Reducing Effect in Footing Resistance Against Heavy Impulse Current (II)

(Profitable Use and Promotion of Streamer in the Soil)

By

Muneaki HAYASHI*

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Distortion and promotion of the electric field intensity in the vicinity of earth electrode strengthen the reducing effect of footing resistance against heavy impulse current; and by a little mixing material in concrete, the earth resistance of concrete electrode that imitates the concrete block of tower foot is reduced.

I. Electrode Equipped with Needles

1) Introduction

It may be possible to strengthen the reducing effect of footing resistance of a tower by promoting the electric field intensity in the vicinity of footing electrode i.e. by enlarging the streamer with a pointed wire attached to the electrode, since the reducing effect of footing resistance chiefly depends on the streamer in the soil, whose characteristic is described in the preceding paper.

Previously in 1951, H. Norinder investigated the decrease of earth resistance comparing a counterpoise equipped with pointed wires (needles) of 15 mm length, to one without needle. He reached the conclusion that needles were not effective, while powdered charcoal or powdered oxide iron in the vicinity of a counterpoise was rather effective. However, since the effect of needles attached to electrodes may depend on the earth resistivity, length and number of needles, crest value of the applied impulse voltage or current, and its wave form, it is likely that his experiments were performed under a certain condition where needles had little effect. However, in this paper, the results of experiment concerning many parameters above described are reported, and the effects of needles have been cleared.

* Department of Electrical Engineering

2) The Figures of Streamer Propagating from the Electrode Equipped with Needles

The relation between needle and streamer in the soil, i.e. the relation between needle and earth resistance are studied by the observation of the streamer figure obtained on the vertically embedded X-ray film under the earth electrode.

(a) Spherical earth electrode of 4 cm diameter equipped with one needle

An impulse voltage of 55 kV crest value is applied, to a spherical earth electrode equipped with one needle of 1.4 cm length, as shown in Fig. 1-1, or to one without needle, then Figs. 1-2 (a) and (b) are obtained respectively as the streamer figures, in which the lengths of streamer of both figures are consistent. The length of streamers in these figures is about 25 cm, and is much longer than the needle.

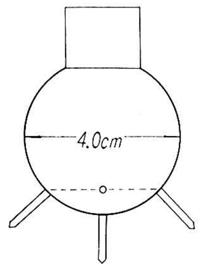
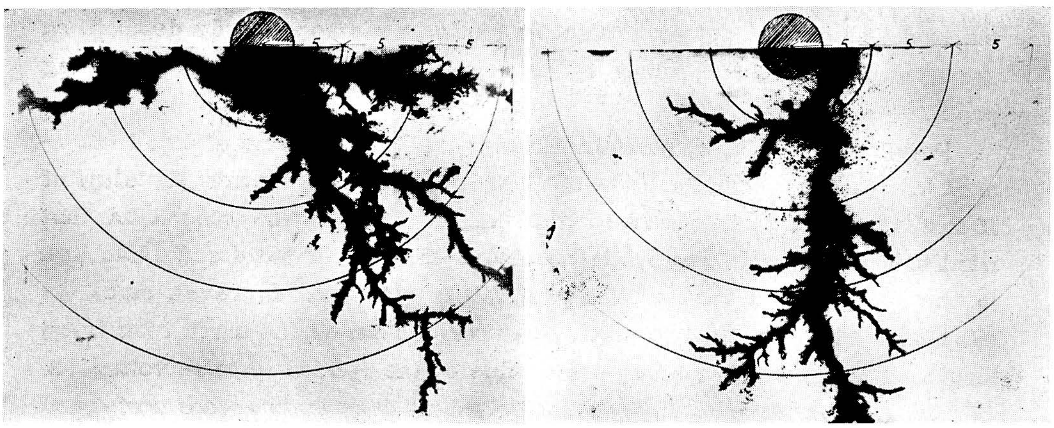


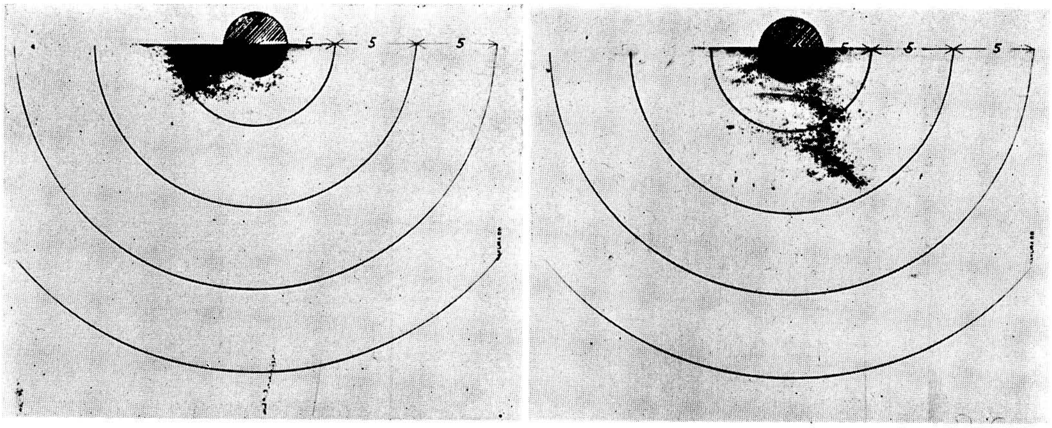
Fig. 1-1. Spherical electrode equipped with needles.

When a 48 kV impulse voltage (10% smaller than preceding voltage) is applied to the electrodes described above, the streamer scarcely propagated regardless of the existence of a needle as shown in Fig. 1-3. So that the needle does not affect the reduction of earth resistance against impulse voltage.



(a) Without needle (b) With one needle of 1.4 cm

Fig. 1-2. Streamer figures propagating from spherical earth electrode equipped with or without needle.
Diameter of sphere ; 4.0 cm
Applied voltage ; 55 kV
Earth resistivity ; 30 kΩ-cm



(a) Without needle (b) With one needle of 1.4 cm

Fig. 1-3. Streamer figures propagating from spherical earth electrode with or without needle.

Diameter of sphere ; 4.0 cm
Applied voltage ; 48 kV
Earth resistivity ; 30 kΩ-cm

It is deduced from these tests, that a needle attached to the electrode has practically no effect on the reduction of the earth resistance under this condition.

(b) Cylindrical earth electrode equipped with one needle

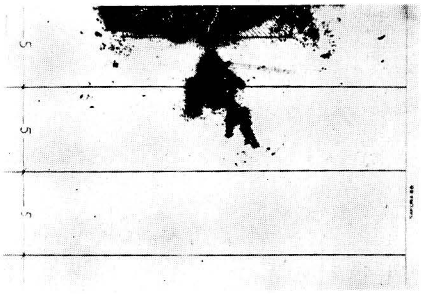
The cylindrical electrode used here is 4 cm in diameter, 10 cm in length, and has rounded edges to avoid the end effect (i.e. distortion of the electric field and propagation of streamer from the edges).

