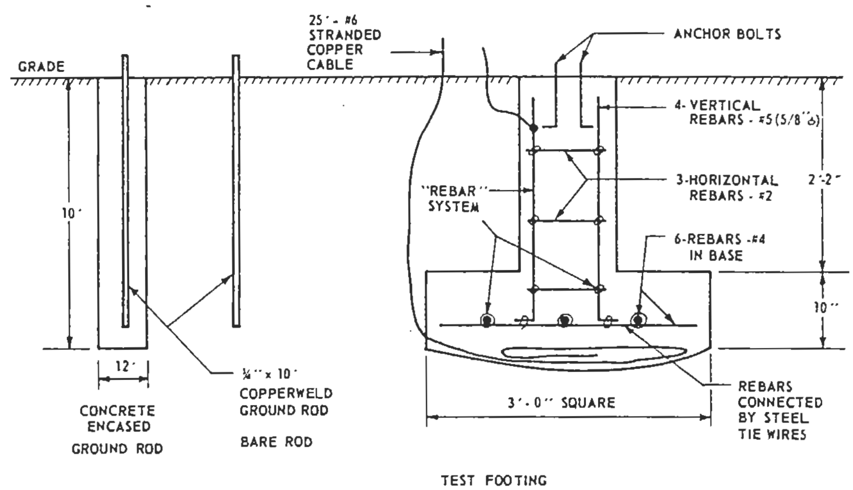


Fig. 2. Chestnut Run test installation.

inherent surge impedance of the steel column is such that the average "anchor bolt" grounding resistance is compatible.

A similar situation occurs at the base of most metal towers of high voltage transmission lines. The tower footing is frequently a drilled hole in the earth, into which a metal footing base member is inserted then poured full of concrete. In most cases, the four corner footings of each tower provide an adequately low ground resistance such that no additional grounding means are required. There are no records of these tower footing concrete envelopes failing from lightning discharges. Appendix II indicates why these footings perform adequately under lightning surge conditions.

Test Program

The test program initiated through this study involved actual field measurements at six locations in the United States and impulse testing of electrodes at a seventh location. The measurements at two of the locations were on electrodes specifically constructed for test purposes. Measurements at the other five locations were on structures which are actual building column footings.

Site No. 1: Chestnut Run, New Castle County, Del. (Approximately One Mile West of Wilmington)

Three test electrodes were installed at this site specifically for this study. They were the following:

1) a driven bare copperweld steel ground rod (3/4-inch OD by 10 feet long);

2) a copperweld steel ground rod (3/4-inch OD by 10 feet long) in a poured-concrete cylinder of 12-inch OD;

3) a typical building column footing, as shown in Fig. 2.

Actual column footings at other locations are similar except depth varies from 3 to 12 feet and base varies from 3 to 6 ft^2. At the Houston location, one anchor bolt is welded to one vertical rebar.

The soil resistivity at the Chestnut Run location was measured at 5000 $\Omega \cdot$cm at 40°F in March, 1969, after a dry winter. The bare ground rod was driven in mid-April, 1968. The encased rod was installed in mid-October, 1968. Fig. 3 shows ground resistance recorded on both ground rods. The test instrument was a megger null balance earth tester.

The weather from May to July of 1968 was fairly wet in the Wilmington area. It was extremely dry from about July 15 through September 30. During December, 1968, and January, 1969, it was fairly cold for the area—the temperature remained below freezing for 2 and 3 week stretches. The only significant snowfall of the winter was in early March of 1969.

The reduction of resistance of the driven ground rod during October and November seems to conflict with other data at the same site. The rod is located close to a lunch facility for construction workers. It is possible that the soil was subjected to "chemical treatment."

Since December of 1968, both rods have exhibited approximately the same value of ground resistance. This is to be expected where the resistivity of the soil is approximately the same as that of the concrete (3000 $\Omega \cdot$cm versus 5000 $\Omega \cdot$cm). Fig. 4 shows the resistance values recorded on various portions of the test footing shown in Fig. 2. The two anchor bolts were measured individually and as a pair. They were not connected to the reinforcing bars. Values for the footing correspond closely with the theoretical data of Appendix III. The wire coil was simply a length of no. 6 stranded copper (25 feet long) laid in the hole just before the beginning of the concrete pour. The resistance values for the anchor bolts are seen to be very much affected by surface soil conditions (high resistance when the top portion of the soil is either extremely dry or frozen). The resistance values for the rebar and the wire coil both follow the general curve for the ground rods, although since they do not extend as deeply into the earth, these actual resistance values are slightly higher.

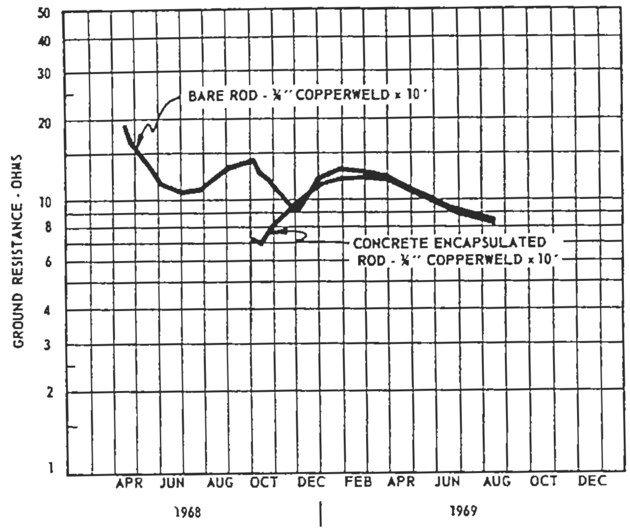


Fig. 3. Ground resistance, Chestnut Run rods.

