# On the Electrochemical Consolidation of Soil using Aluminium Electrodes

## La consolidation électro-chimique du sol au moyen d'électrodes d'aluminium

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### Summary

Since *L. Casagrande* developed electrochemical consolidation using aluminium electrodes in 1934, many experiments have been treated by several researchers. But the mechanism of consolidation has been unknown.

Here, although only on laboratory scale, we make clear the mechanism of electro-chemical consolidation and its practical application is discussed.

### Sommaire

Depuis que *L. Casagrande* a mis au point la méthode de consolidation électro-chimique du sol au moyen d'électrodes d'aluminium, en 1934, différentes expériences ont été tentées par de nombreux spécialistes. Le mécanisme de la consolidation est cependant demeuré inconnu.

Dans ce travail, bien qu'il soit basé uniquement sur des expériences de laboratoire, nous sommes parvenus à éclaircir le mécanisme de la consolidation électro-chimique, et nous présentons le résultat de nos recherches sur l'application pratique du procédé.

### Experiments

Table 1 and Fig. 1 show the characteristics and curves of the mechanical analysis of soils used for our experiments.

Table 1 Characters of each sample

| *Samples* | *Liquid Limit %* | *Plasticity Index %* | *pH value* |
|---|---|---|---|
| Yoshidayama clay | 42.60 | 21.23 | 6.20 |
| Amagasaki clay | 76.20 | 47.30 | 7.68 |
| Osaka silty clay | 39.00 | 10.72 | 7.34 |

One type of apparatus used is illustrated in Fig. 2. This apparatus consists of a vessel of synthetic resin and aluminium electrodes 0.8 mm thick which are inserted into two porous pots.

These pots are used to facilitate the release of $H_2$ and $O_2$ gases from each electrode and to prevent any local heating caused by the increase of electric resistivity at the electrodes. When there is no pot, the electric current decreases suddenly like curve II in Fig. 3, but if the pots are used the current does not decrease so suddenly as shown in curve I. To avoid the consolidating effect of dehydration and to give conductivity, the pots are filled with water, and both water surfaces are continually kept at the same level by siphons.

The degree of consolidation of the soil is measured by the penetration depth of the needle (apparatus to measure the setting of cement) from the surface of the soil. Before and

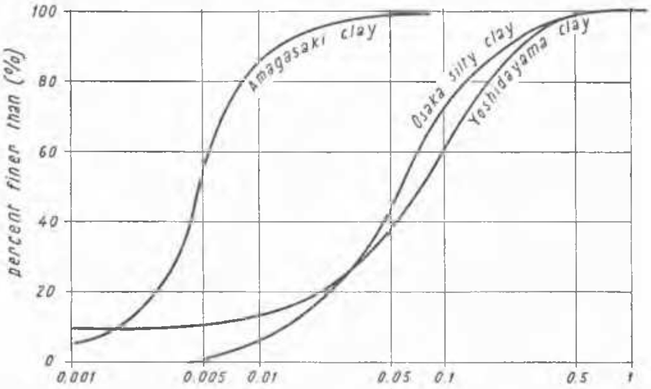

Fig. 1 Size Distribution Curve of Soil Samples
Courbes granulométriques

after the treatment the $pH$ of soil is measured with the $pH$-meter, or $pH$-indicating paper, with 4 g of soil to which 10 $cm^3$ of distilled water has been added.

Applying the current (at 50 volts) for about 20 hrs., the consolidated zone clearly appears in the Amagasaki clay and in the Osaka silty clay. The relations between the penetration depth and the $pH$-values are shown in Figs. 4 and 5 for each soil sample. It is clear from these figures that the consolidated zone where the penetrating depth is zero is formed in the narrow zone whose centre is the line of $pH = 7$. But the consolidated zone is formed near the anode in the case of the Amagasaki clay (original $pH = 7.68$), and near the cathode in the case of the Osaka silty clay (original $pH = 7.54$).

