Consolidation Deformation Characteristics of Hachirogata Clay Ground with Salt Leaching and Its Settlement Prediction

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ABSTRACT
A thick, soft alluvial clay layer is deposited in the Hachirogata reclaimed land, Akita in Japan. There is necessary to re-examine the consolidation characteristics and carry out appropriate maintenance for renewal agricultural structures. As differential settlements of the irrigation structure occur at the site, this phenomenon lower the function of water supply for the irrigation channel. In this study, assuming that the cause of differential settlements of the ground is the salt leaching of the sediments, the effect of salt leaching on physical properties of Hachirogata clay was examined. From results of this study, it was confirmed that the leached Hachirogata clay has the delay of consolidation deformation, the decrease of permeability and the remarkable creep behavior. It was suggested the salt leaching affects the physicochemical and mechanical properties of the clay and is one of the factors that cause differential settlements in Hachirogata.

RESUME
Une couche d'argile alluviale épaisse et molle est déposée dans les terres récupérées d'Hachirogata, Akita au Japon. Il est nécessaire de réexaminer les caractéristiques de consolidation et d'effectuer un entretien approprié pour le renouvellement des structures agricoles. Comme des tassements différentiels de la structure d'irrigation se produisent sur le site, ce phénomène diminue la fonction d'alimentation en eau du canal d'irrigation. Dans cette étude, en supposant que la cause des tassements différentiels du sol est le lessivage du sel des sédiments, l'effet du lessivage du sel sur les propriétés physiques de l'argile Hachirogata a été examiné. Les résultats de cette étude ont confirmé que l'argile d'Hachirogata lessivée présente un retard de la déformation de consolidation, une diminution de la perméabilité et un comportement de fluage remarquable. Il a été suggéré que le lessivage du sel affecte les propriétés physico-chimiques et mécaniques de l'argile et qu'il est l'un des facteurs qui provoquent des tassements différentiels à Hachirogata.

Keywords—Hachirogata clay, Leaching, Coefficient of secondary consolidation, Differential settlement

1 INTRODUCTION

When structures are built on soft clay soils, differential settlement and residual settlement are major problems. The Hachirogata reclaimed land has a thick layer of soft alluvial clay, which causes long-term differential settlement of agricultural structures such as water facilities and accelerates the decline of the water supply function. Therefore, there is necessary to re-examine the consolidation characteristics and to conduct appropriate maintenance and management.

Many studies have been conducted on the soil properties of the Hachirogata clay. Tanaka (2007) reported on the engineering characteristics of the Hachirogata clay, pointing out that the soft clay layer is more than 45 m thick, and the activity *Ac* of the Hachirogata clay is very high compared to other marine clays. Tanaka and Locat (1999), Locat and Tanaka (2001) and Shiwakoti et al. (2002) found that the diatom microfossils in the clay are the factors for its high consistency index. Kanayama et al. (2020) experimentally investigated the consolidation deformation characteristics of the remolded Hachirogata clay and numerically analyzed the amount of consolidation deformation. As a result, they showed that the consolidation deformation of Hachirogata clay takes a long time, the amount of deformation increases, and the deformation continues over time after the main deformation is completed. According to Takahashi et al. (2021), the settlement of the Hachirogata clay ground was predicted by considering the consolidation theory and secondary consolidation behavior for the pipeline buried structure ground model based on the soil constants obtained from the soil test results. As a result of predicting the settlement of the irrigation structure in consideration of the secondary consolidation, it was suggested that the differential settlement and reverse gradient between the main irrigation channel may occur based on the adopted calculation conditions. From these works, it can be seen that the compressibility of the Hachirogata clay is large and the deformation continues for a long period of time, and it is useful to consider secondary consolidation when evaluating the long-term settlement of the structure.

However, the mechanism of ground differential settlement of the ground is not well known. There are various possible causes, such as inhomogeneous loading, differences in permeability, and differences in grain size distribution and so on. In this work, the effect of salt leaching on the mechanical properties of clay is focused. At the site in Hachirogata, the differential settlement is observed not only between channels but also on the surrounding roads. With regard to salt leaching, Bjerrum (1967) reported that liquid limit decreases by 11% after salt leaching and decrease in salt concentration from 21 g/L to 1 g/L caused 1% settlement in Norwegian clay. From leaching tests on Norwegian clays, Torrance (1974) showed that a decrease in salinity up to 2 g/L resulted in a decrease of consolidation yield stress and an increase of settlement. The dispersion and flocculation phenomena of clay are reported as follows. Iwata et al. (1998) reported that repulsive and attraction forces between negatively charged clay particles produce dispersion and flocculation phenomena of clay and resulting in impermeable dense orientation in the dispersed state and permeable random

orientation in the flocculated state. From the above, it can be seen that the ion concentration in the pore water influences the orientation of the clay and affects the physicochemical and mechanical properties of the clay.

