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ELECTRICAL HARDENING OF CLAYS ADJACENT TO ALUMINUM FRICTION PILES

M G SPANGLER, *Research Professor of Civil Engineering, Iowa State College* AND HARRY L. KING, *Construction Engineer, Lytle-Green Construction Company, Anchorage, Alaska*

SYNOPSIS

The paper reports the results of a small scale laboratory study directed toward the determination of certain facts relative to the L. Casagrande method of electro-chemical stabilization of soils in the vicinity of aluminum or aluminum sheathed friction piles The specific objectives of the tests were to determine the relationship between the clay content of the soils in which model piles were driven, the maximum increase in bearing capacity of the piles and the optimum amount of electrical treatment to produce maximum bearing capacity. An attempt was made to study the relationship between the type of predominate clay minerals in the soil and the above factors, but the results of this part of the work were inconclusive.

A series of ten pairs of model piles consisting of ½-in dia aluminum alloy rods were driven in various soils contained in waterproof boxes Each pair of piles was spaced 7 in c to c. and was driven 16 in. into the soil The soils were mixtures of various materials and ranged in two-micron clay content from 2 8 to 48 percent. Half the soils were montmorillonitic and half were kaolinitic. The soils were kept saturated throughout the tests by maintaining a layer of water about ½-in. deep over the soil.

After the piles were driven, initial bearing capacity of each of the piles was determined. Then a direct current of electricity was passed from one pile of a pair to the other and the amount of current and the voltage were measured. During the period of electrical treatment, measurements of the bearing capacities of the piles were made at frequent intervals It was found that the bearing capacity in all cases increased to a maximum value as treatment progressed

and that further treatment beyond this optimum amount caused a marked decline in bearing capacity

It was found that both the maximum bearing capacity and the optimum treatment increased as the amount of two-micron clay content of the soils increased Also, the optimum treatment was, in every case, greater for the negative electrode piles than for the positive electrode piles However, there was no definite relationship between the maximum increase in bearing capacity and the polarity of the piles

After the electrical treatment was discontinued, the piles were pulled from the soil It was found that the soil adjacent to the piles was impregnated with a substance which appeared to cement the soil grains together and which probably accounted for the increase in bearing capacity of the piles Also, a white powdery substance had formed at the surfaces of the piles and appeared to have reduced the skin friction between the piles and the adjacent stabilized soil in the later stages of treatment A cylindrical mass of soil adhered to a few of the negative electrode piles All of the piles were extensively corroded as a result of the treatment.

Stabilization of foundation soils by application of electrical energy has been demonstrated to have considerable practical significance by the research work of Dr. Leo Casagrande (*1*)[1], (*2*), (*3*) during the past 15 or 20 years, although there are many aspects of the various phenomena involved, concerning which very little is known This paper reports the results of a series of laboratory tests on small-scale aluminum alloy friction piles which were designed to throw additional light upon Casagrande's electro-chemical soil hardening process. Particular attention has been directed toward a study of the amount of electrical treatment required to produce maximum increase in pile bearing capacity and the relationship between maximum bearing capacity, optimum treatment and the clay content of the soil. The results of this study are, of necessity, only qualitative in character since small-scale models were used and no convenient method of applying the results quantitatively to prototype piles is available.

REVIEW OF LITERATURE

Leo Casagrande's studies in electrical soil stabilization have been directed along two principal lines, electro-osmotic drainage and electro-chemical hardening of soil Electro-osmosis is applicable to the problem of unwatering a relatively impervious soil in which the flow of water to well points or drains by gravity alone is very slow. It is primarily a physical process in which the soil water, which generally carries a positive charge, is attracted to a negative electrode and repelled from a positive electrode. Casagrande has used well points as negative electrodes in conjunction with steel sheet piling and steel rods as positive electrodes and thereby greatly increased the flow of water from the soil to the well points for removal by pumping. He has applied the process with good results to large excavations in connection with the construction of submarine pens at Trondheim, Norway; a deep railway cut at Salzgitter, and a tunnel in the Lerkendal Valley, both in Germany (*3*)

The electro-chemical method of strengthening soil consists of passing a direct current through the soil by means of two or more aluminum electrodes buried therein Laboratory tests on this process conducted by L. Casagrande (*2*) in 1930 showed that permanent stabilization of the soil was produced by using aluminum electrodes and that this effect was not obtained by using electrodes of other substances Metals other than aluminum, even with the aid of chemicals (such as aluminum salts), produced only temporary strengthening which was lost after slaking in water for a short time. On the other hand, soils treated in conjunction with aluminum electrodes remained unaltered during a slaking test which extended over 3 yr In all cases where aluminum electrodes were removed from the soil after treatment it was noted that they were strongly corroded, whereas other metals were not similarly affected Adjacent to the aluminum electrodes, insoluble salts were deposited in the soil, which appeared to cement the soil grains together Casa-

[1] Italicized figures in parathenses refer to the list of references at the end of the paper

grande believed that these salts were responsible for the strengthening of the soil. He also found that all clayey soils were suitable for electro-chemical stabilization and that strengthening took place about both electrodes Further model tests on the method were conducted by Erlenbach (*4*) in 1936, the results of which, in general, confirmed those obtained by Casagrande.