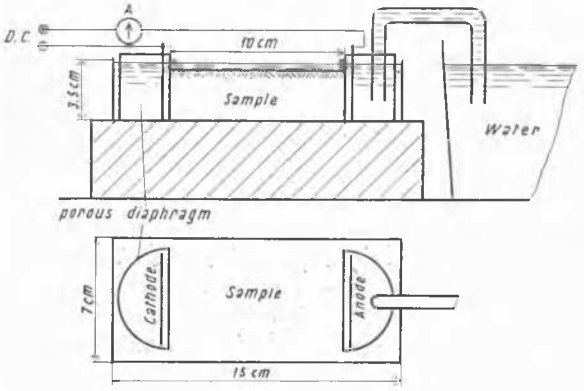

Fig. 2 Apparatus for Electrochemical Treatment of Soils
Dispositif pour le traitement électro-chimique des sols

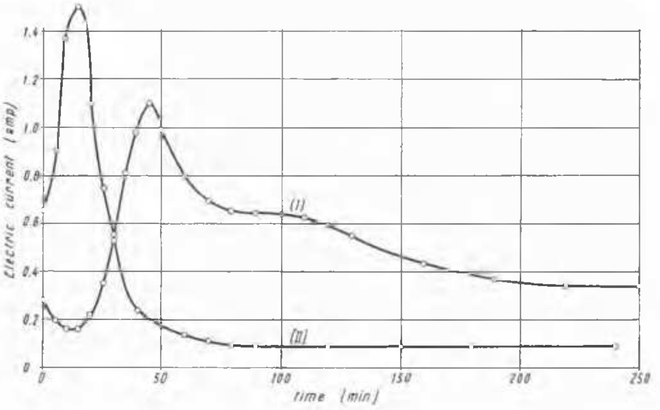

Fig. 3 Time/Electric Current Curves
Courbes temps/courant électrique

In the case of the Yoshidayama clay (original $pH = 6.20$), on the contrary, consolidation never occurs in spite of several days' electric treatment. But when the Yoshidayama clay is treated by adding 1 % solution of NaCl, the consolidated zone is formed around the middle zone of both electrodes. When a solution of $Al_2(SO_4)_3$ is added instead of NaCl, the consolidation does not appear.

## Considerations on the Experiment

Consideration on the reason why the consolidated zone occurs in the narrow zone whose centre is the line of $pH = 7$:

The soil contains a soil colloid which absorbs anions $A^+$, cations $B^-$ and water.

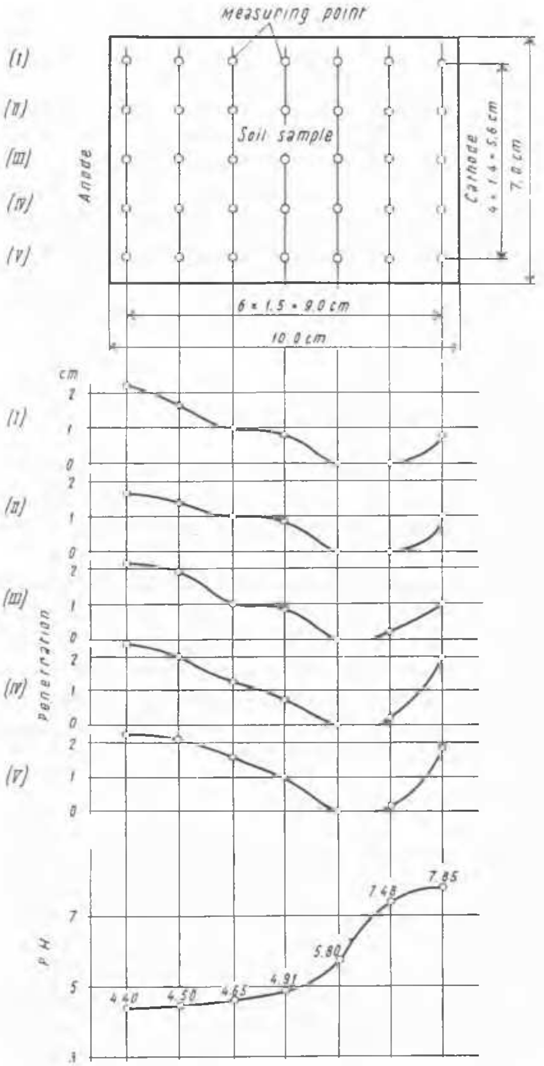

Fig. 4 Results of Penetration Tests and $pH$ Value of the Silty Clay of Osaka
Résultats d'essais de pénétration et valeur $pH$ de l'argile d'Osaka