In this study, soil tests were conducted using the prepared leached and non-leached samples, and the obtained soil constants were compared in order to understand the effect of salt leaching on the consolidation and deformation properties of the Hachirogata clay. Moreover, the microscopic structure was also evaluated using scanning electron microscopy (SEM).

2 HACHIROGATA RECLAIMED LAND AND HACHIROGATA CLAY

Hachirogata reclaimed land is located in western Akita, facing the Sea of Japan. On the east side of the reclaimed land to the north of Hachirogata and the Oga Peninsula, hills of 100 to 200 m elevation are formed, and terraces of 10 to 50 m elevation extend at the foot of the hills. The surrounding area is an alluvial lowland, there are the dunes 10 to 20 m elevation on the northwest and south sides. The Hachirogata reclaimed land consists of flat land at elevations of -5 to 0 m below sea level.

The total area of Hachirogata was 22,173 ha, and the second largest lake in Japan after Biwa lake. Lake Hachiro was a sea trail lake on the Oga Peninsula formed by sediment discharged from the Yoneshiro and Omono Rivers, and a blackish lake connected to the Sea of Japan in the southern part. In 1957, a national project to increase farmland was performed to solve food shortages. The gaverment managed Hachirogata Reclamation Project was initiated with technical assistance from the Dutch aid agency and was completed in 1977. The embankment for reclamation was constructed from 1958 to 1964. In areas where the lake bottom was soft, the bottom was dug out 2 m and replaced with high-quality sand, and in areas where the lake bottom was firm, sand was placed directly on top of it. The total length of the embankment is approximately 52 km, divided into three sections.


Figure 1. The canal in Hachirogata

3 METHODS

3.1 Sample Preparation Method

A boring sample (undisturbed sample) was used with a depth of about 5 to 7 m obtained from the geological survey of irrigation canal in Hachirogata. Leached specimens using the sample were artificially prepared. Distilled water and its sample mixed at a ratio of 2: 1, and the mixture was sufficiently stirred. The mixture was placed in a dialysis membrane, stood in distilled water for a certain period of time, and the salinity in the clay was leached by osmotic pressure in this situation (Figure 2). In this research, leached specimens were prepared with a standing period of about 2 weeks and about 4 weeks. All samples were in remolded condition.

3.2 Test Procedures

Consistency tests (JIS A 1205, JGS 0141) and the conventional consolidation test (JIS A 1217) were performed in non-leached and leached sample. The non-leached and leached samples were used. The number of the non-leached, 2weeks leached and 4weeks leached is 4, 4, and 2, respectively. The average values for the consistency tests are shown in Table 1.

In consolidation test, the specimens were in remolded condition and were 60 mm in diameter and 20 mm in height. The specimens were packed in consolidation rings and placed in a consolidation testing machine (Maruto Corporation, S43-3UL-1) with the filter paper between the specimens and the porous stone, and the loading pressure p was started at 9.8 kN/m^2 with a pressure


Figure 2. Leaching process

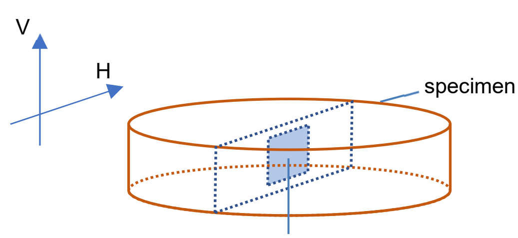

Figure 3. The area and orientation of all imaging

Table 1. Result of consistency tests

Sample (Leaching Period)	Electric conductivity Ec(ms/cm)	Liquid limit w_L (%)	Plastic limit w_P (%)	Plasticity index I_P
Non-leached	6.48	206.6	87.4	119.2
Leached (2weeks)	0.38	206.7	80.3	126.4
Leached (4weeks)	0.72	168.9	72.0	96.9

increment ratio of 1. Loads were placed every 72 hours to ensure sufficient consolidation time and consolidation pressure was ranged from 9.8 to 1256 kN/m^2. Settlement was measured every second by connecting the end of the displacement transducer to a data logger. Consolidation tests were performed on non-leached sample and 2 weeks leached sample. 2 leached samples were prepared.

