Electro-chemical Stabilization of Ground under Foundation

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Abstract

In this paper a summary is given of the principles of the electro-chemical stabilization applied to weak ground under foundation of structures, the reasons for the application, the design and the results of the practice.

1. Introduction

As a result of the investigation of the foundation ground made prior to the design and plan of the Mainichi Kaikan Building, it was discovered that a soft clay stratum exists to a depth of about 13 m below the foundation slab of the building.

Presuming that this stratum will have a grave effect on the settlement of the building after its construction, various measures of preventing the settlement were discussed and as a result the electro-chemical stabilization was finally applied.

Namely, after inserting electrodes into the soft stratum, direct current is swiitched on making the porewater in the clay move from the anode to the cathode. Thus an extraordinary increase is seen in the water pumped up from the well point made near the cathode and the consolidation of the weak clay stratum is expedited. At the same time the ground is hardened by the aluminum compound produced by the electrolysis of the aluminum used as the electrodes (This reaction does not react reversely). Compared with other foundation methods as piling foundation, this method was effective and economical because the cost was cut down and the period of construction shortened.

From the results obtained in the foundation ground of the abutment of the Atsuta-Tenma overbridge (Nagoya city) on the No. 1 National Highway and the foundation of the approach of the Minoru bridge (Okayama Pref.) on the No. 30 National Highway to which this method was applied previously and the results of the soil survey and preliminary experiments made concerning this building, it was confirmed that this method was advantageous. The outline of this method will be explained in the following.

2. Principle of this method.

When a pair of electrodes buried in saturated fine grained soil is connected to direct electric current, the following phenomena occur.

(1) Porewater flows to either one of the electrodes, with most soils to the cathode. This phenomenon is called electro-osmosis.

(2) Whith compressible soils, the volume usually decreases, but in some cases it increases. When the volume decreases, this is accompanied with the increase in the soil strength. This phenomenon is called electro-chemical hardening.

(3) Ions adherring to the surface of clayey minerals are exchanged with other ions existing in the porewater or brought by the electric current. This phenomenon is called base exchange.

(4) As a result of the electro-chemical resolution of the electrodes, metal salts fill up the gaps in the colloidal substance. Such metal salts sometimes react upon other free particles occasionally exsisting in the porewater or on the surface of the molecules. If the soil particles gather together as a result of this reaction, this is called electro chemical hardening.

When treating soils electrically, all these phenomena sometimes occur simultaneously. According to the kind of soil and metal material used as the electrodes. two or more of the above phenomena become useful in increasing the strength of the soil treated by this method. With the case explained in this paper, phenomena (1) and (4) are used mainly.

3. Summary of building and ground under foundation.

The building is the Mainichi Osaka Kaikan of which the reinforced concrete mat foundation is constructed at G.L.–12,300 m and the main structure is of reinforced concrete with 3 floors underground and 12 floors above (height of eaves G.L.+31,000 m, max. height G.L.+43,000 m). The building area is 321 tsubo (1 tsubo 3.3 m^2) and the total floor area 3,982 tsubo. The construction was started on July 18 th. 1954 and completed on June 30th 1956.

The situation of the building site is as follows. There is the Printing Bureau of the Osaka Mainichi Press (reinforced concrete structure, 1 floor underground and 3 floors above)on the east side, a 2 storied wood building on the opposite side of a road 8 m wide on the south side, Namboku Road of Osaka City on the west side and the Mainichi Press Building (reinforced concrete structure, 1 floor underground, 5 floors avove) on the north side.

Next, the outline of the foundation ground made clear by several holes bored in the building site is as follows.

A sandy stratum lies to a depth of about 10 m from the surface and then the first

clayey stratum (this is the stratum in problem) exists below this to a depth of about 25 m. This clay stratum is over 10 m thick and the nature of the clay becomes worse as it gets deeper.

A sandy and gravelly stratum about 13 m thichk lies below the first clay stratum and another clay stratum appears again from a depth of about 38 m. This clay stratum is also comparatively thick reaching to a depth of about 48 m and provides the 2nd problem.

A Sand and gravel stratum exists from 48 m to 71 m, clay stratum from 61 m to 83 m and then a gravel stratum below 83 m.

These strata seem to be distributed horizontally within the site of this building.

The natural underground water level is 1.9 m below the ground surface and it was found by the pumping test that a considerable amount of water exists in the sandy stratum down to a depth of about 8 m. Furthermore, the second underground water wihch has a comparatively large head, is recognized in the gravelly stratum 25～27 m deep.

4. Reasons for the application of this method.

In constructing a considerable large building as the Mainichi Kaikan in the soil condition such as mentioned above, the most trustworthy method is to drive piles or sink caissons down to the reliable soil stratum.