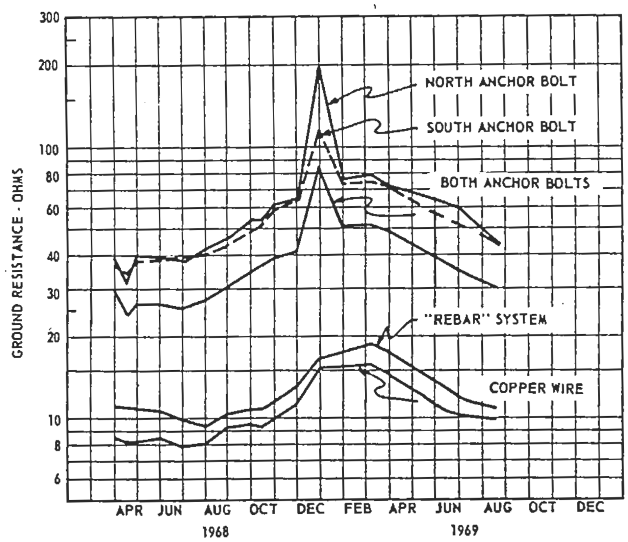


Fig. 4. Ground resistance, Chestnut Run test footing.

Site No. 2: Glasgow, Del. (Approximately 15 Miles Southwest of Wilmington)

The measurements at this site were on actual column footings used in a fairly large industrial building. The footings were similar to those shown in Fig. 2. The rebars were interconnected with standard wire ties. A no. 6 copper wire welded to the rebar was brought out for testing. The anchor bolts were not tied to the rebars.

The footings were isolated from one another. The tests were made before grade beams and structural steel (which would eventually tie the rebars together) were installed. Table I shows the test results. It is probable that the anchor bolts of column $J12$ were actually touching the rebar system. A test pigtail was not run out from the rebar of this footing so it was not possible to measure the resistance of the rebar structure. The test at Glasgow was made in the late fall of 1968 when the weather was generally dry and cool. Footings $J2$ and $J3$ were measured on November 14, 1968, 2 days after a 1-inch rainfall. The other footings were measured on December 5, 1968, 1 day after a rainfall of 0.4 inch.

TABLE I

TEST RESULTS: GLASGOW, DEL.

Footing	Resistance (ohms) Rebar	West Anchor Bolt	East Anchor Bolt
$J2$	10.4	39.5	45.5
$J3$	11.1	42.8	39.5
$J10.8$	5.6	34.0	23.0
$J12$	—	19.4	19.1
$G13$	8.7	33.2*	53.4†

* South anchor bolt.
† North anchor bolt.
Resistance of building ground system is 3.0 ohms.

Site No. 3: Houston, Tex.

The soil resistivity of the Houston site is extremely low. It is located just off Galveston Bay (200 yards from the Houston ship channel) and was recently a salty swamp. Two tests of soil resistivity were made with the following results:

1) 650 Ω·cm with test rods at a 10-foot spacing;
2) 620 Ω·cm with test rods at a 20-foot spacing.

With soil resistivity as low as this, it would be expected that a bare driven rod would have lower ground resistance than an encased one. This was demonstrated as shown below:

1) bare driven ground rod 8 feet long, 3.42 ohms;
2) encased ground rod 10 feet long, 8.36 ohms.

The rods were located near column $D1$ (Fig. 5). The measurements at this site were made on the exterior column footings of an industrial building measuring 80 by 122 feet. The construction of the footings was similar to that shown in Fig. 1. The average depth was 10 feet. One anchor bolt was welded to a rebar. The others were not purposely tied to the rebars although in two instances they were obviously touching.

The tests were made on November 25, 1968, with a megger null balance earth tester. Fig. 5 shows the building plan and Table II shows the test results. The rebar structures of all footings, with the exception of $A2$, $A3$, and $A4$, were tied together with the rebar system in the grade beams. The grade beam along column line A had not yet been installed. As noted previously, the resistance of footings $A2$, $A3$, and $A4$ are appreciably higher since they are the only ones not tied together by the rebars in the grade beams. These values represent the real individual footing resistance. The others are the parallel resistance of the one connected to, plus all the other footings with some resistance in the paralleling connections.

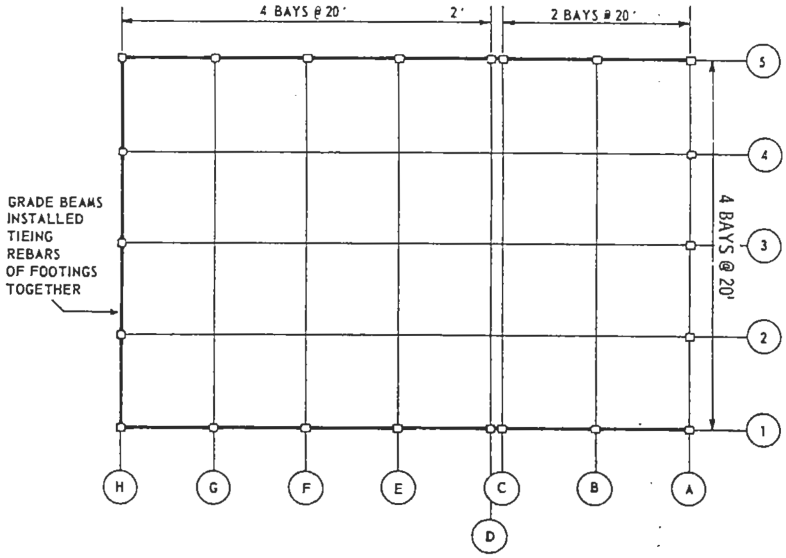


Fig. 5. Houston, Tex., test installation.

TABLE II
TEST RESULTS: HOUSTON, TEX.