The soil structure of non-leached and leached sample was observed using scanning electron microscopy (SEM) to evaluate the microscopic structure. The vertical cross section of the specimen was observed, after oven dried. The area and orientation of imaging is shown in Figure 3.

4 RESUTS AND DISCCUSSION

4.1 The Consistency Tests

For the non-leached sample, the liquid limit w_L was 206.6% and the plastic limit w_p was 87.4%. For 2 weeks leached sample, the w_L was 206.7% and the w_p was 80.3%. For sample 4 weeks leached, the w_L was 168.9% and the w_p was 72.0%. Comparing the non-leached and 4 weeks leached sample, the liquid limit and plastic limit are reduced by about 30% and 15%, respectively, and the plasticity index I_p is also reduced. The flow curves (log n - w) showed that the slope of the straight line for leached sample was more gradual (Figure. 4). These results indicated that the leached sample was changed to flowable property with the variation of water content. However, the difference in the liquid and plastic limits were not well observed between non-leached sample and the sample with a leaching period

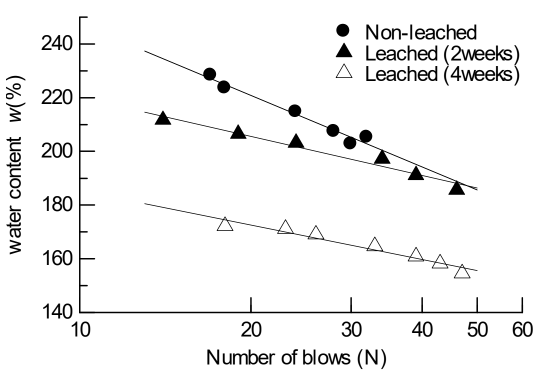

Figure 4. The flow curves (Number of blows N – water content w)

of 2 weeks. It was probably suggested that the salinity in the pore water were leached, but salinity adsorbed on the clay particles were not leached due to short leaching period.

4.2 The Conventional Consolidation Test

Figure 5 shows the settlement time curves for the non-leached and leached samples. There was a delay in the settlement phenomenon of the leached sample throughout the entire process, compared to the non-leached sample. The remarkable delay in the settlement phenomenon was observed, especially at the lower consolidation pressures, and the differences became smaller as consolidation pressure increased. At a consolidation pressure, 9.8 kN/m^2, sample Leached2 exhibited remarkable linear creep behavior with logarithmic time after the end of primary consolidation, compared to sample Non-leached. No significant difference in final consolidation settlement was observed.

Figure 6 shows the coefficients of consolidation c_v, volumetric compressibility m_v, permeability k, and secondary consolidation C_{ae} for the non-leached and leached samples, versus average consolidation pressure. The c_v values increased with increasing consolidation pressure. The c_v values of the non-leached sample were ranged from about 19 to 50 cm^2/d, while those of the leached sample were ranged from about 3 to 25 cm^2/d. The c_v values of the leached sample decreased about 1/8 to 1/2 of the non-leached sample. Therefore, it can be seen that the leached sample requires more time for completing consolidation than the non-leached sample. The m_v values decreased with increasing consolidation pressure and were ranged from about 10^{-4} to 10^{-2} m^2/kN. Although it was assumed that the m_v values of leached sample at the lower consolidation pressure become a higher value than non-leached sample, the leached sample showed almost the same value as the non-leached sample throughout the entire process. Therefore, it is necessary to conduct experiments and accumulate the amount of data in the future. The k values decreased with increasing consolidation pressure, and those of the non-leached sample were ranged from about 10^{-10} to 10^{-9} cm/s, while those of the leached sample were ranged from 10^{-11} to 10^{-10} cm/s. The leached sample had a lower value than the non-leached sample because it is affected by the low c_v value. It was confirmed that the permeability reduced after salt leaching. The C_{ae} values showed almost the same value throughout the entire process and were ranged from about 0.03 to 0.06. However, as the C_{ae} value of sample Non-leached and Leached2 were 0.04, and 0.08, respectively, at consolidation pressure, 9.8 kN/m^2., those of the leached sample were higher than the non-leached sample at the lower consolidation pressure.