In the case of this building, if the bottom side of the foundation is assumed as being 12 m down from the ground surface, it is considered to have reached the upper part of the 1st clay stratum. Therefore, if the piling or caisson foundation method is adopted, it means driving piles or sinking caissons till they reach the gravel stratum about 26 m down from the surface. The settlement in this case which is effected by the soil below the 2nd clay stratum is assumed as being about 5 cm. However, to construct a sure foundation down in the gravel stratum existing 26 m from the surface which is considered as reliable will inevitably be very expensive in this case.

It is not always reasonable to defray an enormous sum of money in order to make a foundation allowing little or no settlement. The problems is the degree of the effect due to the settlement.

On the other hand, it can be considered to make a technical treatment of allowing the structure to sink without resisting against the universal settlement of the surrounding ground. In considering the case when the foundation of the buiding is made as a mat foundation on the premise of making an adequate technical treatment, the effect of the 1st clay stratum appears mostly in the settlement.

In this case the consolidation settlement and plastic flow settlement of the clay

Table 1. Time-Settlement Predictions

Settlement (%)	Time factor	Years	Settlement (cm)
20	0.03	0.45	4.6
30	0.07	1.05	6.9
40	0.12	1.80	9.2
50	0.20	3.00	11.5
60	0.29	4.35	13.8
70	0.41	6.15	16.1
80	0.56	8.40	18.4
90	0.85	12.70	20.7
93	1.00	15.00	21.4

stratum is considered as the main cause of the settlement of the building. Judging from the soil survey and calculation of the ultimate bearing power, there is no fear of the plastic flow settlement occuring in the case of this building. Consolidation settlement in the case of the mat foundation is calculated to become about 20～25 cm in 20～30 years. The change in the settlement with the elapse of time becomes as shown in Table 1.

The next problem is the occurrence of unequal settlement. The north east part of the new-building is adjoined with the old building and as the soil under the old building is considered as being settled, the tendency of declining to the south west is great when the new building is built. It is difficult to estimate this inclination. Supposing a difference of 10 cm occurs between the north and south ends, the slope of the length of 40 m in this direction is 10/4000=2.5/1000, from which there is actually no harm (among the buildings now existing, there are some already inclining about 10/1000, but an inclination of this degree is usually unperceivably). Moreover, it can be designed so that the effect of the unequal settlement on the main structure can be neglected.

Next, in considering the effect the settlement of the new building has on the old building, it was found that the old building is caused to incline slightly to the south west direction, but as the plan of the old building is of an L form and quite broad compared with the new building, it resist as a whole and no serious effect is recognized in the strength of the structure. Even if by any chance a crack due to unequal settlement should occur, it could be repaired at a low cost.

A comparison of the various methods of construction is as shown in Table 2.

Table 2. The Comparison of Methods of Foundation Construction

Type	Period*	Settlement**	Differential Settlement	Vibration and Noise During Construction	Expense***
Piling Foundation	about 3 months	about 5cm	little	much	50,000,000
Caisson Foundation	about 6 months	about 5cm	little	little	70,000,000
Mat Foundation	0	about 20～25cm	much	little	0

* Only for piling or caisson

** Consolidation of the 1st and 2nd clay strata

*** Rough estimation of the expense for piling or caisson, and extra expense due to the delay of the work is not included.

When the mat foundation is adopted, the cost is cut down and the period of the construction shortened if the building is allowed to sink. In this case, it is necessary to consider the following points in the design and execution of the work.

(1) To devise some means of expediting the consolidation settlement of the 1st clay stratum. For this purpose, the settlement mus be made to end as quick as possible by removing the water contained in the clay stratum by means of electro-chemical stabilization.

(2) To provide against unequal settlement due to slide caused by basement construction work in the neighbourhood and other unexpected causes, the inclination of the building should always be measured during the construction and if by any chance the inclination becomes greater than 10/1000, it should be arranged beforehand to control the unequal settlement by such methods as underpinning.

(3) Due to the difference in the settlement of the new and old buildings, a slight dislocation may occur at the joint, but as they are joined by a stairway, it can be repaired easily.

(4) The various pipes which are drawn in to the new building are apt to be cut at the junction by the settlement of the building, but this can be prevented by devising a proper expansion joint.

(5) The difference in the floor of the ground floor and the front street can be solved by slightly repairing the street if the elevation of the floor is properly determined in the design.

In view of the above points, the mat foundation was adopted taking into consideration the measures to be taken against the unequal settlement which might not occur. Furthermore, electro-chemical stabilization is applied to the weak ground in order to expedite the consolidation and strengthening of the ground and holes for underpinning were prepared in the foundation slab to provide against emergencies.