When an impulse voltage of 38 kV crest value is applied to this needleless electrode, the streamer, as shown in Fig. 1-4 (a), extends itself concentrically to the electrode, and when a needle of 5 cm length is attached to this electrode, the tree formed streamer, as shown Fig. 1-4 (b), propagates additionally. It is deduced from this test that this additional streamer is due to the effect of the attached needle, and magnifies the reducing effect of earth resistance. When the length of needle is elongated under the same condition, the streamer propagates more widely as shown in Fig. 1-4 (c), therefore the effect of the needle increases as it becomes longer.

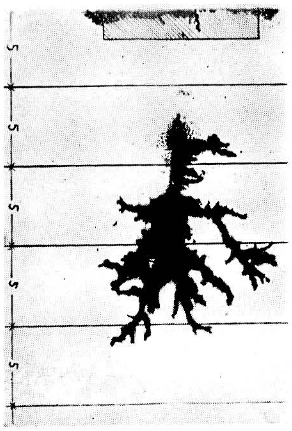
(c) Spherical earth electrode of 8 cm diameter equipped with one needle

It is evident from the tests in terms (a) and (b) in this section, that the effect of needles varies with the size and form of the electrode, and the crest value of the applied impulse voltage. An impulse voltage of 55 kV crest value

(a) Without needle



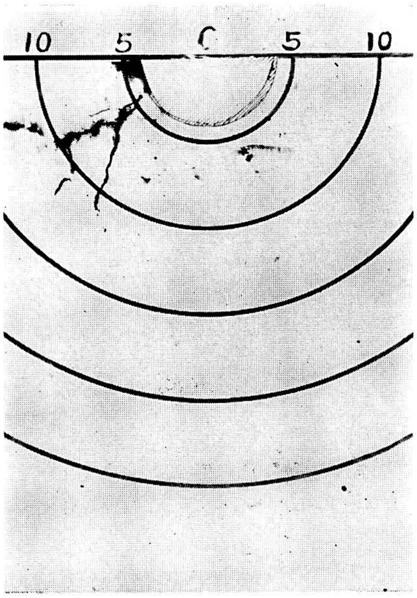
(b) Equipped with one needle of 5 cm



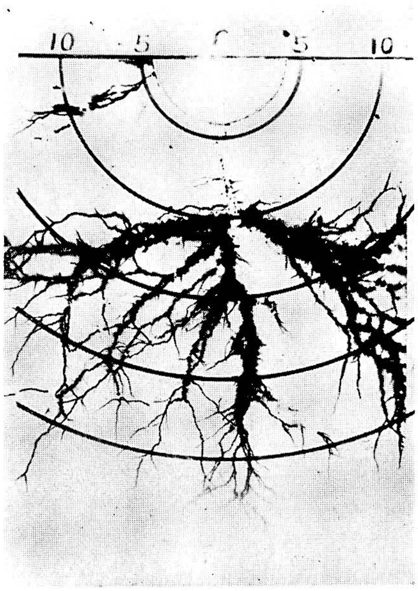
(c) Equipped with one needle of 10 cm

Fig. 1-4. Streamer figures propagating from cylindrical electrode with or without needle.

Diameter of cylinder ;	4.0 cm
Applied voltage ;	38 kV
Earth resistivity ;	30 kΩ-cm



(a) Without needle



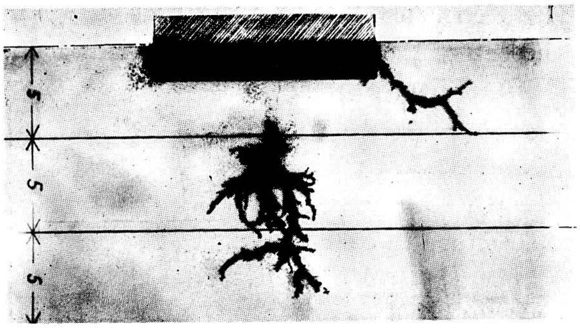
(b) With one needle of 10 cm

Fig. 1-5. Streamer figures propagating from spherical earth electrode equipped with or without needle.

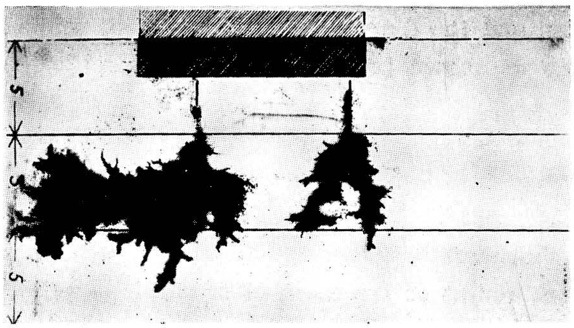
Diameter of sphere ;	8.0 cm
Applied voltage ;	55 kV
Earth resistivity ;	30 kΩ-cm

is applied to a spherical electrode of 8 cm diameter equipped with 10 cm needle, then Figs. 1-5 (a) and (b) are obtained, where an additional streamer due to the needle is observed. From these figures, the effect of the needle is evident under this condition.

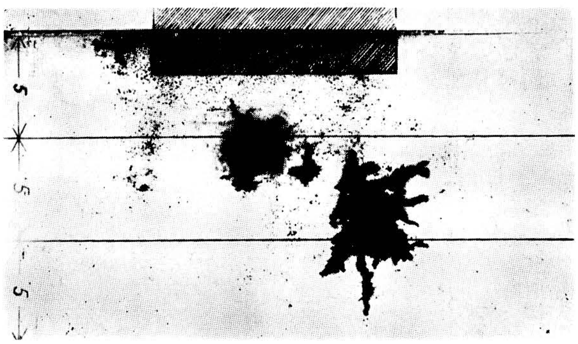
(d) Cylindrical earth electrode equipped with several needles



(a) With one needle of 4.0 cm length



(b) With two needles of 4.0 cm length



(c) With four needles of 4.0 cm length

Fig. 1-6. Relation between streamer and number of needles.
Diameter of cylinder ; 4.0 cm
Applied voltage ; 30 kV
Earth resistivity ; 30 kΩ-cm

As described above, the size of streamer increases with the increase of needle length. However, there is little variation of streamer size as the number of needles are increased as shown in Figs. 1-6 (a), (b) and (c). Therefore, it is deduced that, to increase the size of streamer, the elongation of the needle is more effective than increasing the number of needles.

3) Measurement of Earth Resistance of Electrode Equipped with Needles

In this section, one of the copper spherical electrodes of 3.5～15 cm diameter, equipped with a needle of 1.0～12.0 cm length is used as a center electrode. An impulse voltage (crest value; 25～100 kV) of standard wave form ($1\times40\,\mu$S) is applied to this electrode and the apparent resistance is calculated for an earth resistance. Earth resistivity and the radius of the vessel of soil are described in each measurement.

(a) Earth resistance against length of needle at constant radius of center electrode

When the diameter of the electrode is 8 cm, and the earth resistivity is 46.6 or 10.5 kΩ-cm, and the diameter of the vessel of soil is 166 cm, results of measurement are as shown in Figs. 1-7 and 8, from which the followings are deduced.

(1) The reducing effect of earth resistance by means of attached needles decreases as the crest value of the applied voltage is raised.

(2) That effect disappears practically in sufficiently high voltages.

(3) Elongation of needles increases the effect.