On the basis of the favorable results obtained in the model tests, Casagrande (*1*) undertook full scale tests in 1937. The location selected was near the Reichsautobahn in the vicinity of Chiemsee. It was favorable for the project because of the high compressibility and moisture content of the soil The site was covered with 8 to 12 in. of water. The nature of the soil was determined by borings to a depth of about 200 ft It was found to be a homogeneous clayey silt at all elevations down to this depth, except the upper 6 5 ft. which contained some humus Mechanical analysis indicated that the soil contained about 3 percent of 2-micron clay particles. The natural moisture content was slightly below the liquid limit

Six wooden piles about 1 ft. in diameter were driven to a depth of about 20 ft. The embedded length of each pile was sheathed with aluminum 1 mm thick held in place with nails. Three pairs of piles, spaced 4, 5 and 6 feet apart respectively, were tested. They were driven with a single acting steam hammer with moving parts weighing 3500 lb and a stroke of about 10 in All the piles penetrated about 6 5 ft under the dead weight of the hammer alone. During driving each pile penetrated about 12 in. per blow Loading tests conducted after driving indicated that the bearing capacity of the piles before treatment was between 7 and 9 tons per pile

The soil adjacent to the first pair of piles was treated by passing a direct current from one pile to another under a potential of 220 volts. The amount of current at this potential was from 40 to 60 amperes. Treatment was continued until about 1000 kilowatt hours of energy had been applied Later, treatment was resumed and another 100 kwh applied. The second pair of piles was treated in the same manner until about 260 kwh was consumed Next the second and third pairs of piles were connected in parallel and each pair was treated under 110 volts and about 25 amperes. The second pair received 60 kwh of additional treatment under these conditions or a total of 320 kwh. The third pair of piles received only 60 kwh of treatment Violent evolution of gas took place at both electrodes during treatment. Loading tests on the piles were made at infrequent intervals as the treatment progressed

In these full-scale tests, Casagrande noted that the bearing capacity of the piles increased up to a maximum value and then decreased as treatment was continued The average maximum strength of about 40 tons per pile was reached after about 30 kilowatt-hours of energy had been consumed. This unexpected result was confirmed by further model tests using the same soil and piles about 1 in in diameter and 16 in long (embedded length). The maximum strength in these model tests occurred after about 1.75 kilowatt-hours of treatment

After the full-size loading tests were completed, the piles were withdrawn from the soil. It was noted that the soil was firmly bonded to the aluminum sheath, and that only the soil near the piles was altered by the treatment. There was no apparent change in the soil at distances greater than 12 in from the pile surface. As in the model tests, it was noted that the aluminum was strongly corroded.

Casagrande (*2*) has reported large scale tests of this nature which were conducted by Grun and Bulfinger in 1938. Unfortunately, in these tests it was impossible to apply loads of sufficient magnitude to determine the full strength of the piles after electro-chemical treatment, and the tests were discontinued before the optimum amount of treatment had been applied. However, it may be concluded from the data presented that the strength of the piles was at least doubled

From the foregoing brief review of literature it is apparent that friction piles driven in soft clay can be materially strengthened by sheathing the piles with sheet aluminum and passing a direct electrical current through the soil from one pile to another or from one pile to a group of adjacent piles There are, however, many practical problems associated with the Casagrande process, concerning which very little is known, and much additional research plus extensive accumulation of experience data will be necessary before engineers can intelligently employ the process in the design and construction of pile foundations The tests reported herein (*5*) were designed to demonstrate the phenomenon of optimum treatment to produce maximum increase in pile bearing capacity and to determine the relationship between maximum bearing capacity and optimum treatment and certain properties of the soil, particularly the amount of clay in the soil and the predominate type of clay mineral in the clay fraction

MODEL TESTS

The model piles used in this series of tests consisted of ten pairs of aluminum[2] alloy rods ½ in in diameter and 24-in long Each pair of piles, spaced 7-in. center to center was driven into soil contained in a waterproofed wooden box whose inside dimensions were 8-in. by 12-in in plan and 19-in deep. The soil was placed in the box to a depth of 16-in and the piles penetrated 12-in. into the soil. The upper end of each pile, beginning at the soil surface, was painted with three coats of an oil base paint to insulate it from the standing water above the soil. Each pile was fitted at the top end with a pressed steel flange to which a 5½-in square wooden platform was attached with screws. Weights were placed on this platform to drive the pile into the soil and later to measure the bearing capacity of the pile.