Even if the electro-chemical stabilization and underpinning were adopted together, there is no great difference in the cost compared to that of driving piles from the beginning and as the period of construction can be shortened about 2 months, the building can be utilized that much quicker. If underpinning becomes unnecessary, the cost of the foundation is very low compared with other construction methods. Thus, taking a twofold measure, two methods were prearranged for the construction of the foundation of this building and by making a careful observation and accurate judgement during the construction, the construction was stopped at any time it was considered that the foundation works were sufficient and the foundation was completed.

Such means were useful in constructing the necessary and sufficient foundation and the policy of this method may be explained as an experimental design and construction of an actual buliding which is the characteristic of this foundation design.

5. Design of this method.

In order to presume the various fundamental values necessary in executing the plan of this method, a preliminary experiment was performed using a 1/100 scale model. The principles are explained in the other report by the author, but the conclusions can be summarized as follows.

(1) Required electricity

If the electricity necessary to dispose of 1 m^3 of soil is 10 kWh, the total electricity required is 120,000 kWh as the total soil to be treated by this method is 12,000 m^3, the site of building being 40 m×30 m=1200 m^2 and the depth 10 m.

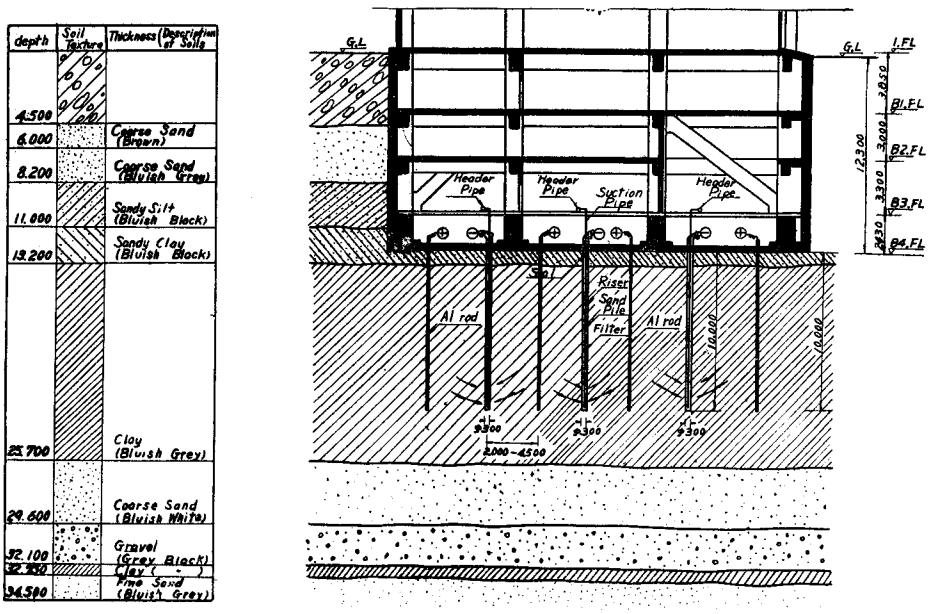

Fig. 1. General Sketch of Construction for Electro-Chemical Stabilization.

(2) Quantity of Al required.

Using 50 electrodes, the electricity for 1 electrode is 24,000 kWh. As 0.35 g of Al is extracted from 1 Ah, the Al per one electrode becomes 0.35 g×24,000=8400 g≒9 kg. For 50 electrodes the quantity becomes 9 kg×50=450 kg, but about 1 t (approx. 900,000 Yen) of aluminium is used considering various allowances.

(3) Period of electrification

Turning on the current 10 hours a day, a period of 6 months was planned. The method shown in Fig. 1 was adopted from the results of the preliminary experiments and the circumstance of the site. The various parts of the arrangement were as follows.

(1) Anode

An aluminium pipe of which the outer diameter is 50 mm, thickness 8 mm and

length 10 m and of purity of about 99% was used. A special care was necessary in manufacturing it and putting in into place. Photo. (1) is taken from diagonally above and the upper end of the anode is just seen and the wire are connected.

(2) Cathode

The cathode was of a sandpile structure 240 mm in diameter and 10 m deep and a steel pipe (4″) was inserted inside it as a water collecting pipe. Also a gas pipe (1″) was inserted inside the steel pipe as a suction pipe to which a vacuum pump was connected.

Photo. 2 was taken from obliquely above and the upper end of the cathode is just visible. The object projecting out at the center is the suction pipe.

(3) Arrangement of electrodes and wire connection.