An equivalent radius of the earth electrode is calculated from the data shown in Figs. 1-7 and 8, and from the following equation (1-1),

$$\frac{1}{r_t}=\frac{1}{r_e}+R\frac{2\pi}{\rho} \tag{1-1}$$

where

r_t ; equivalent radius of center electrode against an impulse voltage

r_e ; radius of external electrode (vessel of soil)

R ; earth resistance of center electrode

When r_e is infinite in the above equation, i.e., at the field,

$$r_t=\frac{\rho}{2\pi}\cdot\frac{1}{R} \tag{1-2}$$

Then, r_t, equivalent radius, is proportional to the reciprocal of earth resistance. In author's test also, as the second term in the right side of equation (1-1) is very small compared to the first, equation (1-2) always holds approximately. Figs. 1-9 and 10 are obtained from the data of Figs. 1-7 and 8, and

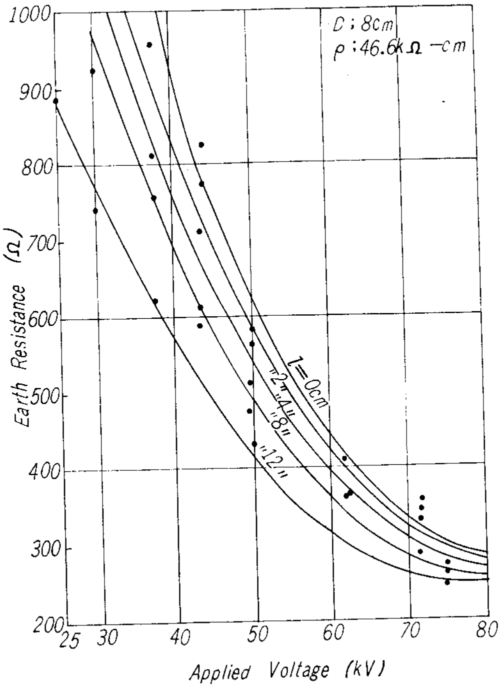


Fig. 1-7. Earth resistance of spherical electrode equipped with one needle (I).

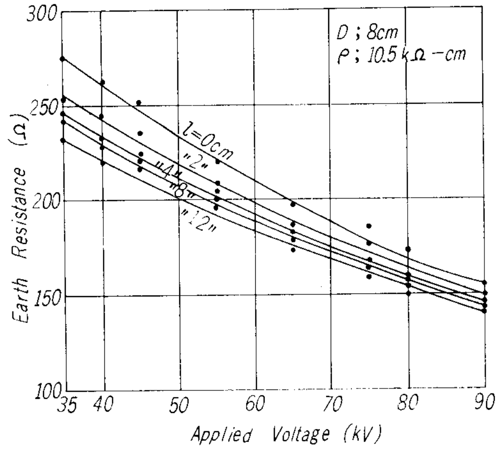


Fig. 1-8. Earth resistance of spherical electrode equipped with one needle (II).

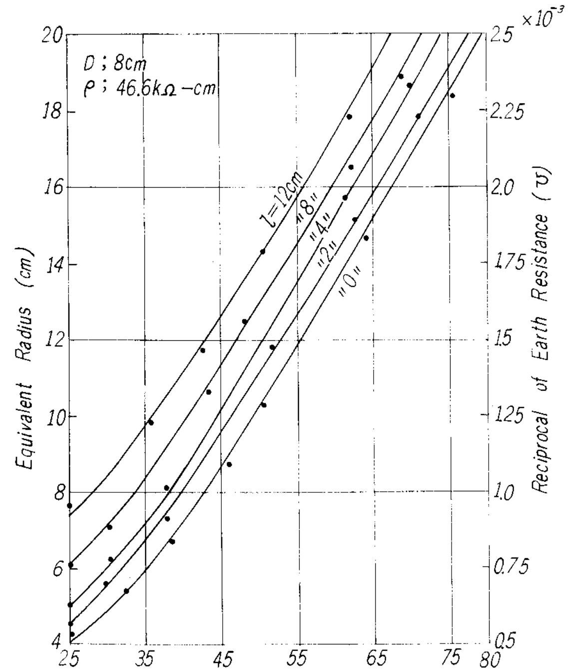


Fig. 1-9. Equivalent radius of spherical electrode equipped with one needle (I).

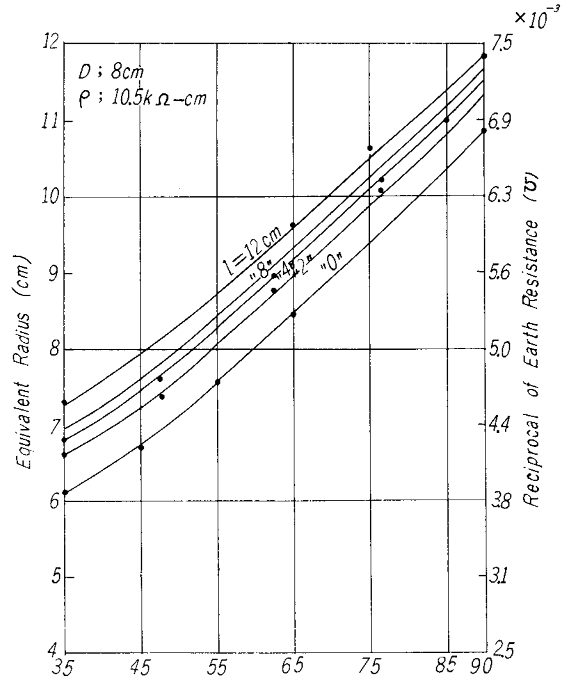


Fig. 1-10. Equivalent radius of spherical electrode equipped with one needle (II).

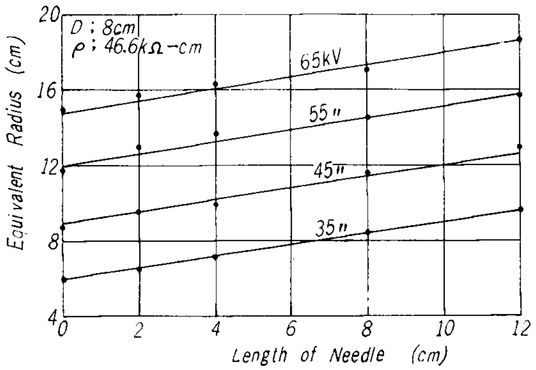


Fig. 1-11. Equivalent radius of spherical electrode equipped with one needle (I).