Each of three of the boxes was filled with a natural soil; Edina silty clay loam subsoil, Thurman fine sandy loam subsoil and "Nevada"[3] clay The remaining seven boxes were filled with various mixtures of the Thurman and Edina soils and of Thurman and Nevada clay, in order to obtain soil mixtures having a wide range of clay content. The soils were thoroughly mixed and water was added to bring the moisture content above the liquid limit before they were placed in the boxes The soils were kept saturated throughout the tests by maintaining the water level above the soil surfaces. The properties of the soils and soil mixtures with respect to the percentage of various clay particle sizes, the type of predominate clay mineral, and the density at which they were placed in the boxes are shown in Table 1

TABLE 1

Soil and Box No.	Soil Mixture	Dry density of soil as tested pcf	Clay Content (%)			Predominate Clay Mineral
			5μ	2μ	1μ	
1	Edina silty clay loam	82.5	57.3	37.0	27.8	Montmorillonite
2	"Nevada" clay	87.4	65.0	48.0	30.8	Kaolinite
3	"Nevada" clay plus Thurman fine sandy loam	102.0	48.2	35.4	22.6	Kaolinite
4	"Nevada" clay plus Thurman fine sandy loam	104.0	31.8	23.1	14.8	Kaolinite
5	"Nevada" clay plus Thurman fine sandy loam	112.0	17.1	12.2	7.6	Kaolinite
6	Thurman fine sandy loam	124.0	3.9	2.8	1.7	Not tested Probably Montmorillonite
7	"Nevada" clay plus Thurman fine sandy loam	114.0	15.1	10.7	6.8	Kaolinite
8	Edina silty clay loam plus Thurman fine sandy loam	128.0	11.6	7.8	5.6	Montmorillonite
9	Edina silty clay loam plus Thurman fine sandy loam	94.5	27.5	19.3	14.3	Montmorillonite
10	Edina silty clay loam plus Thurman fine sandy loam	114.0	7.7	5.1	3.6	Montmorillonite

Each pile was driven into the soil by applying sufficient dead weight to the wooden platform to cause the pile to penetrate at a perceptible rate. When the desired penetration of 12-in was reached the weight was removed and the pile allowed to "set" before starting the electrical treatment During this period load tests were performed frequently until it appeared that the time effects generally associated with friction piles in cohesive soil had reached a state of equilibrium. For these and all subsequent load tests the "bearing capacity" of the piles was arbitrarily established

[2] The rods were aluminum alloy R317T.

[3] "Nevada" clay is a purely local term It refers to ground-up soft shale from the Nevada Brick and Tile Co. plant at Nevada, Iowa It has been used extensively in Ames and surrounding territory as a binder soil for stabilized gravel road surfaces.

as the maximum load which caused a pile to settle a distance of 0.01 mm in 30 sec. The driving load for each pile and the initial bearing capacity, that is, the bearing capacity at the end of the set period and before all electrical treatment was started, are shown in Table 2, along with the maximum bearing capacity developed by the pile and the optimum electrical treatment required to produce the maximum bearing capacity.

TABLE 2

Box No.	Positive Electrode Pile				Negative Electrode Pile			
	Driving load lb.	Initial bearing capacity lb	Optimum Treatment Amp-hr	Max. bearing capacity lb	Driving load lb	Initial bearing capacity lb.	Optimum Treatment Amp-hr.	Max. Bearing Capacity lb
1[a]	22	23	32	62.5	15	21.5	38	83.5
2	13	9	90	107	13	13	111	114
3	10	11	71	90	6	9.5	90	99
4	4	6	45	85	3	6	66	68
5	2	2.7	34	110.5	3	2.7	55	82
6	14	5.5	13	60.5	12	7.6	20	17
7[a]	21	5.8	34	126	33	5.8	37	179
8	3	2.5	30	39.5	4	2.5	38	51
9	1	2.0	36	57	1	2.6	59	50
10[a]	10	4.0	21	51	8	4.0	33	49

[a] Positive electrode piles in boxes No 1, 7 and 10 broke during test due to excessive corrosion

The model piles were connected with a source of direct current as shown in the wiring diagram in Figure 1. The power supply was drawn from the college light circuit of approximately 110 volt 60 cycle alternating current through a transformer which reduced the voltage, a full-wave rectifier which changed the alternating current to a pulsating direct current and a filter which changed the pulsating current to a steady direct current. A self-starting electric clock was placed in the power supply line to facilitate measurement of time during which treatment was applied. A variable resistance was introduced in the circuit to give the investigator control over the voltage across the pairs of piles.