Column	Resistance (ohms) Rebar	Anchor Bolts
*A*1	1.01	50.1
*B*1	0.69	52.0
*C*1	0.70	43.3
*D*1	0.69	47.5
*E*1	0.40	0.43
*F*1	0.42	41.1
*G*1	0.49	0.50
*H*1	0.47	47.3
*H*2	0.33	41.6
*H*3	0.32	37.3
*H*4	0.30	51.3
*H*5	0.30	26.1
*G*5	0.30	40.7
*F*5	0.30	36.5
*E*5	0.32	42.6
*D*5	0.39	41.5
*C*5	0.38	44.0
*B*5	0.42	51.9
*A*5	0.42	68.4
*A*4	1.75	73.6
*A*3	1.70	62.9
*A*2	1.96	125

The values for individual footings are in close agreement with theoretical values shown in Appendix III.

On March 26, 1969, additional measurements were made after all grade beams were in place and after the structural steel had been installed, connecting all footings together.

A total of 11 readings were taken with the current rod of the tester 100 to 500 feet from the test point and with the potential rod 25 to 450 feet from the test point. The readings varied from 0.09 to 0.14 ohm. The lower readings were obtained with the potential rod nearest to the test point. When the potential rod was located 350 feet or more from the test point, the readings leveled off at 0.14 ohm. This figure is taken as the actual ground resistance of the structure.

Site No. 4: Brevard, N. C.

Brevard is in the southwestern tip of North Carolina in the Great Smokey Mountains where ground resistance is known to be extremely high due to the leached-out rock and gravel nature of the soil.

The resistance is so high that the structural steel of the entire multibuilding industrial complex previously installed is tied together with copper cable and the cable is tied to well casings in order to reach an adequately low ground resistance. Even with this type of installation, the entire plant ground resistance has been measured in one point to be 7 ohms.

The tests at this location were made on the footings for an elevated cable tray shown in Fig. 6. The construction of the footings was similar to that shown in Fig. 2.

Most footings contain four anchor bolts which were not tied to the rebar system. Each bolt was measured separately, then all on each footing were tied together, and a total reading was taken. The rebar system of each footing had a test lead brought out. Each footing was measured separately, then the test leads for groups of footings were tied together and measured. The test results are shown in Table III.

It can be seen that even where ground resistance is extremely poor, a fairly low resistance can be obtained when a number of column footings are electrically tied together as they will be by the building steel assembly. It is apparent from Table III that a number of anchor bolts were obviously touching the rebar system. The values of footing 5 are low because the concrete for that particular footing is actually in contact with the plant ground cable.

TABLE III

TEST RESULTS: BREVARD, N. C.

Footing	Ground Resistance (ohms)						
	Anchor Bolts					Rebars	
	Northeast	Southeast	Southwest	Northwest	All	Individual	Group
1	158	156	159	158	144	138	16.8
2	86.2	83.4	94.8	93.4	75.5	70.0	
3	68.2	53.7	73.1	75.1	53.8	53.7	
4	69.2	69.7	60.4	49.8	48.8	46.7	
5	40.9	36.1	33.2	38.6	25.9	21.3	11.4
6	82.7	84.2	70.6	65.9	65.5	64.3	
7	68.6	60.6	48.0	70.7	47.9	47.9	
8	70.7	51.6	51.6	66.8	51.6	51.6	
9	112	91.1	91.1	91.1	91.1	91.1	66.8
10	187	182	164	164	164	164	
11	—	164	—	164	144	119	49.6
12	—	160	—	160	140	120	
13	—	300	—	300	280	250	250
14	—	310	—	320	290	250	

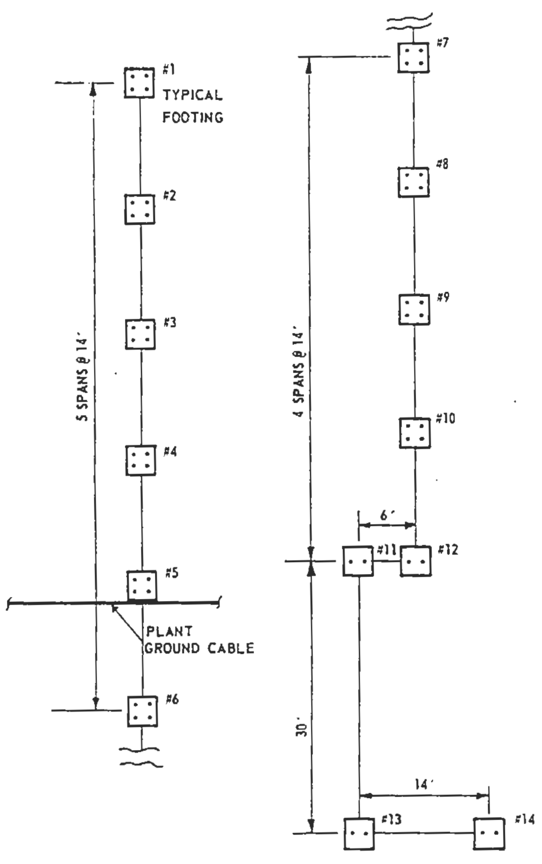


Fig. 6. Brevard, N. C., test installation.

Site No. 5: Aiken, S. C.

The soil at this location is very sandy and quite poor for grounding purposes. Deep-driven ground rods (70 to 140 feet) have been used to obtain adequately low values of ground resistance in previous installations there.

Measurements were taken on the rebars of four pair of footings (similar to Fig. 2). The bottoms of the footings are $8^1/_2$ feet below grade. At the time of the tests, the anchor bolts in each pair of footings were connected with a steel beam 3 feet above grade. A test lead had not been brought out from the rebar structure. Only the anchor bolts were available for tests.

TABLE IV

TEST RESULTS: AIKEN, S. C.

Footing Pair Number	Ground Resistance (ohms)
1	30
2	25
3	40
4	30
Steel tank	25

In this case, ohmmeter readings were made from each pair of footings to a nearby reference point on the plant grounding system. An additional reading was taken from a nearby ungrounded steel tank to the same reference point. The results are shown in Table IV. The point of interest here is that resistance readings are in the range of 25 to 40 ohms when no attempt had been made to ground the system. The anchor bolts had not been tied to the rebar system.