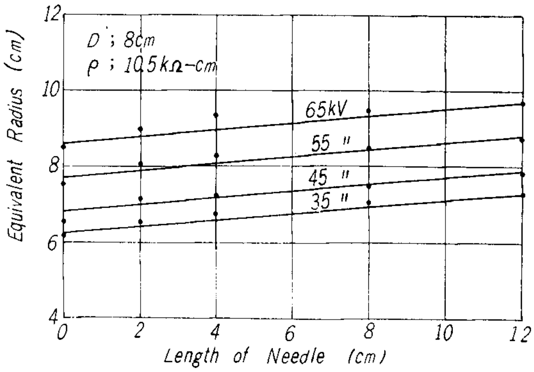


Fig. 1-12. Equivalent radius of spherical electrode equipped with one needle (II).

suggest that r_t is a linear function of l taking applied impulse volage as a parameter. This can be ascertained according to Figs. 1-11 and 12 obtained from the same data.
Then

$$r_t = r_{i0} + k_1 l \tag{1-3a}$$

where r_{i0} ; equivalent radius of needle-less electrode against an impulse voltage
k_1 ; constant determinated by the conditions
l ; length of needle

On the other hand, application of Eq. (1-2) to the above equation yields the following equation,

$$\frac{1}{R_i} = \frac{1}{R_{i0}} + k_2 l \tag{1-3b}$$

where R_i ; earth resistance of electrode equipped with needles against an impulse voltage
R_{i0} ; earth resistance of needle-less electrode against an impulse voltage
k_2 ; constant determinated by the conditions

When the data of Figs. 1-11 and 12 are plotted in a semi-log. graph, Figs. 1-13 and 14 are obtained and a linear relation between l and r_t holds.
Consequently

$$\log_{10} r_t = \log_{10} r_{io} + k_3 l \tag{1-4a}$$

where k_3 ; a constant determinated by conditions
From Eqs. 1-2, 1-4(a)

$$\log_{10} R_i = \log_{10} R_{i0} - k_4 l \tag{1-4b}$$

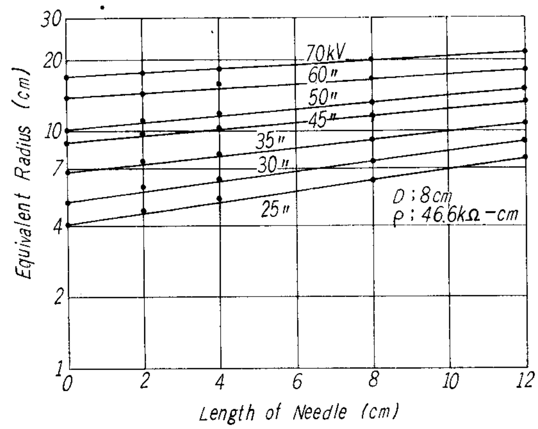


Fig. 1-13. Equivalent radius of spherical electrode equipped with one needle (I).

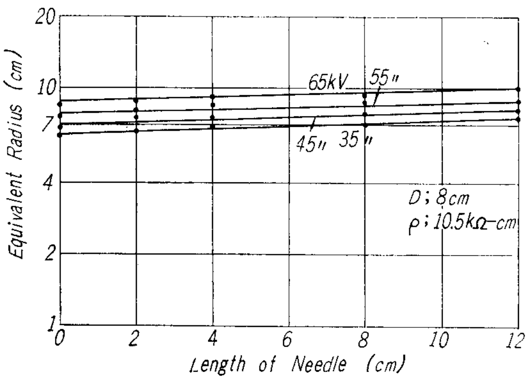


Fig. 1-14. Equivalent radius of spherical electrode equipped with one needle (II).

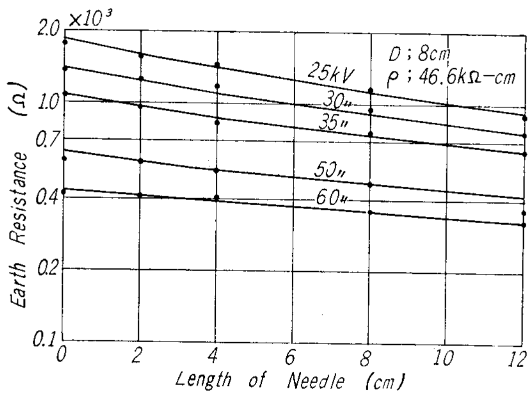


Fig. 1-15. Earth resistance of spherical electrode equipped with one needle (III).

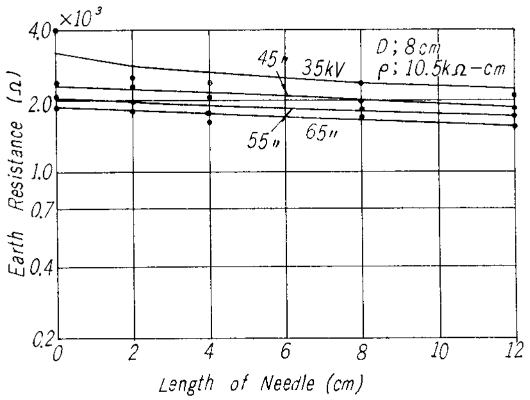


Fig. 1-16. Earth resistance of spherical electrode equipped with one needle (IV).

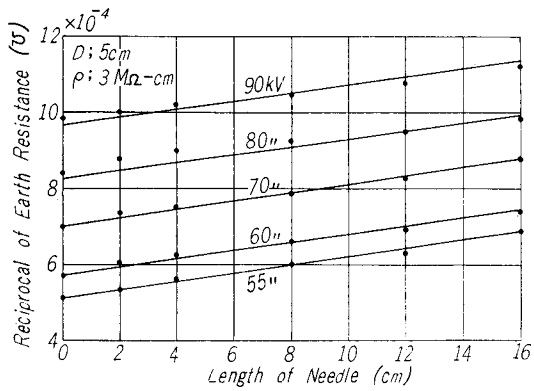


Fig. 1-17. Earth resistance of spherical electrode equipped with one needle (V).

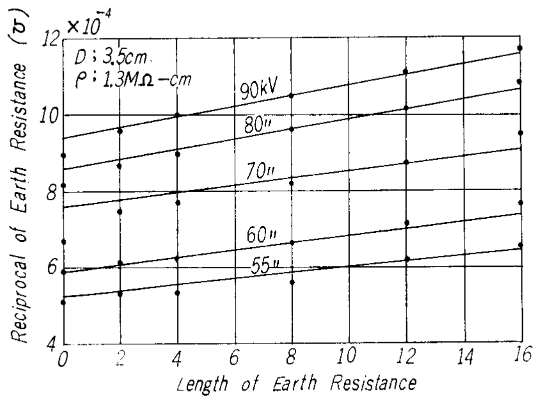


Fig. 1-18. Earth resistance of spherical electrode equipped with one needle (VI).

Then there are many methods for description about the effect of needles, but Eq. 1–3 (b) is most simple, and applicable over a wide range of applied voltage. While, in the relation of Eq. 1–4 (b), the resistance value of earth electrode (R_i) is directly plotted in semi-log. graph, avoiding the calculation of the reciprocal of earth resistance or equivalent radius from measured value.

For instance, the data of Figs. 1–9 and 10 are shown is Figs. 1–15 and 16, by Eq. 1–4 (b), where the curves are concave in low voltage. R_{i0} and r_{i0} in Eqs. 1–3 (a) and (b), are investigated by many research workers, and described as a function of applied voltage, size and form of electrode, and earth resistivity. The length of needle (l) is also known. After all, the problem to be studied is the determination of k_1 or k_2 as a function of applied voltage and etc., by experiments.