As shown in figure 1, the ten pairs of piles were connected in parallel. With this arrangement the potential across each pair was the same and was measured by a voltmeter connected in parallel with the pairs. It was held to an average value of 20 volts throughout the tests. The current through each pair of piles was not the same, however, but depended upon the conductivity of the soil in which the piles were driven The current through each pair of piles was measured by means of a milliameter graduated to 0.01 ampere, but capable of being estimated to the nearest one or two milliamperes. The voltmeter was graduated to 0.2 volt. Photographs of the arrangement of the boxes and the power supply equipment in the laboratory are shown in Figures 2 and 3.

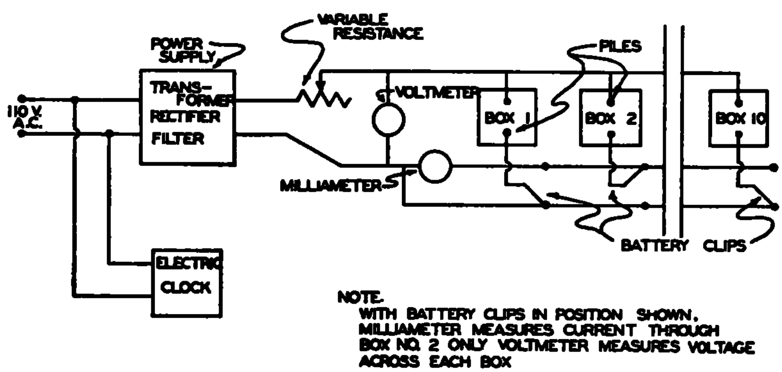

Figure 1. Wiring Diagram

After the current was turned on, the bearing capacity of each of the piles was measured at frequent intervals These observed bearing capacities are plotted against the amount of electrical treatment expressed both as kilowatt-hours of energy and as ampere-hours of electricity, and shown in Figures 4 to 13, inclusive. It will be noted that in the case of each soil used, there was a definite optimum treatment required to produce the maximum increase in bearing capacity of the model piles and that treatments beyond the optimum caused a marked and rapid reduction in bearing capacity. This finding was true of both the positive and negative piles and is in harmony with the results published by Leo Casagrande (*1*). One new fact in this regard, however, is revealed by these tests, namely that the positive piles attained their maximum bearing capacity at less amounts of treatment than the negative piles, whereas in Casagrande's published curves, the optimum amount of treatment is shown to be the same for both piles of a pair. However, his curves are based upon only a relatively few points and it is possible that this phenomenon was masked by the paucity of bearing capacity measurements.

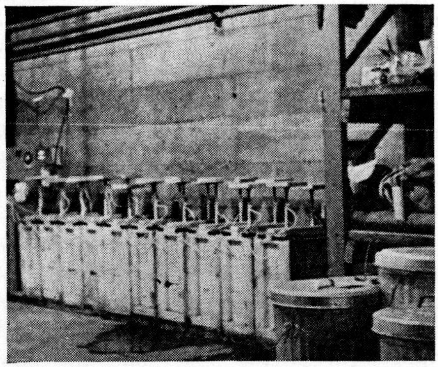

Figure 2. Arrangement of Boxes Containing Model Test Piles

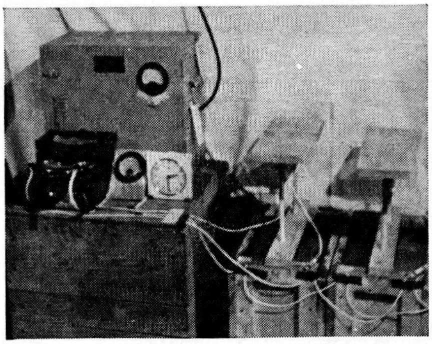

Figure 3. Power Supply Equipment for Model Pile Tests

A study of the optimum amount of electrical treatment to produce maximum increase in bearing capacity reveals a definite relationship between this quantity and the amount of clay material in the soil, as shown in Figure 14. Here the optimum amounts of treatment are plotted against the 2-micron clay content of the several soils. The 2-micron size was arbitrarily chosen for the study of this phenomenon. Similar plots using the 1-micron and 5-micron sizes revealed essentially the same kind of relationship.