Site No. 6: Circleville, Ohio

The soil at this site is a mixture of sand and gravel. The present installation employs a ground cable which interconnects the steel structure of all buildings. This cable is, in turn, tied to two well casings in opposite ends of the plant.

Soil resistivity was measured at 15 300 Ω·cm. The measurements were taken December 3, 1968, 2 days after an all-day rain. There was some surface water on the ground. Measurements were made with a Biddle series 4 galvanometer-type earth tester.

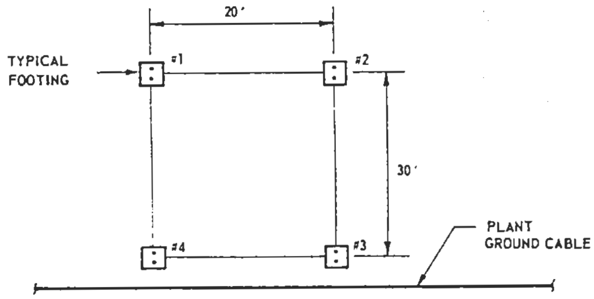


Fig. 7. Circleville, Ohio, test installation.

TABLE V
TEST RESULTS: CIRCLEVILLE, OHIO*

Footing	Ground Resistance (ohms) Anchor Bolts North	South	Both
1	45	50	45
2	90	90	75
3	45	42	35
4	32	30	23

* December 3, 1968.
The building ground loop is 0.5 ohm.

The measurements were taken on the anchor bolts (not rebar) of a small building extension which was adjacent (but not connected) to the plant ground cable. See Fig. 7 and Table V for test results. Footings 3 and 4 are both within a few feet of the plant ground cable.

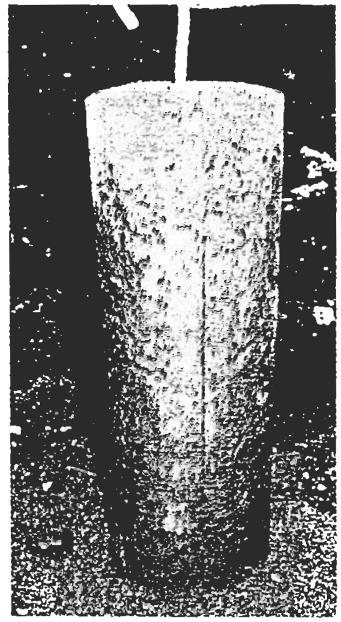
On December 20, 1968, an additional reading was taken after all grade beams had been poured and when the structural steel was in place (doweled but not bolted). The ground resistance reading was 2.5 ohms, taken at the north anchor bolt of footing 1.

Site No. 7: Impulse Test, Trafford, Pa.

It was felt that test work would be incomplete unless it included some data which showed the effect of high current discharges on the physical structure of a concrete-enclosed electrode. Arrangements were made with the Westinghouse Electric Company to run such a test at their High-Voltage Test Laboratory at Trafford, Pa.

Six concrete cylinders (approximately 15-inch OD by $3^1/_2$ feet long) were poured with standard 3/4-inch rebars encased in the cylinders. Three units were poured with a single 3/4-inch rebar on the axis. The other three were constructed with two 3/4-inch rebars doubled over so as to give the effect of four 3/4-inch rods at corners of a 10-inch square. The cylinders are shown in Fig. 8.

The cylinders were poured above grade and placed in the earth on November 26, 1968. The tests were conducted on December 2, 1968. The day was damp and overcast. It had rained all the previous day. There was surface water in the area and after the test, when the cylinders were removed from the ground, it was found that water was 2 inches deep in two of the holes.



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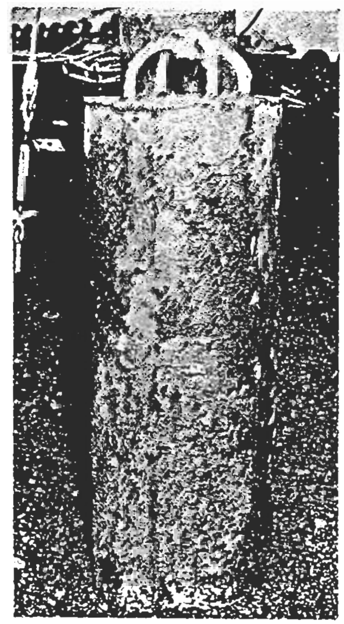

(b)

Fig. 8. Test electrodes, Trafford, Pa.

Electrodes were symmetrically placed in a grid approximately 10 by 20 feet. The ground resistance of each was measured before testing. They were then subjected to current impulses ranging from 1900 to 9300 amperes (see Table VI and Fig. 9).

Peak currents were reached in 2 to 5 μs. The total energy level was relatively low when compared with Wiener's work [4] where the duration was longer. This test does, however, show relative immunity to rate of rise and peak current. The resistance of each electrode

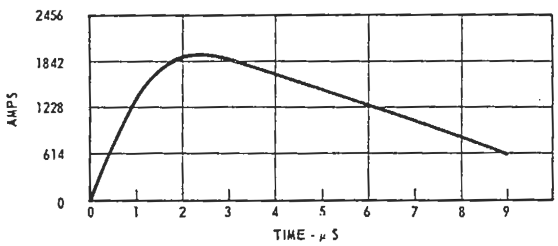

Fig. 9. Electrode 5; current during impulse test, Trafford, Pa.

TABLE VI
IMPULSE TEST: TRAFFORD, PA.