(b) Earth resistance in the earth of high resistivity (clay)

The experiments described above were performed in the earth of low resistivity (ρ; 10.5~46.6 kΩ-cm), while clay of high resistivity (ρ; 1.3~10 MΩ-cm) is chosen here as a specimen of soil. For a propagation of large streamer, the soil vessel of a large diameter (300 cm) has been equipped. The center electrode and needle are the same as in the previous sections and the crest value of applied voltage is 50~150 kV. The result of the experiment is shown in Figs. 1–17 and 18 by means of Eq. 1–3 (b). From these results, it is evident that in spite of earth resistivity, the relations of Eqs. 1–3 (a) and 1–3 (b) always hold.

(c) Earth resistance of ring electrode

In the test described above, spherical electrodes have been used, while a ring electrode equipped symmetrically with two needles shown in Fig. 1–19, is used here. The earth resistance of this electrode is shown in Fig. 1–20, consequently Eq. 1–4 (b) holds here also. These results suggest that Eq. 1–3 holds not only in a spherical or ring electrode but also in an arbitrarily formed electrode.

(d) Variation of earth resistance against diameter of spherical electrode and against earth resistivity

Constant k_2 in Eq. 1–3 (b) is a function of the diameter of the center electrode (D) and earth resistivity (ρ). To investigate the characteristic of k_2, the earth resistance with various ρ and D is measured, and from the results of this measurement, the variation of k_2 with D is calculated and compiled in Table 1–1. Consequently constant k_2 increases with increasing D for comparatively small value of D. After k_2 reaches a maximum value, it decreases with increasing D.

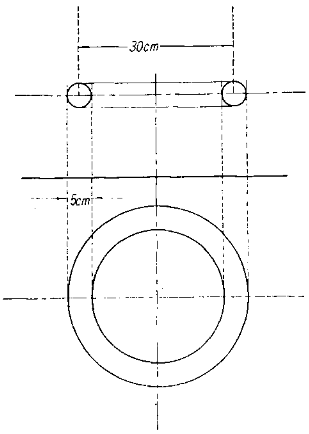


Fig. 1-19. An example of ring electrode.

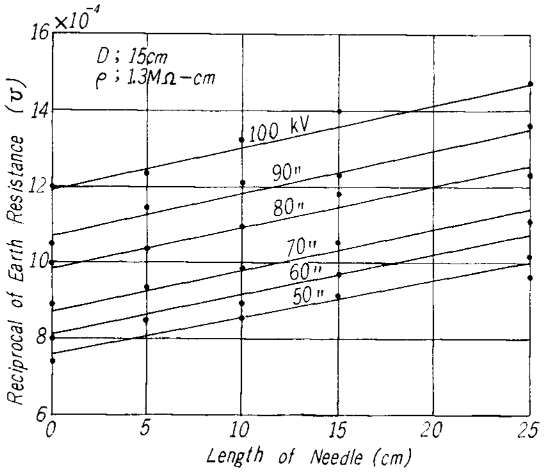


Fig. 1-20. Earth resistance of ring electrode equipped with needles.

Table 1-1. Value of k_2 (m℧/cm) (Spherical electrode).

D (cm)		3.5	5.0	8.0	10.0	15.0
k_2	ρ: 61.7 kΩ-cm	0.58	*	0.68	0.68	0.68
	″ : 160.0 ″	0.53	0.75	0.70	0.65	0.58
	″ : 270.0 ″	0.65	1.05	0.97	0.84	0.80
	″ : 1300.0 ″	0.83	0.92	1.06	1.17	0.83

*: Not measured and so forth.

(e) Earth resistance with diameter of ring electrode

By the same method as term (*d*), the effect of needles attached to the ring electrode is measured, and from this result k_2 about the ring electrode is calculated and compiled in Table 1-2.

Table 1-2. Value of k_2 (m℧/cm) (Ring electrode). ρ : 54.7 kΩ-cm

D (cm)	15	20	25	30	35
k_2	0.53	0.47	0.42	0.37	0.35

4) Mean Propagating Velocity of Streamer from Earth Electrode Equipped with One Needle

By means of an intermediate electrode described in the preceding paper, the time required for a streamer to reach the internal electrode from the center electrode is measured and compiled in Table 1-3. It is evident from

Table 1-3. Time for propagation of streamer. D: 3.5 cm, ρ: 20 kΩ-cm

	T_f (μS)	1.0	1.5	3.0	6.0
Applied voltage 68 kV	needle 0 cm	6 μS	7 μS	11 μS	14 μS
	" 1 "	2.4 "	3.0 "	5 "	8.6 "
60 "	" 0 "	15.0 "	*	13 "	16.0 "
	" 1 "	4.0 "	4.0 "	5 "	8.4 "
52 "	" 0 "	18.0 "	20.0 "	20.0 "	*
	" 1 "	9.0 "	12.0 "	20.0 "	23.0 "

Diameter of intermediatd electrode: 20 cm

the table, that the propagating velocity of a streamer started from an electrode equipped with one needle of 1.0 cm length is about twice as much as that of a streamer from a needle-less electrode. In this test, the length of the needle is restricted by the diameter of the internal electrode, but if it is not restricted, the propagating velocity of the streamer may become larger than this result. Increasing the propagating velocity of the streamer is also effective in hastening the reducing effect of the resistance.

5) Consideration About Earth Resistance of An Electrode Equipped with Needles

The earth resistance of an electrode equipped with needles against an impulse currents may be theoretically calculated by the following equation.

$$\frac{1}{R_{iol}} = \frac{1}{R_{io}} + \frac{1}{R_{il}} - \frac{1}{R'_{il}} \tag{1-5}$$

where R_{iol}; earth resistance of an electrode equipped with needles against an impulse voltage

R_{io} ; earth resistance of a needle-less electrode against an impulse voltage

R_{il} ; earth resistance of a needle only against an impulse voltage

R'_{il}; mutual effect between an original electrode and needles

Comparing to Eq. 1-3(b), yields following equation,

$$\frac{1}{R_{il}} - \frac{1}{R'_{il}} = k_2 l \tag{1-6}$$

On the other hand, the percentage of the increment of the earth conductance due to needles attached to the electrode, indicates the effectiveness of the needle, then,

$$\epsilon = R_{i0}\left(\frac{1}{R_{i0l}} - \frac{1}{R_{i0}}\right) \tag{1-7}$$

In the above equation, since it is evident from experimental result that R_{i0} decreases as the applied voltage increases and (k_2l) is approximately constant against applied voltage, ε decreases as the voltage increases.

II. Earth Resistance of Concrete Electrode

1) Introduction

A concrete foot of a line tower contributes to the reduction of the footing resistance, as is generally known. As the tower foot is deeply driven in and contacts widely with the earth, it becomes a good driven earth rod, if the concrete becomes conductive containing a little mixing material. For this purpose, the electrical and mechanical properties of the concrete containing a little conductive or semi-conductive material is investigated.

2) Concrete Electrode

The earth electrode in this test is composed of a center copper electrode and a hemispherical concrete block in its vicinity as shown in Fig. 2-1. This electrode imitates electrically the concrete foot of a tower. The mixing proportion of this concrete is compiled in Table 2-1.

As mixing material, powder of charcoal, oxide iron, barium titanate, graphite or common salt are used, and the concrete is cured in water for two weeks, and dried in the air for two weeks, then the age of the material is four weeks.