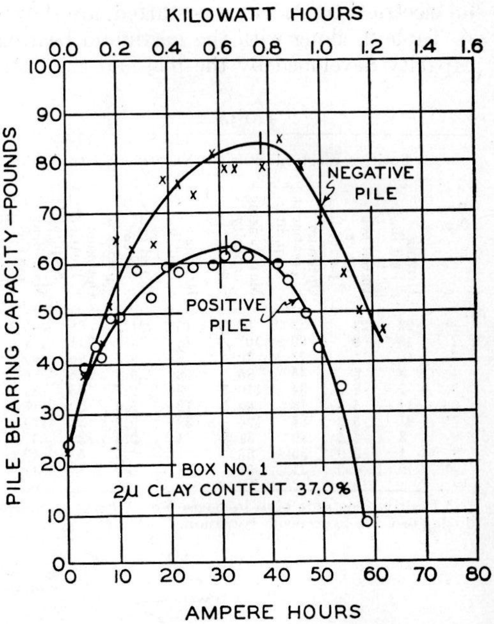

Figure 4

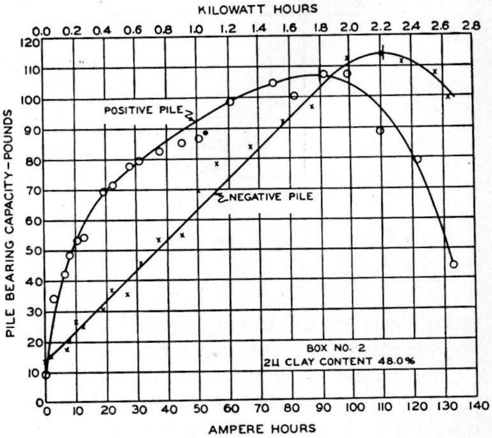

Figure 5

Also, it appears that the maximum bearing capacity developed by the piles is a direct function of the 2-micron clay content of the soil, as shown in Figure 15. Although the data shown in this figure are somewhat scattered, the trend toward increased maximum bearing capacity with increased clay content is fairly definite

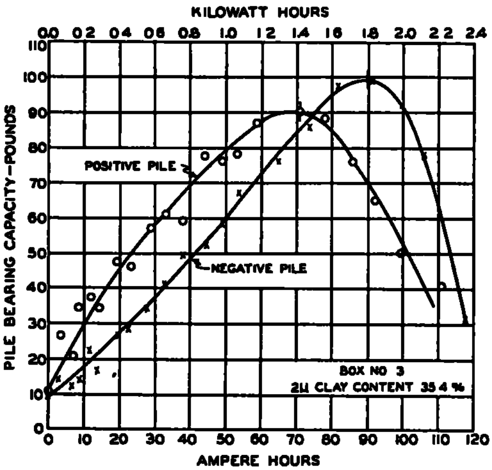

Figure 6

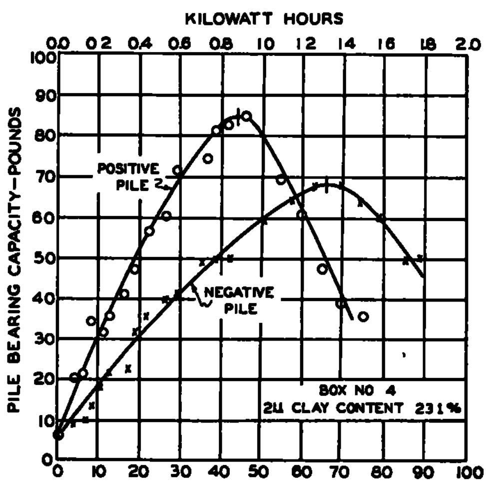

Figure 7

One of the objectives of these model tests was to study the influence of the predominate type of clay mineral in the soil upon the optimum amount of electrical treatment and the maximum bearing capacity of a pile As shown in Table I, half the boxes were filled with montmorillonitic soil and half with kaolinitic soil. The results of this phase of the study indicate, as a generalization, that the type of clay mineral in a soil does not materially influence the optimum electrical treatment or the maximum bearing capacity of piles, as shown in Figures 14 and 15. However, these results are not conclusive, particularly with reference to optimum treatment, since the data for box No. 1 containing 37 percent of 2-micron montmorillonitic clay indicates a relatively low value of optimum treatment as shown in Figure 14. Further information is needed