Unit	Number of Rods	Volts (kV)	Current (amperes)	Resistance (ohms) During Test	Resistance (ohms) Prior to Test	Time Peak I (μs)
1	1	150	9300	3.2	30.9	4.5
2	4	120	9100	5.9	18.0	4.0
3	1	110	5200	4.5	32.4	5.0
4	4	87	5220	16.7	10.0	4.0
5	1	50.3	1900	25.9	25.6	2.0
6	4	16.9	2260	7.5	13.0	2.0

during surge tests was calculated and compared to the measured value before test.

After each two electrodes were tested, they were pulled from the ground and inspected for physical damage. No evidence of damage was found from visual inspection. It was noted that there was 2 inches of water in the bottom of test holes 4 and 5 after the cylinders had been removed.

Cylinders 1 and 2 were sent to a physical test lab for petrographic analysis. Microscopic examination was made of sample disks cut from both electrodes. The examination failed to disclose any evidence of distress or change of the concrete that appeared to result from the impulse testing. Microcracks (0.002 to 0.003 mm wide and 3 to 10 mm long) were found to extend radially from some of the rebars in the samples which had four rebars. These were attested to be tension fissures from shrinkage such as are common in Portland Cement concrete followed drying. No microcracks were found in the samples which had only one rebar.

CONCLUSIONS

The results obtained in these tests and those of earlier work indicate that the reinforcing bar network of reinforced concrete footings provides adequately low grounding resistance, with fault and surge current capability suitable for all types of structure and circuit grounding. Electrodes provided in this manner provide grounding function at least equal to and in most cases superior to that of previously used grounding electrode systems. The decreasing suitability and availability of the most widely used existing system (water lines) makes consideration of the rebar type doubly desirable. Not the least of the advantages of the rebar system are its ready availability and low cost.

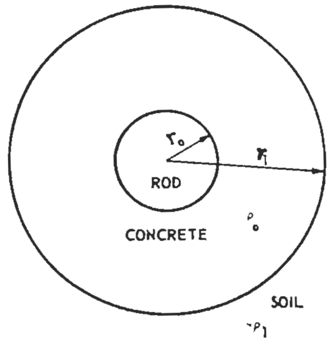

Fig. 10. Concrete-encased rod electrode in soil.

TABLE VII

Encased ρ_0 (concrete)	Encased ρ_1 (earth)	Encased Resistance (ohms)	Unencased ρ (earth)	Unencased Resistance (ohms)
	500	5.46		
	2000	7.89	500	1.60
3000	5000	12.75		
	10 000	20.85	1000	3.21
	50 000	85.7		
	500	8.56	2000	6.42
	2000	11.0		
5000	5000	15.85	5000	16.0
	10 000	23.95		
	50 000	88.75	10 000	32.1
	500	13.21		
	2000	15.64	20 000	64.2
8000	5000	20.50		
	10 000	28.6	50 000	160.0
	50 000	93.4		

Grounding resistances with encased and unencased rods 10 feet spacing, 3/4-inch diameter. ρ, ρ_0, and ρ_1 in Ω·cm.

APPENDIX I
CALCULATION OF THEORETICAL GROUNDING RESISTANCE AT A CONCRETE-ENCASED ROD ELECTRODE

The basic formula for grounding resistance [7] is

$$R = \frac{\rho}{2\pi L}\left(\ln\frac{4L}{r} - 1\right)$$

where

R grounding resistance, ohms
ρ resistivity of surrounding medium, Ω·cm
L rod length, cm
r rod radius, cm.

Expanding this to include the case where the "ground" is a dual nature medium, this becomes (Fig. 10) $R = R$ derived from rod r_0 into concrete of ρ_0, less R from r_1 into concrete of ρ_0, plus R from rod r_1 into earth of ρ_1, or

$$R = \frac{\rho_0}{2\pi L}\left(\ln\frac{4L}{r_0} - 1\right) - \frac{\rho_0}{2\pi L}\left(\ln\frac{4L}{r_1} - 1\right) + \frac{\rho_1}{2\pi L}\left(\ln\frac{4L}{r_1} - 1\right).$$

TABLE VIII

Rod Diameter (inches)	A^2s per 80°C	A^2 per 0.0001 Second	A^2 per 1/120 Second	A^2 per 1/30 Second	A^2 per 1/6 Second
1/2	2080	20.8×10^6	24.8×10^4	6.25×10^4	1.25×10^4
5/8	3010	30.1×10^6	36.0×10^4	9.05×10^4	1.81×10^4
3/4	4120	41.2×10^6	49.2×10^4	12.1×10^4	2.47×10^4
1	6670	66.7×10^6	80.2×10^4	20×10^4	4.0×10^4
$1^3/_8$	12 100	121×10^6	145×10^4	36.2×10^4	7.27×10^4

TABLE IX

Rod Diameter (inches)	Cm^3 of Concrete 1/8-Inch Shell	Total Gram Calories	W·s per 80°C	Resistance of 1/8-Inch Shell (ohms)	A^2s per 80°C
1/2	48.3	26.4	8850	4.25	2080
5/8	57.8	31.6	10 600	3.52	3010
3/4	67.6	36.9	12 350	3.00	4120
1	86.9	47.4	15 500	2.33	6670
$1^3/_8$	116	63.25	21 150	1.75	12 100

TABLE X

PERMISSIBLE GROUND CURRENT IN AMPERES RMS FOR EACH FOOT OF ROD LENGTH

Rod Diameter (inches)	0.0001 Second 100 μs*	0.008 Second One Half-Cycle†	0.032 Second 2 Cycles‡	0.167 Second 5 Cycles‖
1/2	4500	498	250	112
5/8	5490	600	301	135
3/4	6420	701	347	157
1	8170	895	447	200
$1^3/_8$	11 000	1204	602	270

* Typical duration of lightning stroke.
† Typical clearing time of current-limiting fuse.
‡ Typical clearing time of low-voltage circuit breaker.
‖ Typical clearing time of high-voltage circuit breaker or high-voltage fuse.