The soil colloid is represented as follows:

$$[A^+ \text{ (soil colloid) } B^-] \cdot H_2O.$$

When D.C. is applied through the soil, $A^+$ ions ($Na^+$, $K^+$, $Ca^{++}$, $Al^{+++}$, etc.) migrate to the cathode and gather around

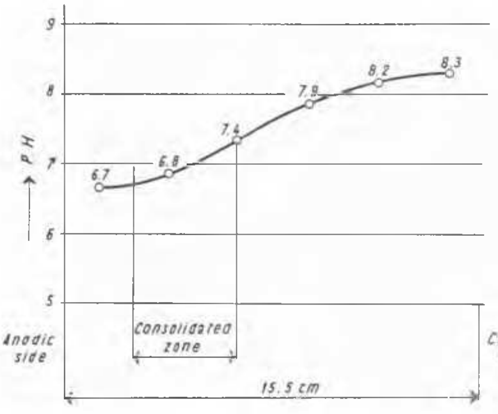

Fig. 5 $pH$ Value and Consolidated Zone of Amagasaki Clay
Valeur $pH$ et zone consolidée de l'argile d'Amagasaki

it, and $H_2$ gas is separated according to the following equation:

$$2A^+ + 2e^- + 2H_2O \rightarrow 2\,AOH + H_2\uparrow.$$

Therefore NaOH, KOH, etc. (alkaline salts) grow at the cathodic side, and the *p*H of the cathodic side increases. On the other hand, absorbed anions $B^-$ ($SO_4^{--}$, $Cl^-$, $CO_3^{--}$, etc.) migrate to the anode, and $O_2$ or $Cl_2$ gas appears, soil becomes acid at the anodic side which may be expressed by the following equations.

$$2B^- + 2e^+ \rightarrow B_2\uparrow$$

or

$$2B^- + 2e^+ + 2H_2O \rightarrow 2H_2B + O_2\uparrow.$$

As the soil colloids usually have a negative charge, and absorbed water is positively charged, some of the soil colloids move to the anode (electro phoresis) and the absorbed water, to the cathode (electro osmosis).

Besides the above-mentioned movement aluminium plates are dissolved to form $Al^{+++}$ ion by electricity at anode and alkaline water at cathode. Then at the anodic side $Al^{+++}$ and $H^+$ co-exist together in the water and at the cathodic side $Al^{+++}$, $OH^-$ and $AlO_2^-$ (aluminate ion) co-exist together because at the alkaline cathodic side $Al^{+++}$ combines with $OH^-$ as it may be expressed by the following equation.

$$Al^{+++} + 4\,OH^- \rightleftarrows AlO_2^- + 2H_2O.$$

As $Al(OH)_3$ is an amphoteric colloid, it coagulates at the neutral zone (where $pH \fallingdotseq 7$), and moreover the clayey soil is less permeable, so the permeability of the neutral zone largely decreases and the migration of ions is prevented to pass through by electric attraction. Then the $H^+$ and $Al^{+++}$ in the anodic side of this zone and $OH^-$ and $AlO_2^-$ in the cathodic side keep the state of equilibrium of *Donnan*, and these ions in both sides move into the neutral zone only by diffusion. These diffused ions combine together to make $Al(OH)_3$ as shown in the next equations.

$$Al^{+++} + 3OH^- \rightarrow Al(OH)_3$$

$$AlO_2^- + H^+ + H_2O \rightarrow Al(OH)_3.$$

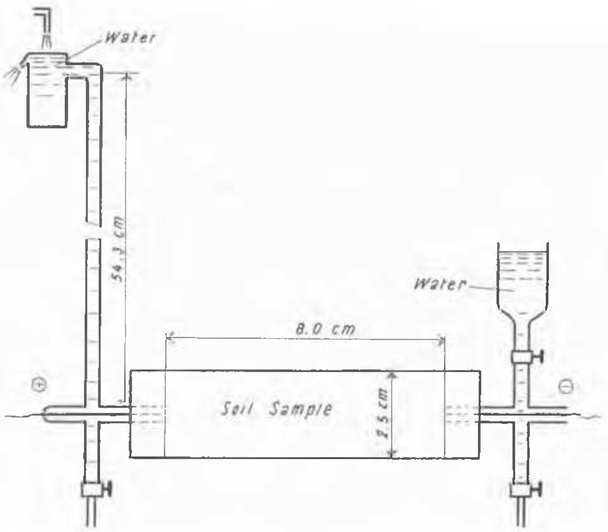

Fig. 6 Apparatus Used for the Electric Cell and the Permeameter
Dispositif pour cellule électrique mesure de la perméabilité