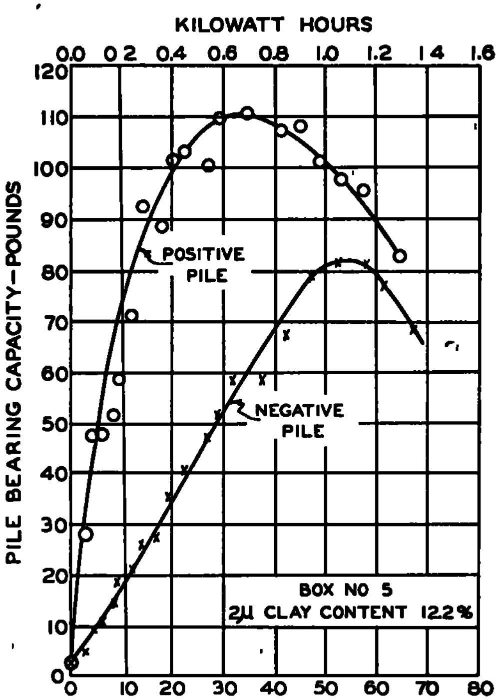

Figure 8

before a definite conclusion with reference to this relationship can be drawn

In the early stages of electrical treatment there was considerable evolution of gas at both electrodes in each of the boxes. This produced a disturbance in the water above the soil similar to boiling, and some colloidal material became suspended in the water In later stages of treatment, the evolution of gas gradually diminished and finally ceased, and the suspended matter was precipitated. Most of this precipitation occurred near the positive piles, causing a small mound of soil to form at these electrodes, while a crater developed at the negative piles. Also it was noted that the treatment caused fissures in the top surface of the soil which were at least $\frac{1}{4}$-in. deep. These fissures could not have been caused by simple drying, because the soil was kept covered by water at all times.

After completion of the electrical treatment, the piles were withdrawn from the soil

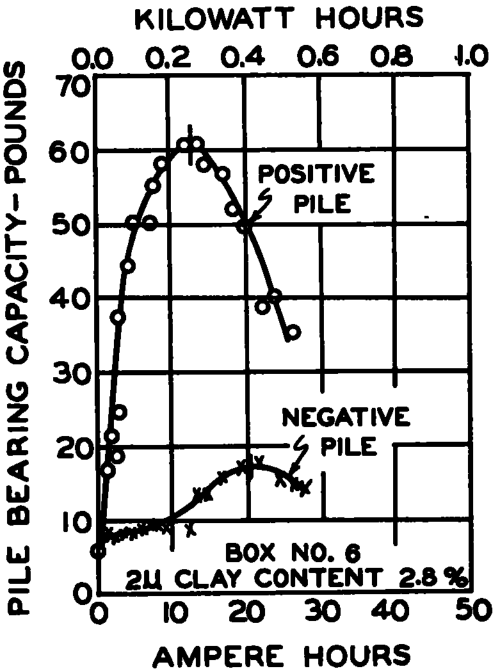

Figure 9

and examined. In all cases, they were very strongly corroded, and as has been noted, the positive $\frac{3}{8}$-in. diameter piles in boxes 1, 7 and 10 were corroded completely through at points a little below the soil surface. The corrosion of these model piles apparently was much more extensive than that of the sheet aluminum in the full scale pile tests described by Casagrande (*1*). The reason for this more extensive corrosion is not definitely known. It may have been due to the particular kind of aluminum alloy used, to differences in current density in the two experiments, or it may have been caused by the fact that in the Ames experiments, treatment was carried on to a considerable extent beyond the optimum treatment. In all cases the corroded rods were completely altered in character. The aluminum alloy appeared to have been changed to a hard black brittle substance which was formed

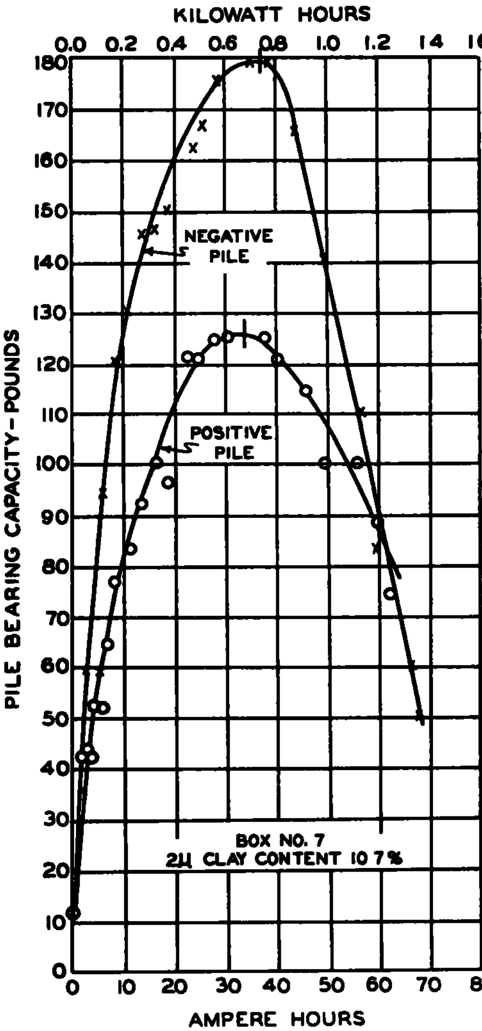

Figure 10

in concentric rings, much the same as the annular rings in wood.