The anodes were arranged to surround the cathodes, the distance between the anodes being 3～5 m. The 13 cathodes were divided into 7 groups

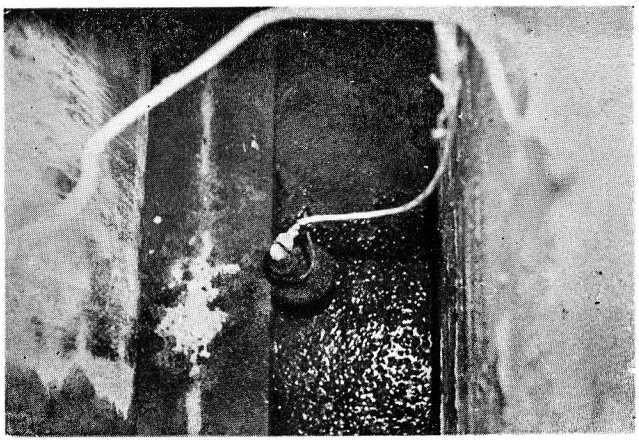

Photo. 1.

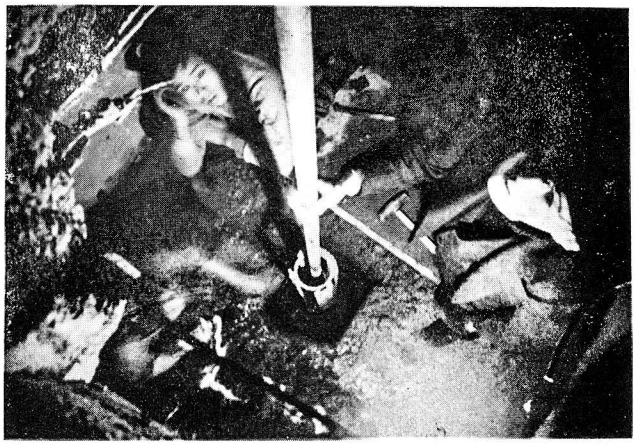

Photo. 2.

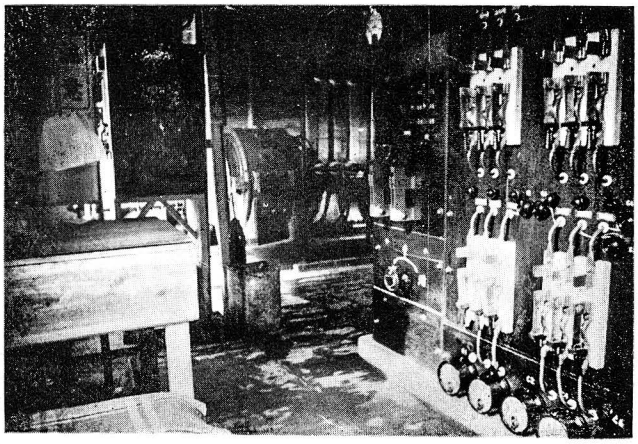

Photo 3.

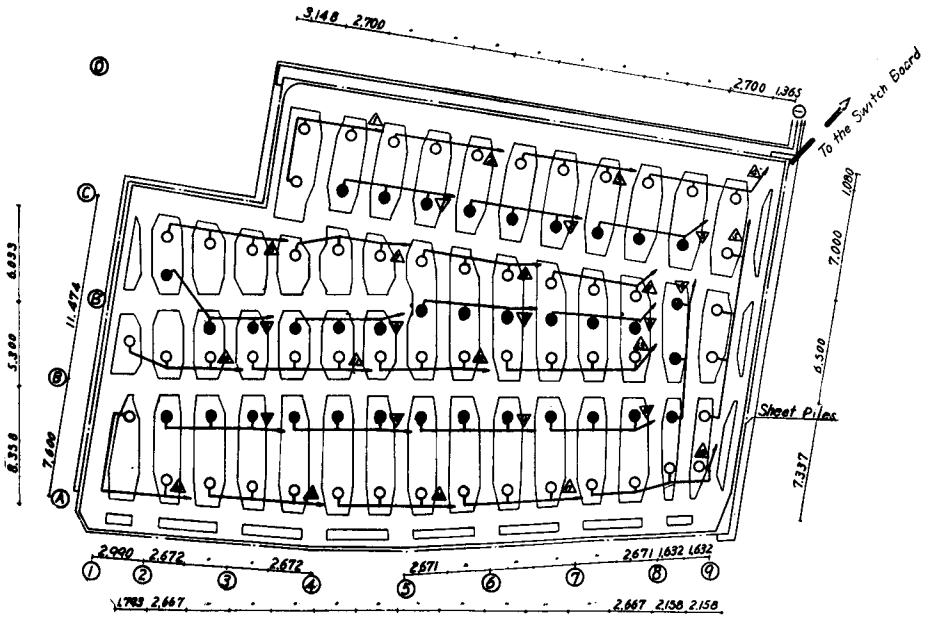

Fig. 2. The Arrangement of the Electrodes and Wire Connection.