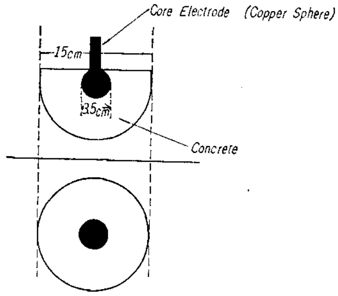


Fig. 2-1. Concrete electrode.

Table 2-1. Mixing proportion of concrete.

Cement	Sand	Gravel	Water	α**
1	2	4	0.6	0~0.4

** Note: α is ratio of weight of mixing material to one of cement.

3) Measurement Result of Earth Resistance of Concrete Electrode

The concrete electrode, above dercribed, is arranged in the center of a soil vessel, then an impulse voltage of 60~120 kV crest value is applied to this electrode. The result of the test is shown in Figs. 2-2~7. From these results, it is evident that the earth resistance against an impulse voltage varies due to the kind and quantity of the mixing material.

When the reducing percentage (D_α) is defined by the following equation 2-1, the characteristics of many kinds of concrete electrodes can be indicated

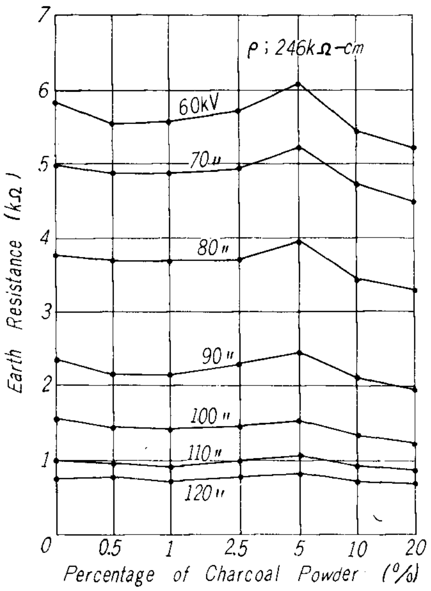


Fig. 2-2. Earth resistance of concrete electrode containing charcoal powder.

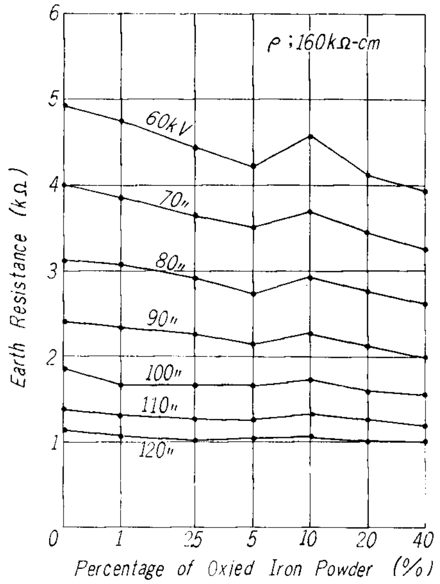


Fig. 2-3. Earth resistance of concrete electrode containing oxide iron powder.

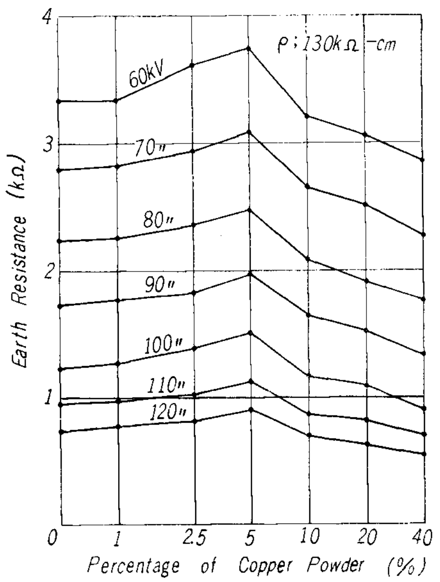


Fig. 2-4. Earth resistance of concrete electrode containing barium titanate powder.

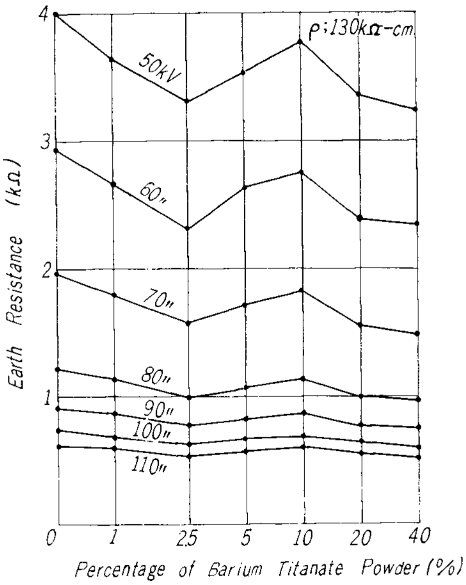


Fig. 2-5. Earth resistance of concrete electrode containing copper powder.

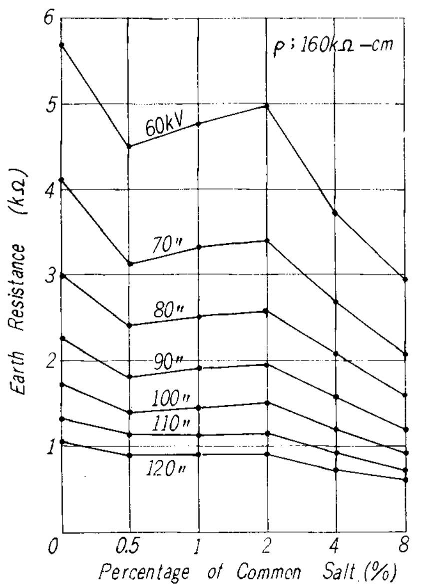


Fig. 2-6. Earth resistance of concrete electrode containing common salt.

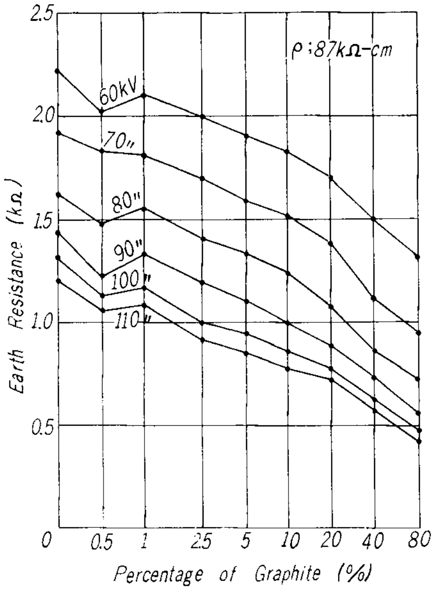


Fig. 2-7. Earth resistance of concrete electrode containing graphite.

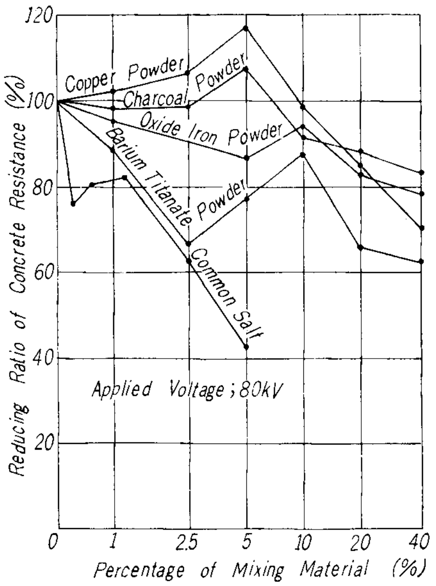


Fig. 2-8. Reducing ratio of concrete containing various mixing material.