This reduces algebraically to

$$R = \frac{\rho_0}{2\pi L}(\ln r_1 - \ln r_0) + \frac{\rho_1}{2\pi L}(\ln 4L - 1 - \ln r_1)$$

(from F. D. White, Portland, Oreg.).

Using the above relation, Table VII may be calculated, showing the relative effect of differing resistivities on a 10-foot 3/4-inch diameter rod, encased in 16-inch diameter concrete and unencased.

It is evident that in soil of about 5000 Ω·cm and lower resistivity, the ground resistance of a rod driven directly into the earth will be lower than if the rod were encased in a 16-inch diameter concrete cylinder. In soil of higher resistivity than about 10 000 Ω·cm., a concrete-encased rod will have lower ground resistance than one directly driven. While published values of concrete resistivity are 6000 to 10 000 Ω·cm, results of tests described here indicate resistivity of about half these values for concrete in contact with soil, evidently due to inherently higher moisture content than the previously tested samples.

Appendix II
Current–Time Capability of Concrete-Encased Ground Rods

Current density and heating rate are highest immediately outside the metal surface. Consider an incremental shell of concrete 1/8 inch thick surrounding the rod. Successive shells outside this will have lower current densities and lower heating rates, so will not be limiting. Neglect heat transfer to the rod, but do consider the heating of the concrete as well as its water content. Make calculations on a per foot of rod length basis:

initial temperature 20°C
final temperature 100°C (no boiling)
density of concrete 2.1 g/cm^3
specific heat of concrete 0.21 cal/g
water content of concrete 5 percent by weight
rod sizes 1/2-, 5/8-, 3/4-, 1-, and $1^3/_8$-inch diameter
concrete resistivity 3000 Ω·cm at 20°C; 1000 Ω·cm at 100°C; 2000 Ω·cm average.

Results of these calculations are presented in Tables VIII–X.

Appendix III
Approximate Resistance of Rebar-Footing Electrodes

An estimating value of grounding resistance of column footing electrodes may be calculated, based on the following approximations.

1) Effectively, four reinforcing bars of 3/4-inch diameter are near the corners of the footing pedestal. While possibly only one bar is directly connected to the system to be grounded, the other three are effectively connected to it by multiple horizontal rib bars and tie wires.

2) The effective concrete layer around each bar is a 3/4 cylinder (270°) of radius 2 inches from the bar surface. Neglect the volume and surface of concrete except for these four 3/4 cylinders (see Fig. 11).

3) Neglect the size of the spread footing base, considering it as merely a linear extension of the pedestal. Consider the electrode as having length equal to the buried total depth of the footing.

4) The resistivity of the soil is uniform from top to bottom of the pedestal (below earth surface). Effectively,

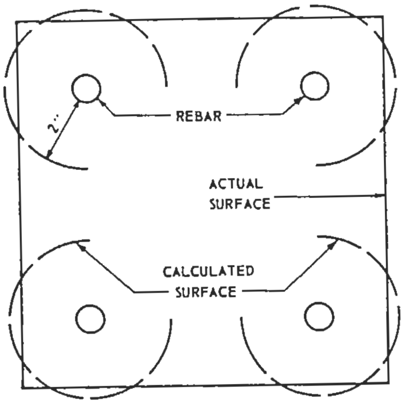

Fig. 11. Comparison of actual and calculated surfaces of 4-rebar pedestal; unbroken line represents actual surface; broken line represents calculated effective surface.

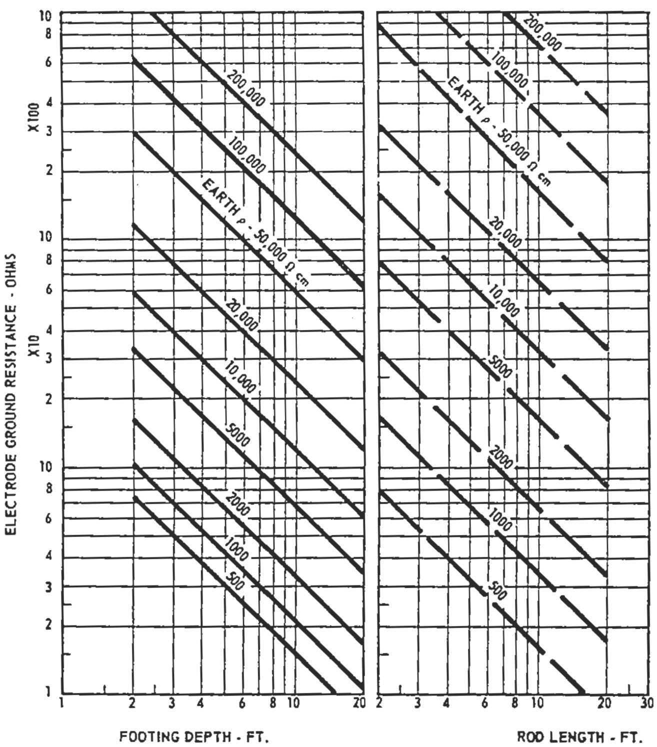

Fig. 12. Grounding resistance of concrete reinforcing electrode (piers) and driven rods (3/4-inch diameter).

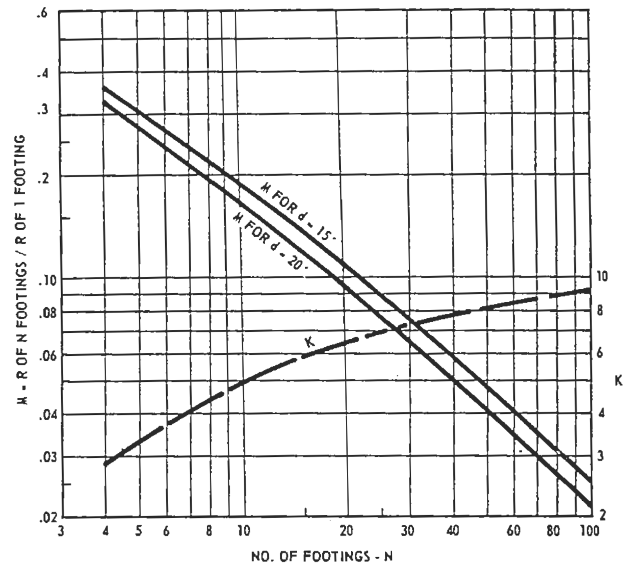

Fig. 13. Multiplier for multiple electrodes in hollow square or broad rectangle.

a value for resistivity at 2/3 of the depth may be used, or a value determined by measurement, using test electrode spacing equal to the height of the pedestals.