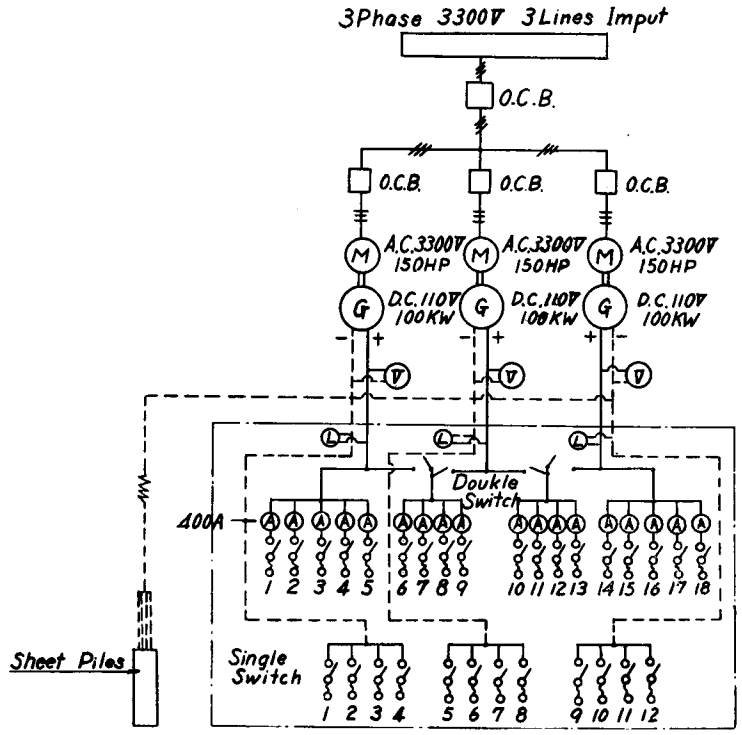

Fig. 3. Electric Power Supply and Circuit of Switch Boord.

and the 37 anodes into 9 groups and a separate connection made for each group (Refer to Fig. 2).

(4) Electric source and operation chamber.

As the electric source, a 75 kW direct current generator capable of adjusting the voltage was used. Various meters and a board indicating where the electric current is on are equipted together inside an operation chamber neat the site (Ref. Photo. 3; motor of direct current generator and switchboard are seen).

(5) Equipment for pumping up and draining water.

A vacuum tank is installed at a certain place on the 3rd floor. This is used as the main suction pipe and the suction pipes of the cathodes are connected to it with pressure durable rubber hoses. The vacuum pump to make the vacuum tank vacuum is automatically arranged to operate when the pressure becomes 500 mmHg and stope when the pressure rises to 650 mmHg by a vacuum switch. A gauge is fixed to the draining pipe so that the quantity of water pumped up can be measured which is one of the standards of knowing the effects of this method. The draining equipment used in the example stated before was not of such a large scale as this. Although the circumstances are extraordinary such as the 3rd floor of the building underground, this is neither a requisite equipment nor an original part of this method.

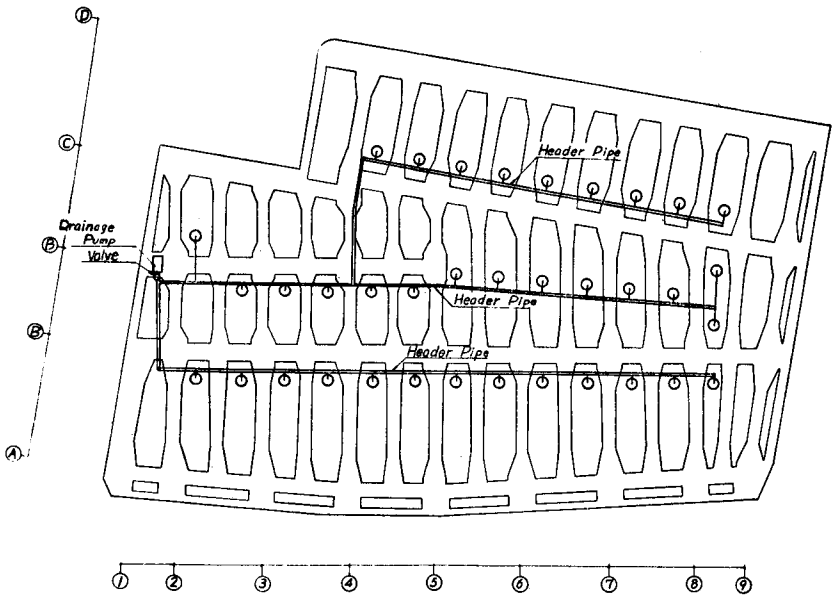

Fig. 4. The Set-up of the Cathode Suction Pipe.