In some cases a cylindrical mass of soil adhered to the negative piles when they were pulled, and in all cases the soil adjacent to both the positive and negative piles had been altered in character by impregnation with a substance which appeared to be the same as the insoluble salts described by Casagrande (*1*). The outside surface of the piles was coated with a friable powdery substance which turned white soon after exposure to the air, as indicated in the photograph in Figure 16 Previous investigators have observed a similar substance around treated piles which they found to be chemically the same as the mineral bauxite

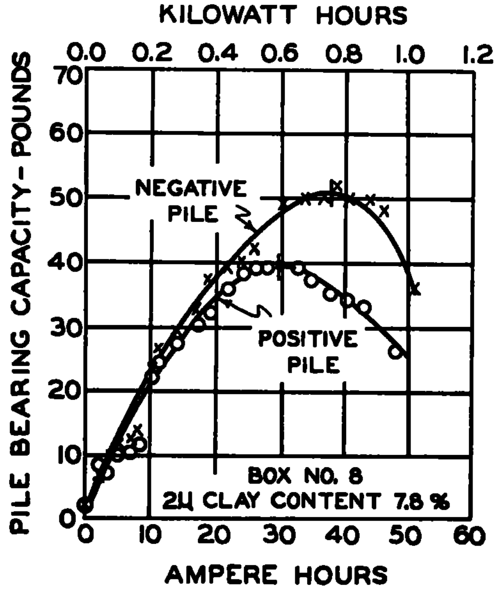

Figure 11

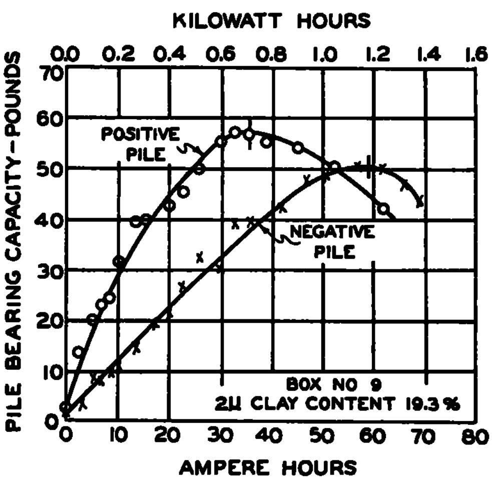

Figure 12

This white powdery substance at the outer surface of the piles appeared in some cases to have destroyed the skin friction between the pile surfaces and the surrounding soil which had been hardened by the electrical treatment Its presence gives rise to a possible hypothesis relative to the observed optimum treatment phenomenon, which is as follows· Early applications of the electrical treatment increase the bearing capacity of the piles by virtue of the fact that the adjacent soil is strengthened by the deposition of insoluble salts in the soil However, as treatment progresses, this white substance forms at the outer surface of the piles, causing a gradual reduction in the skin

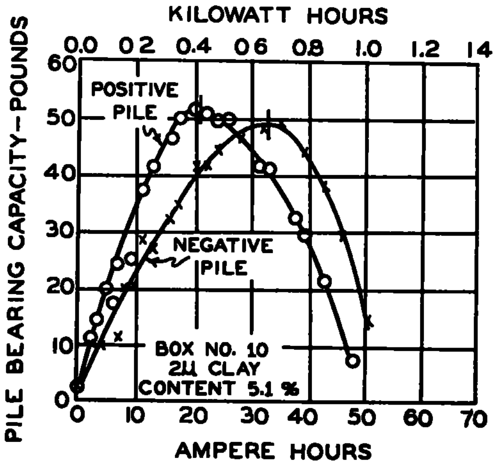

Figure 13

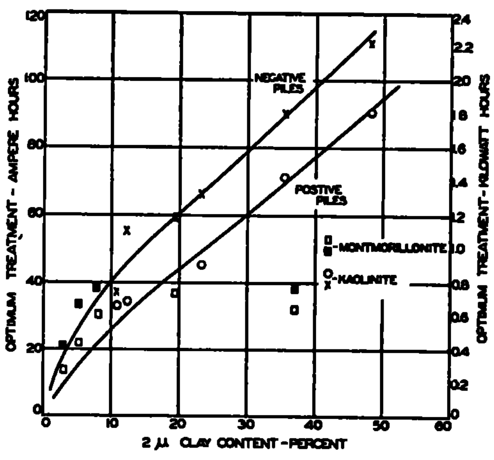

Figure 14

friction between the piles and soil. Finally, the reduction in skin friction is so great that it offsets the increase in soil strength, and