Thus, precipitated $Al(OH)_3$ is dehydrated by heat and electro-osmosis subsequently, and becomes the crystalized bauxite $AlO(OH)$ or alumina $Al_2O_3$.

$$Al(OH)_3 \xrightarrow[-H_2O]{} AlO(OH) \xrightarrow[-H_2O]{} Al_2O_3.$$

Those dehydration may probably continue slowly after the electric current is stopped. $AlO(OH)$ and $Al_2O_3$ are insoluble in water and chemically stable. It is considered that the soft soil becomes strong, impervious and stable as the crystalised $AlO(OH)$ or $Al_2O_3$ binds the soil particles. Because merely dried up soil which has been premixed with colloidal $Al(OH)_3$ is destroyed at once when it is dipped in water, but the electrochemically consolidated soil does not.

When the consolidated soil is analysed, it is found that this soil contains more aluminium than the untreated soil.

On other experiments (Fig. 6) which are performed with pure sand and 1% of NaCl solution, a precipitation of $Al(OH)_3$, although very slight, is found and makes the sand impervious. From this fact, as the sand contains no colloids, it seems that the base exchange for soil colloids is not a principal cause of consolidation.

## Consideration on the Existence and Position of the Consolidated Zone

The *p*H of the Amagasaki clay and the Osaka silty clay is larger than 7, so it is naturally supposed that the ions of $Na^+$ or $K^+$ and that of $SO_4^{--}$ or $Cl^-$ are absorbed in them. Therefore on the above experiments, the consolidated zone occurs only by introducing D.C. to them.

On the other hand, as the Yoshidayama clay is an acid soil, the ions of $Na^+$ or $K^+$ are exchanged by the $H^+$ ions. In this soil, when D.C. is applied, the gradient of *p*H cannot become so steep as to reach $pH = 7$ and the neutral zone cannot grow. When NaCl is added to it, NaOH is produced in the cathodic side and HCl in the anodic side to make the *p*H gradient so steep as to pass over $pH = 7$ at the cathodic side. The point which indicates $pH = 7$ occurs approximately at the middle of the electrodes, so the neutral zone or consolidated zone occurs approximately at the middle of the electrodes too.

In the case we add $Al_2(SO_4)_3$ to it instead of NaCl, the strong acid of $H_2SO_4$ is produced in the anodic side, and nearly neutral salt of $Al(OH)_3$ is produced in the cathodic side, so the *p*H of this soil cannot increase more than 7. This is the reason why the Yoshidayama clay shows the results mentioned above.

## Effects of this Treatment

In the shearing test with Amagasaki clay, the internal friction angle ($\theta$) and the cohesive strength ($c$) are increased by the treatment as shown in Table 2.

Table 2 Comparison Between the Shearing Test Results Before and After Treatment

| | *Before treatment* | *After treatment* |
|---|---|---|
| Internal friction angle ($\theta$) | 10° 20′ | 13° 25′ |
| Cohesive strength ($c$) kg/cm² | 0.006 | 0.027 |

After treatment with the apparatus shown in Fig. 6, the permeability coefficient of the tand decreases from the original value of $k \fallingdotseq 1.2 \times 10^{-3}$ cm/sec so $k \neq 0$ after applying 50 V of D.C. for 20 hrs.

## Conclusion

(1) The position of the consolidated zone does not always occur in the anodic side, but it varies with the $p$H of soil and ground water; it occurs in the zone whose centre is the line of $p\text{H} = 7$.

(2) The width of the consolidated zone is about 1/10 of the distance between the electrodes.

(3) The position and existence of the consolidated zone can be controlled by adding a suitable salt to the soil.

(4) The consolidated soil contains more aluminium than it did before treatment.

(5) The consolidated soil is strong, less permeable and chemically stable.

(6) The consolidation seems to be caused by the crystallisation of $AlO(OH)$ or $Al_2O_3$. But the base exchange of soil colloid may have some effect on it.