(6) Ventilation equipment.

In order to ventilate the 3 floors underground, pipes and tempoprary ducts were used. Even if the particular circumstances of being 3 floors underground are taken into consideration, this equipment is not necessarily essential. A little hydrogen gas is, it is true, generated at the electrodes, but there is no necessity of worrying about it as it will not explode. When this method is applied outdoors, there is absolutely no apprehension of this. Where applied indoors, it is enough just to prohibit fire strictly.

(7) Equipment for measuring the porewater pressure.

In order to know the effects of this method at any time, porewater pressure gages were fixed at 3 places using the holes bored for soil survey (Ref. Fig. 5). The holes for underpinning shown in the figure were planned to be used as an aid to the bearing power when by any chance the electro chemical stabilization becomes unsuccessful or its efficiency is low. In this case, however, as the electro-chemical stabilization was used exclusively with success, there was no necessity of using the holes and they were all blocked up after the electrodes were disposed off.

(8) Equipment for measuring the settlement.

As one of the means of measuring the effect of this method, a gunmetal piece was fixed to the steel skeleton at GL=1.00 m and grooving a cross on the surface this was taken as the index of measuring the absolute settlement. A definite point on an existing building 70 m apart was taken as a fixed point.

Water gages were equipted at 7 places on the 3rd floor underground to measure the differential settlement. The gages are connected together by gas pipes and are simple and of hight accuracy.

6. Judgement of the efficiency of this method and conclusion.

The main records at the end of 5 months during which period electric current was turned on were as follows.

Consumed electric current		approx.	1,800,000 Ah
Consumed electric power			94,120 kWh
Electric power consumed per unit volume of soil treated			7.84 kWh/m^3
Volume of water pumped up			214 m^3
Total settlement of building		average	16.2 cm
Porewater pressure (5 m below foundation slab)		average	15.8 cmHg
Unconfined compression test	June 6~7. 1955	average	0.69 kg/cm^2
	Nov. 2~8. 1955	average	0.75 kg/cm^2
	Dec. 1955	average	0.82 kg/cm^2
Standard penetration test	Nov. 2~8. 1955	average	3.0 kg/cm^2
	Dec. 1955	average	3.8 kg/cm^2

Discussing these records, the following conclusion is obtained.

(1) Electrolysis of the anode aluminum.

The electro chemical equivalent of aluminium is 0.335 g/Ah.