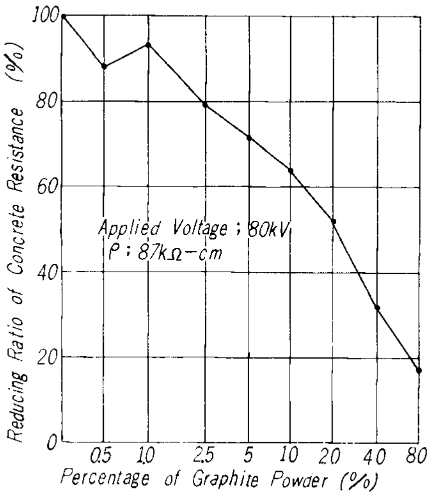


Fig. 2-9. Reducing ratio of concrete containing graphite powder.

together and compared with each other independently of the applied voltage and earth resistivity (ρ) in the vicinity of the concrete electrode.

$$D_\alpha = \frac{R_\alpha - R_m}{R_0 - R_m} \times 100\,(\%) \tag{2-1}$$

where R_α ; earth resistance of concrete electrode of mixing percentage α against an impulse voltage

R_0 ; earth resistance of concrete electrode without mixing material against an impulse voltage

R_m; earth resistance of copper spherical electrode of 15 cm diameter against an impulse voltage, where the diameter of concrete electrode is 15 cm, too

The measurement result of D_α is shown in Fig. 2-8, and the effect of graphite is remarkable as shown in Fig. 2-9. As it is evident from these graphs, graphite has the greatest effect, and common salt and barium titanate come next. These phenomena may be due to the fact that these substances have large conductances or dielectric constants.

The resistivities of these concretes for 60 c/s a.c. are measured by the circuit shown in Fig. 2-10 and compiled in Table 2-2. They have little difference between each kind of concrete though resistances against an impulse voltage have much difference. They are lower than the earth resistivity against a.c., but, against an impulse voltage, the resistances of concretes are

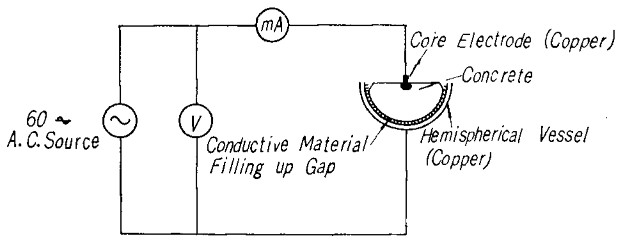


Fig. 2-10. Circuit measuring concrete resistivity.

Table 2-2. Concrete resistivity (kΩ-cm)

Kind of mixing material	α (%)	Resistivity	Kind of mixing material	α (%)	Resistivity
Charcoal	0	73	Oxide iron	2.5	92
"	2.5	71	"	20	77
"	20	85	Barium titanate	5	73
Copper	10	70	"	40	80
"	40	90	Common salt	4	60

higher than that of earth. The reason why resistance of concrete against an impulse voltage is much greater than resistance of earth against a.c. is that the electric breakdown intensity of concrete is about 10 times as much as one of the earth, so that the propagation of a streamer in concrete is more difficult than in earth.

4) Breakdown Field Intensity of Concrete

An impulse voltage is applied to the electrode in the circuit shown in Fig. 2–10, and the critical field intensity of concrete breakdown is obtained by the minimum breakdown voltage. Assumption that the streamer in concrete extends itself spherically and concentrically to the center copper electrode and the radius of this discharge space is r cm, yields

$$g = \frac{V_0}{r(1-r/r_a)} \tag{2-2}$$

where g ; electric field intensity on surface of hemispherical discharge space
r_a ; radius of concrete block
V_0 ; applied voltage

The critical breakdown field intensity (g_B) of concrete is as follow

$$g_B = g\left(r = \frac{r_a}{2}\right) = 4\frac{V_0}{r_a} \tag{2-3}$$

The result of measurement is compiled in Table 2–3 where r_a is 7.5 cm. According to this result, the breakdown field intensity of various kinds of concrete is 20∼30 kV/cm.

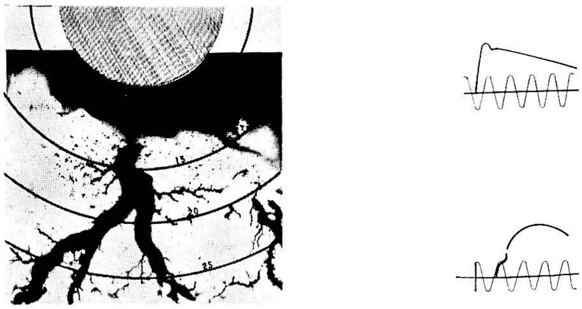
Table 2-3. Breakdown of concrete electrode.
V_B : Breakdown voltage (kV)
g_B : Electric field intensity of breakdown (kV/cm)

	%	0	0.5	1.0	2.5	5	10	20
Charcoal	V_B (kV)	28	41	32	20	20	20	25
	g_B (kV/cm)	14.9	21.8	17.1	10.7	10.7	10.7	18.7
Oxide iron	V_B (kV)	28	34	23	*	32	14	28
	g_B (kV/cm)	14.9	18.3	12.2		17.2	7.5	14.9
Barium titanate	V_B (kV)	28	45	70	60	70	70	*
	g_B (kV/cm)	14.9	24.0	37.3	32.0	37.3	37.3	
Copper	V_B (kV)	30	27	28	38	30	18	28
	g_B (kV/cm)	16	14.4	14.9	20.2	16.0	9.6	14.9
Common salt	V_B (kV)	30	37	24	27	24	50	*
	g_B (kV/cm)	16	19.7	12.8	14.4	12.8	26.6	

5) Streamer Propagation from Concrete Electrode in the Earth

(a) Figure of streamer around the concrete electrode

As described in the preceding section, it is recognized that the footing resistance of a tower has the decreasing effect against impulse currents. This phenomenon occures due to the fact that the streamer propagating in the concrete goes into the earth. By means of an embedded film described in the preceding paper, the streamer leaving from a concrete electrode is observed as in Fig. 2-11 (a), and the wave form of the voltage and current corresponding to this streamer is obtained as in Fig. 2-11 (b), where the current leaps at the moment when the streamer goes out of the concrete.



(a) Streamer growing from concrete electrode

(b) Wave form of impressed voltage and current

Fig. 2-11. Image of streamer and leap of current.

(b) Propagating velocity of streamer in the concrete

As the electric breakdown field intensities of concrete and earth are 20~30 kV/cm and 2~3 kV/cm respectively, the electric breakdown of concrete is more difficult than that of earth. Therefore, the propagating velocity of a streamer in concrete is less than in earth.