Estimating grounding resistances of this "equivalent footing" in various resistivity soils are displayed in Fig. 12. Good correspondence of measured footing resistances with Fig. 12 was obtained in tests.

Calculated grounding resistances of 3/4-inch diameter rods are also shown in Fig. 12. Except at the lowest soil resistivities, these indicate that a 10-foot rod exhibits about the same grounding resistance as a 5-foot deep footing electrode in average soils, 3 to 4 feet in high resistance soils. In extremely conductive soil, equal depths are required to obtain equal resistances.

Appendix IV

Effect of Multiple Concrete-Encased Rebar Grounding Electrodes in Hollow Rectangular Configuration

Using the method of equivalent hemispherical electrodes of Tagg [8], the effect of using multiple rebar electrodes may be estimated. By this method, applied to hollow square electrode arrays,

$$M = \frac{\text{resistance of } N \text{ electrodes in parallel}}{\text{resistance of 1 electrode}} = \frac{1 + k\alpha}{N}$$

where

$$\alpha = \frac{r}{d}$$

- r radius of equivalent hemisphere which is 2.5 feet for 10-foot electrode $\gg$ 6-inch diameter
- d spacing of electrodes, feet
- N total number of electrodes
- M multiplier to obtain array resistance from single electrode resistance.

Values of k and M for spacings of 15 and 20 feet and N up to 100 are shown in Fig. 13. For practical purposes, when $N \gg 10$, $M = 2/N$.

Tagg [8] further indicates that the addition of electrodes to fill in a hollow square does not appreciably reduce the total resistance. For footing electrodes, this means that providing connection to the rebar of internal building footings would not be useful in reducing the grounding resistance. Additionally, since the soil within the outer walls of a closed structure receives little moisture from natural precipitation, the individual resistances of footings in this area would tend to be much higher than those on the periphery, and their utility as grounding electrodes would be minimal.

References

[1] H. G. Ufer, "Investigation and testing of footing-type grounding electrodes for electrical installations," *IEEE Trans. Power Apparatus and Systems*, vol. 83, pp. 1042–1048, October 1964.

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[3] L. B. Hertzberg, "The water utilities look at electrical grounding," *IEEE Trans. Industry and General Applications*, vol. IGA-6, pp. 278–281, May/June 1970.

[4] P. Wiener, "A comparison of concrete encased grounding electrodes to driven ground rods," *IEEE Trans. Industry and General Applications*, vol. IGA-6, pp. 282–287, May/June 1970.

[5] H. H. Skilling, *Electrical Engineering Circuits*, 2nd ed. New York: Wiley, 1965, p. 9.

[6] J. H. Morgan, *Theory and Practice of Corrosion Prevention*. New York: Macmillan, 1960, p. 53.

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Discussion

C. A. Harris (Stanford Linear Accelerator Center, Stanford, Calif.): This paper, while exploring much of a widely overlooked subject, leaves two vital questions unanswered. These are possible corrosion of the steel reinforcing members from the ground current, and the possibility of reinforcing members acting as an electrolytic cell or capacitor, the latter observed but not deeply investigated or published.

The acknowledgment by the authors that "rods are in the higher stress zones of the concrete" should be recognized as a need to protect the rebars from corrosion, rather than subjecting them to a condition which could deteriorate their strength. The latter process would result in serious weakening and possible collapse of the structures.

The pressure from corrosion products around the rebars could build up to the point where fracture of the concrete would occur. Is it not possible that some of our older buildings are already subject to this condition? The short-term "impulse test" does not in any way indicate possible long-time deterioration in the rebars.

Many buildings are intended to last several hundred years. Caution is needed to prevent a premature end of useful life of any portion of such structures, including the steel reinforcing of the foundations.

The discusser was involved, some 10 years ago, with a condition which appeared to show that an isolated rebar in concrete sets up an electrolytic zone at the iron surface which tends to isolate it in the concrete, possibly because of the uniform environment. It is possible that this electrolytic barrier inhibits long-term corrosion in the restricted volume. This observation was made during an investigation of intentionally insulating rebars from one another in the foundations for the Bevatron at the Lawrence Radiation Laboratory, University of California, Berkeley. The insulation was required to prevent the heating effect of heavy eddy-current flow in the bars from voltages induced by strong alternating magnetic fields present. The phenomenon observed was a potential of nearly 1 volt between isolated bars, decaying slowly with time. It was not determined whether the condition was due to a battery, polarizing with time and reducing current flow, or a charged capacitor with capacitance of several farads. The phrase "concrete capacitors" was coined by engineers involved, for want of a better term.

It is granted that water piping systems are becoming unsuitable as grounding electrodes. Possibly the authors would be better advised to develop a more satisfactory isolated ground network to protect the foundations rather than subjecting the latter to ground currents.

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Eugene J. Fagan and **Ralph H. Lee**: The aspects of possible augmented corrosion and the electrolytic cell or capacitor suggested by Mr. Harris are real and deserving of attention. The limitations of time and space imposed on technical papers preclude the expansion of the observed data to include all possible aspects of the subject, but require confining the treatment to only that portion of the subject which was investigated.