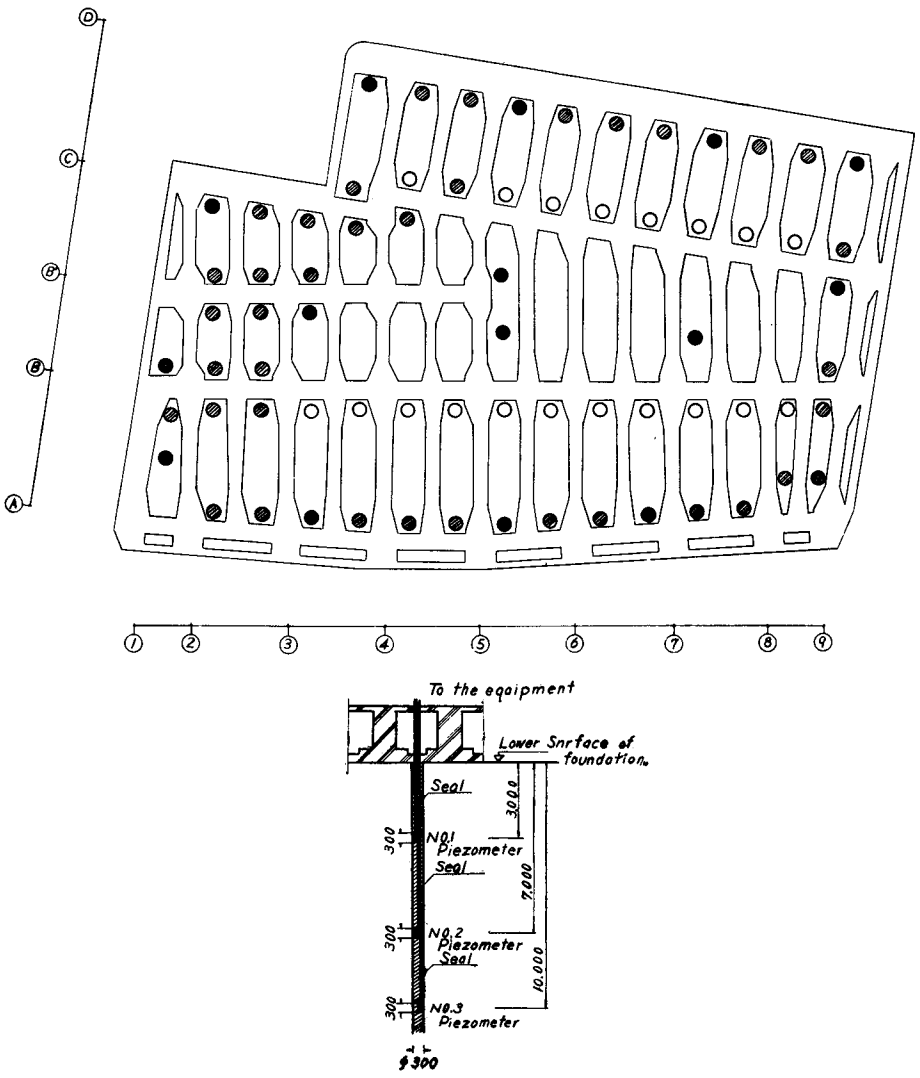

Fig. 5. Arrangement of the Test Holes to Measure the Effects.

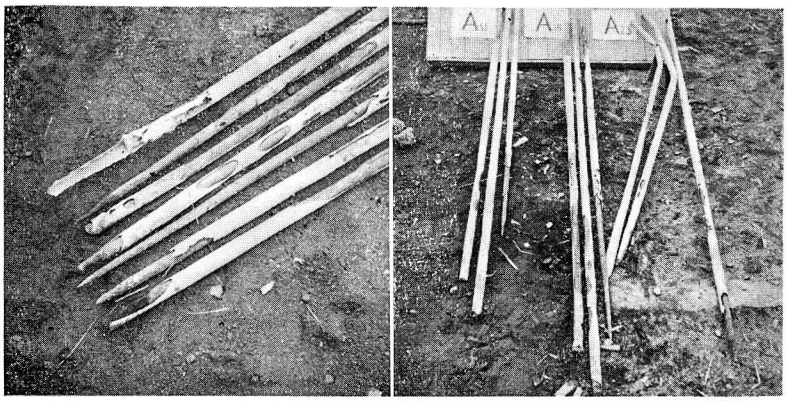

Photo. 4.

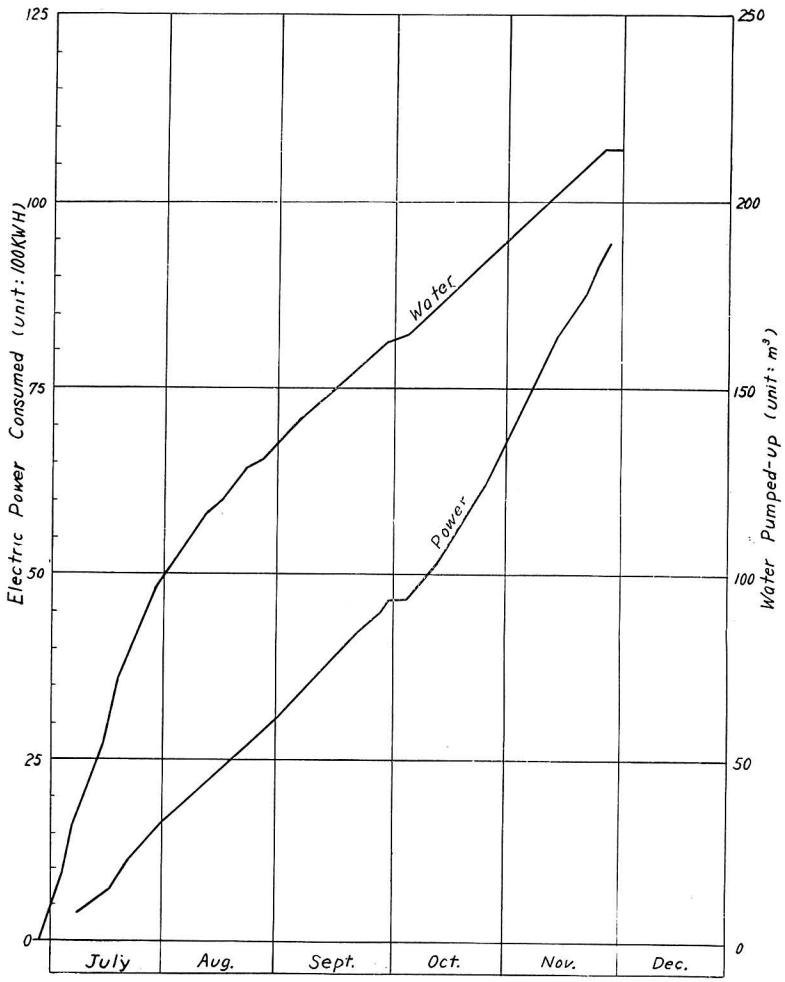

Fig. 6. Electric Power Consumed and Water Pumped Up vs. Time.