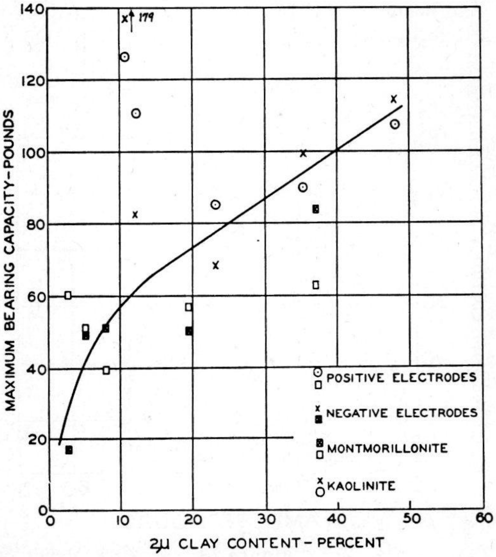

Figure 15

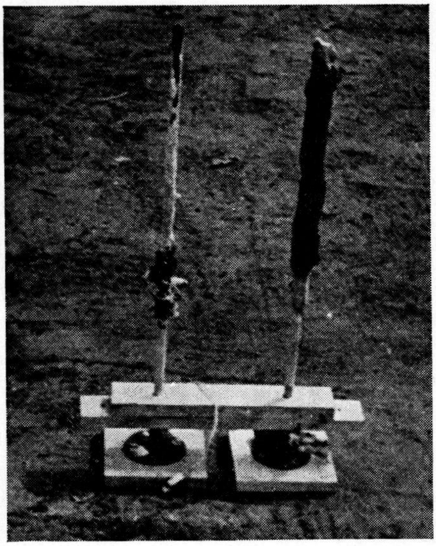

Figure 16. Piles From Box No. 4 After Treatment. Negative Electrode Pile on Right

when this occurs, the optimum effect of electro-chemical treatment has been reached. Further treatment causes further reduction in skin friction which is reflected in reduction of pile bearing capacity. This hypothesis is supported somewhat by the observation that when these model piles were pulled, the stabilized soil adhered to a few of the negative piles, but did not adhere to any of the positive piles. Since the optimum treatment for negative piles was in all cases greater than that for positive piles, the negative piles were not treated as far beyond optimum as the positive piles. Therefore the reduction in skin friction was relatively less and some of the soil adhered to these negative piles.

There is another hypothesis by which the decrease in pile bearing capacity as treatment is carried beyond the optimum amount may be explained. According to Kumutat (7), at least part of the beneficial effect of the Casagrande electrochemical treatment is caused by the action of the trivalent Aluminum ion on the colloidal soil particles which carry a predominantly negative charge. The general principles stated by Kumutat governing this type of reaction make it clear that the action of the aluminum ion would be beneficial only in the case of a negatively charged colloidal and would be harmful in the case of a positively charged colloidal. It is possible that the Casagrande process itself tends to reduce the negative charges on the colloidal soil particles to zero and recharge them with positive charges. If this is the case, one would expect, on the basis of Kumutat's theoretical principles, that the bearing capacity of the piles would increase with increasing treatment only as long as the soil colloids carried a predominantly negative charge. When the charge on the soil colloids became zero (iso-electric point) the bearing capacity of the piles should attain a maximum value. Subsequent to the iso-electric point, the pile bearing capacity should decrease. The variation of pile bearing capacity with the amount of electro-chemical treatment as would be predicted by this hypothesis has been observed in the laboratory. The investigation of the variation of the charges on the soil colloids with the amount of treatment is more within the field of the physical chemist than that of the civil engineer and such investigation was not undertaken in the Ames experiment. In regard to the possibility of a soil carrying a positive charge, it should be mentioned that positive charged soils are infrequently found in nature.

A case of this kind has been reported by Bernatzik (*1*).

RESULTS

The results of these model pile experiments verify the following conclusions of previous investigators:

(1) Both positive and negative electrode aluminum piles are strengthened by the Casagrande electro-chemical process.

(2) There is an optimum amount of treatment which causes the piles to attain a maximum bearing capacity. Treatment beyond this optimum causes a reduction in bearing capacity below the maximum.

(3) The process is applicable to clayey soils. In these experiments, pile bearing capacity was increased in a variety of soils in which the 2-micron clay content ranged from 28 to 48 percent.

(4) Electro-chemical treatment of the soil adjacent to aluminum friction piles is accompanied by extensive corrosion of the aluminum electrodes.

The experiments further warrant the following original conclusions:

(1) For piles of the same dimensions and spacing, the optimum amount of electrical treatment increases as the amount of 2-micron clay in the soil increases.

(2) The maximum bearing capacity attained by electrical treatment of soil adjacent to piles increases as the amount of 2-micron clay in the soil increases

(3) The optimum amount of treatment is greater for negative electrode piles than for positive electrode piles.

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