Relative corrosion rates of steel in concrete and in earth were not investigated in this study. References to the papers of Ufer [1] and Wiener [4] were the bases for the statement that corrosion rates were acceptably low. The work of Ufer extended over more than 20 years; and, while Wiener's was for only about 1 year, the magnitude and duration of his testing currents were greatly in excess of that involved in practical use. Over and above the specific reported investigations, the conventional use of steel anchor bolts alone, in contact with building steel, constitutes an "Ufer ground" of limited surface area at each such footing. With the small surface area, the ground current concentration per unit electrode area is much higher than it would be if the entire reinforcing system were connected, which would tend to magnify the corrosion rate if such existed. However, there has been no general history of troublesome corrosion of anchor bolts, or of bursting of concrete around the anchor bolts. The authors, therefore, concluded that corrosion of steel in concrete was not a real factor and did not pursue that aspect further.

Two verbal discussions of this paper, one at a previous local chapter presentation, are germaine to this question. A responsible industrial electrical engineer indicated his experience that the buildings (with anchor bolts in concrete footings) exhibited lower ground resistance than did the external grounding system of multiple driven rods and buried cables, a phenomenon now explained by this investigation. This would indicate that the anchor bolts were carrying the majority of ground current. It follows that unless deliberate steps are taken to insulate the anchor bolts from building steel, the anchor bolts in concrete will carry ground current in all such buildings. An engineer of an electrolytic installation (very high-current system in which there is appreciable continuous ground current flow) told of experiencing the deterioration of concrete itself between the anchor bolts and the reinforcing bar structure of foundations. One observation of this investigation was that the current flow, in absence of bonding between anchor bolts and rebar, was from anchor bolts radially through the concrete to the rebar, thence through the rebar system and outward through the outer surface of the concrete footing to the earth. In the absence of bonding, the highest concentration of current per unit volume would occur immediately outside the anchor bolt zone, i.e., between the anchor bolts and the rebar structure. In a continuous high-current condition, this could result in excessive heating and drying out of the concrete, resulting in its deterioration. There was no indication of corrosion of the anchor bolts or deterioration of the concrete outside of the rebar structure. Since the current concentration outside the rebar structure would be little changed if a bond were added between anchor bolts and the rebar structure, the addition of such a bond was the indicated solution to this problem.

The "high stress" reference in the paper was simply to account for the spacing between anchor bolt locations and the rebar positioning, requiring a radial bonding member to span the space. The impulse tests of this investigation had no intent to shed light on the effects of corrosion. They were intended merely to investigate the shattering, bursting, or boiling effects of impulse or lightning currents on concrete-encased steel grounding electrodes. While peak currents per foot of length and impulse tail duration available did not approach the calculated thermal capacity of such electrodes, this test did serve to prove that no shattering of concrete from the impulse would occur.

The phenomenon of a "voltaic cell or capacitor" between rebars and/or other grounding electrodes was not observed in this investigation. In fact, the measuring instrument, a Biddle null balance earth tester, consisting basically of a galvanometer, a resistance bridge, and a hand-crank generator, would not have indicated any such voltages had they existed. We can only suggest that the discussor may have been experiencing voltage from current flow in the earth (or concrete) from an external current system, or a voltaic cell formed from different metals in the "electrolyte" of the concrete.

Manuscript received April 15, 1970.

The deterioration of this voltage with time might be the result of polarization of one or both electrodes in the latter case.

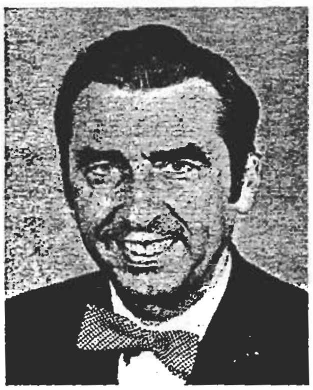
There is always a possibility of corrosion of steel in the electrolyte of earth or concrete when there is also copper or other electronegative material in the earth or concrete and electrically connected to the steel. This condition could exist where copper or copperweld rods and/or copper wires of conventional grounding systems existed. Some unpublished work by Bell Laboratories indicated that corrosion of steel in concrete was negligible, but for steel directly in earth of low resistivity, such a corrosion rate is serious. This is the condition responsible for the excessive corrosion rate of steel in marginal marine regions, where cathodic protection is the corrective measure utilized. It is suggested that the elimination of the electronegative metal, including copper, in the earth, would remove this costly problem. The concrete rebar electrodes proposed in this paper would go far toward this desired end.

Unusual structures, such as the Bevatron foundation, will always require special engineering skills to avoid the consequences of the unique exposures. However, the great majority of residential, commercial, and industrial installations involve no such problems, hence the steel rebar type of electrode could serve as well as, or better than, previously used types.

A probable life of 50 years, rather than the 200 suggested, is more applicable for nearly all structures being built today, although there is no indication that the rebar ground use would be a factor in this.

In the unusual event that a grounding system insulated from the structure or foundation anchor bolts or rebar is desired, data contained in this paper are still useful for the design of separate concrete-encased electrodes for grounding purposes, if such a system were elected.

The authors thank this discussor, and others who commented verbally, for extension of the relatively small fund of knowledge on this subject. Yet grounding is one of the most universal aspects of electrical system use. There is much need for extension of investigation in this field.



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Mr. Fagan is a member of the National Society of Professional Engineers, the present IEEE Representative on the Delaware Council of Engineering Societies, and a Professional Engineer in the States of Delaware and New York.

Ralph H. Lee (SM'48) was born in Las Vegas, Nev., on April 6, 1911. He received the B.Sc. degree in electrical engineering from the University of Alberta, Edmonton, Canada, in 1934.

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Mr. Lee is a member of the National Electrical Safety Code Grounding Committee, the U.L. Ad Hoc Committee of Fire Protection of Tray Cables, and is a Registered Professional Engineer in the State of Delaware.