According to these results, due to salt leaching, the increase of time to finish consolidation, and the decrease of permeability, and the remarkable creep behavior were

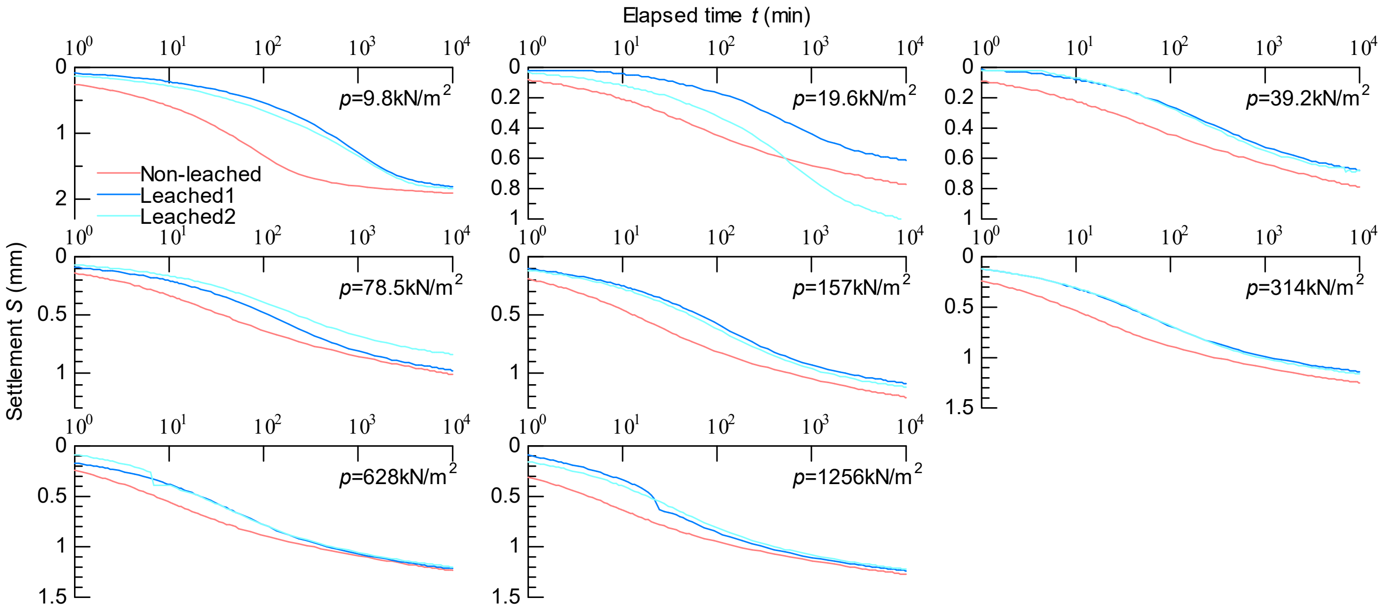

Figure 5. Settlement time curves of non-leached and leached samples

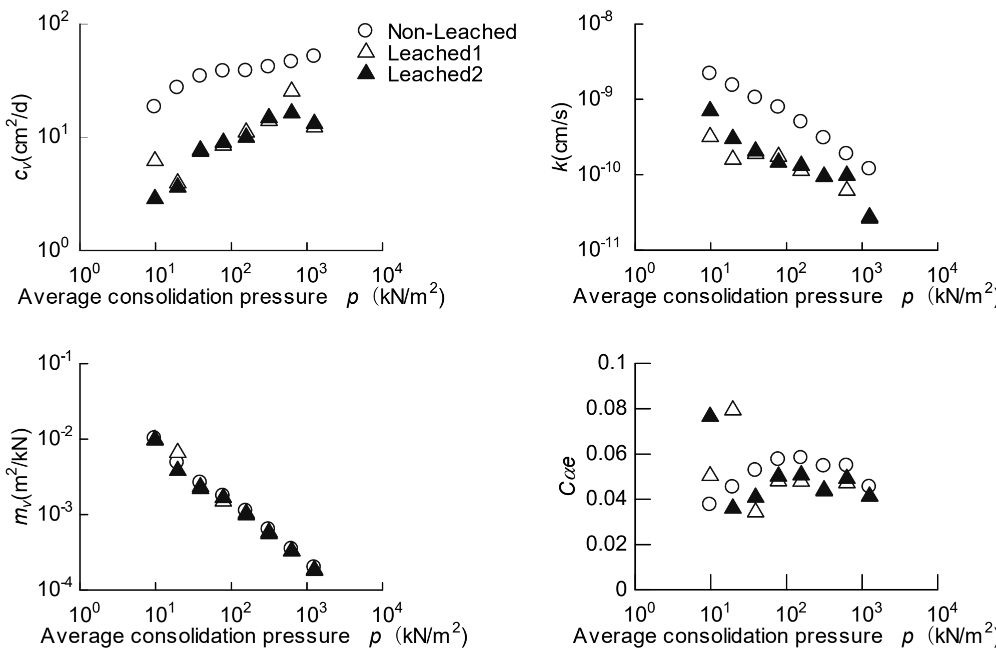

Figure 6. Coefficients of consolidation, volumetric compressibility, permeability and secondary consolidation

confirmed.