The leap of the current in Fig. 2-11 (b) indicates that the streamer goes

Table 2-4. Propagating velocity of streamer in concrete (cm/μS)
V: 105 kV ρ: 130 kΩ-cm

Mixing material \ α (%)	1.0	2.5	5.0	10.0	20.0	40.0
Charcoal	0.85	1.36	1.43	1.43	0.90	*
Oxide iron	1.43	1.43	0.72	1.43	1.14	1.43
Mixing material \ α (%)	**0**	**0.6**	**1.0**	**2.0**	**4.0**	**8.0**
Common salt	1.43	0.57	1.27	1.14	*	*

out of the concrete. By this phenomenon, the mean propagating velocity of a streamer in concrete can be measured. The result of measurement in this experiment is compiled in Table 2-4, and after all, the velocity of a streamer in concrete is one tenth of that in earth.

6) Concrete Electrode Equipped with Needles

As shown in Fig. 2-12, several needles are attached symmetrically to the center copper sphere of a concrete electrode, in order to imitate the concrete

Number of Needles	Its Position
1	A
2	B (X—X)
2	C (Y—Y)

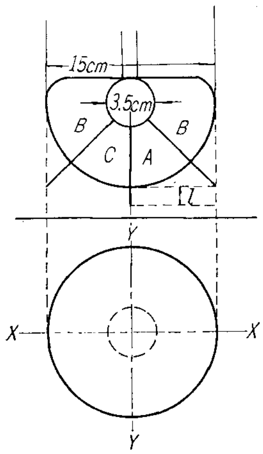


Fig. 2-12. Construction of concrete electrode equipped with needles.

block equipped with an earth angle of a tower foot. In this test, the earth resistance of this electrode is measured against the number and length of the needles.

The mixing proportion and curing of concrete are the same as in the preceding section and there is no mixing material. The results of measurement are as shown in Fig. 2-13. One needle extended from the center electrode to the surface of concrete decreases the earth resistance to 40%, and more needles have approximately the same effects as one needle, especially in a high applied voltage.

If only one needle varies its length out of concrete, the earth resistance is as shown in Fig. 2-14. By the same way as in the preceding chapter, the

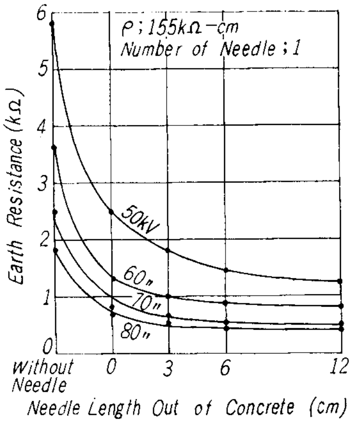


Fig. 2-13. Earth resistance of concrete electrode equipped with one needle.

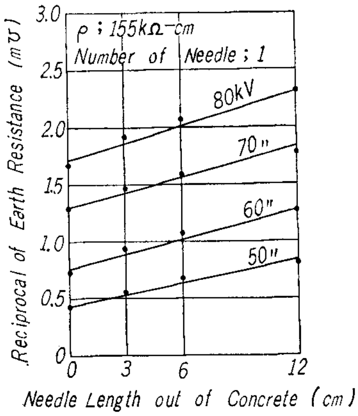


Fig. 2-14. Earth resistance of concrete electrode equipped with one needle.

reciprocal of the earth resistance taken as the ordinate in the graph makes a group of parallel lines to the length of the needle taken as an abscissa. Then,

$$\frac{1}{R_{cl}} = \frac{1}{R_{c0}} + k_c \cdot l \tag{2-4}$$

where R_{cl}; earth resistance of concrete electrode equipped with needles
R_{c0}; earth resistance of concrete electrode without needle
k_c ; constant determinated by conditions
l ; length of the needle out of concrete

7) Mechanical Strength of Concrete Contained Mixing Material

For the sake of testing the mechanical strength of the concrete containing mixing material, cylindrical concrete blocks of 15 cm diameter and 30 cm height, are made according to the Japan architechtural standard and are cured in water for two weeks, and dried in the air for two weeks, and the compression strength of this test piece is measured by Amsler type com-

Table 2-5. Compression strength.

i) one week age, curing in water 5 days (kg/cm²)

Mixing material \ (%)	0	0.5	1.0	2.5	5.0	10.0
Charcoal	154	170	158	159	157	168
Oxide iron	—	158	181	179	183	178
Copper	—	156	158	146	154	156
Barium titanate	—	135	166	174	163	162

ii) 4 weeks age, curing in water 21 days (kg/cm^2)

Mixing material (%)	0	0.5	1.0	2.5	5.0	10.0
Charcoal	250	272	280	267	223	239
Oxide iron	—	226	240	221	226	227
Copper	—	236	231	252	258	245
Barium titanate	—	237	236	242	253	243
Graphite	—	270	271	275	277	276

Mixing material (%)	0	0.5	1.0	2.0	4.0	8.0
Common salt	248	232	235	221	222	201

pressive testing machine. The result of this measurement is obtained as Table 2-5. It is evident from this result that mixing material gives little effect to mechanical strength of the concrete.

III. Conclusion

The experimental results described above are summerized as follows:

(1) An impulse voltage has been applied to the earth electrode equipped with or without needle, then the figure of the streamer on the embedded film is observed as follows:

(a) In the case where the applied voltage is sufficiently low, the streamer in the earth does not propagate from both electrodes. Therefore the needle has no effect in this case.

(b) In the case where the applied voltage is sufficiently high, approximately equal streamers propagate from both electrodes, and there is no difference between both electrodes. Therefore the needle has no effect also in this case.

(c) In the case where the applied voltage is in the intermediate range, a streamer propagates only from the electrode equipped with needles, so that the effect of the needle is observed evidently, and the reducing effect of earth resistance by the needle becomes clear.

(d) An elongation of the needles spreads the range of voltage where needles are effective concerning the phenomenon of reducing the earth resistance.

(2) Measurement of the earth resistance of an electrode equipped with a needle leads to the following results:

(a) By an elongation of the needle, the reducing effect of earth resistance appears more quickly and intensively and the formula describing the phenomenon is shown by Eq. (1-3).

(b) The effect of needles varies according to the shape and magnitude of the electrode, but Eq. (1-3) holds for many cases by varying the constant k_1 or k_2 in the equation.

(c) When earth resistivity is low, the function of the needle becomes more effective.

(d) With a steeper wave front and a longer wave tail, the function of the needle becomes more effective.

(3) By means of an intermediate electrode formed like a shell, the propagating velocity of a streamer started from the electrode equipped with a needle is measured. By the measurement, generally speaking, it is concluded that the velocity is twice as much as that of the streamer from the needle-less electrode.

(4) The conductivity of concrete against an impulse voltage increases by containing a little mixing material. As mixing material, graphite is the most effective, and by mixing it by an amount which does not affect the mechanical strength of the concrete, the resistance of the concrete decreases to 50%.

(5) When an impulse voltage is applied to a concrete earth electrode which contains a copper electrode in its center, the current leaps discontinuously after $2\sim3\,\mu S$ of the wave front. Observation by an embedded film shows that this leap of current is due to the penetration of the streamer from the concrete to the earth.

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