If the total volume of the anode aluminum is divided by the consumed electric current, it becomes 0.64 g/Ah/g. By comparing the reciprocals of each, it is seen that the electric current requited to electrolyse the aluminum of the anode completely is 2.98 Ah/g and the electric current already consumed is 1.58 Ah/g. Accordingly this means that 53% of the anode aluminum has been electrolysed. (Photo. 4 shows the anodes after the electric current was cut off).

(2) Settlement of building and quantity of water pumped up.

The area of the foundation slab is 1,050 m^2 and as it showed an average settlement of 18 cm, $1{,}050 \times 0.18 = 189$ m^3 of porewater must have been displaced. As there might have been, it is true, some change in the soil and water having no direct connection with the consolidation, the result does not necessary agree, but it is approximately equal to the pumped up water volume of 214 m^3. The process of the water pumped up is as shown in Fig. 6.

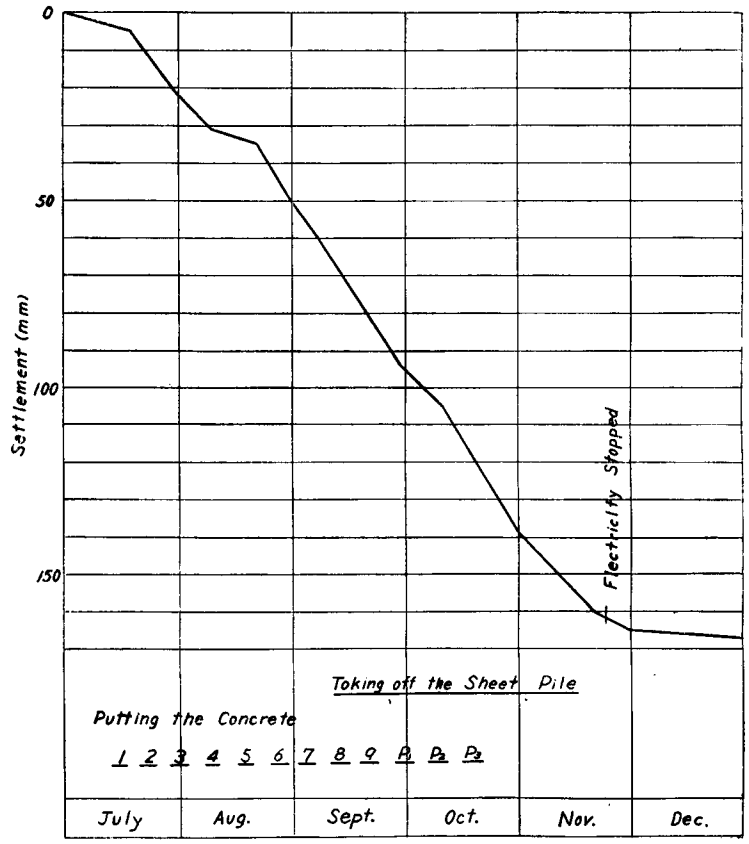

Fig. 7. Settlement vs. Time Curve.

(3) Pore water pressure

The average porewater pressure at a point 5 m below the foundation slab is 15.8 cm Hg, which in the case of ordinary water level, corresponds to a height $15.8 \times 13.55 + 25 + 243 = 472$ cm above the bottom surface of the foundation slab. As this porewater pressure is not a stable value and the water flowing into the pit was being drained, it is not correct to judge the efficiency hastely with this value. It was considered, however, that the fact that the porewater pressures at 3 points which showed a considerable difference at the beginning when the current was truned on became almost the same suggests the consolidation has proceeded a great extent and no great unequal settlement will occur in the future.

(4) Unconfined compression test

The unconfined compression test of the samples collected in June, Nov. and Dec. increased to 0.61, 0.75 and 0.78 respectively and the efficiency this method was recognized.

(5) Standard penetration test

From the standard penetration tests performed in Nov. and Dec., it was recognized that the average number of blows increased from 3 to 3.8.

(6) Expected settlement and actual settlement.

The total settlement as on Nov. 25th was in the average 18 cm, the progress being as shown in Fig. 7. It would take about 8 years to attain this settlement by natural consolidation.

As it was synthetically judged from the above results that the purpose of this method was practically attained without adopting underpinning, the current was cut off at the beginning of Dec. and disposing of the electrode, this method was completed without mishap.

7. Postscript

It was a great pleasure to have the opportunity of applying a certain idea which was constantly in mind and the author wishes to express his respect and gratitude to Mr. Taketsugu Tsukamoto, Mr. Katsuma Simizu, Nikken Design Co. Ltd., Mr. Naotake Taniguchi, Obayashi Gumi Co. Ltd..