4.3 Observation of Soil Structure Using Scanning Electron Microscopy (SEM)

Based on the physicochemical and mechanical properties derived in this study, the models of Hachirogata clay on non-leached and leached samples were considered.

The SEM images, Figure 7, in this study showed that the card house-like structure with negatively charged and positively crystalline planes joined together has developed in the non-leached sample, while the leached sample has more particles with horizontal planes, forming the parallel array structure.

Iwata et al. (1998) reported the following dispersion and flocculation phenomena of clay. In high-salinity water, flocculation occurs because the high ion concentration in the pore water reduces the distance which the electrical repulsive force acts, and allows attractive forces to act. On the other hand, when ions in the pore water are dissolved out (salt leaching), the low ion concentration in the pore water increases the distance which the electrical repulsive force acts, and makes unable to act attractive force, resulting in dispersion (Figure 8).

In the dispersed state, clay particles settle independently and arrange closely to form an impermeable film. In contrast, in the flocculated state, clay particles

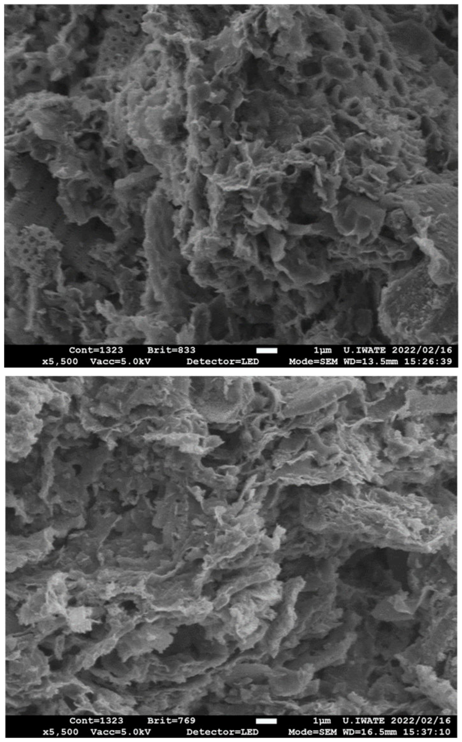

Figure 7. SEM images（×5500）
Non-leached sample（Upper）
Leached sample（Lower）

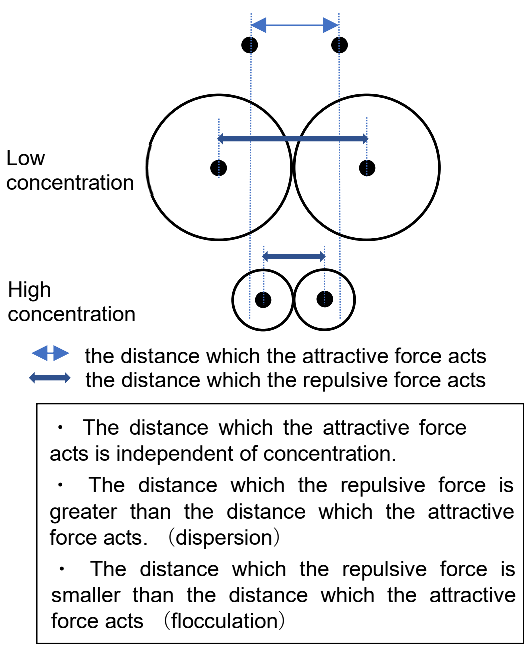

Figure 8. Mechanism of dispersion and flocculation
(from Iwata et al. 1998)

become fluffy flocculence, and the particles arrange randomly into permeable sediments (Figure 9).

Therefore, the random arrangement which develops in the flocculated state (Figure 9(a)) and the dense arrangement which develops in the dispersed state (Figure 9(b)) were considered in non-leached clay and in leached clay, respectively. These models are agreement with the report by Iwata et al (1998). It was suggested that the salt leaching changes the orientation of the clay particles from the random state to the dense state with horizontal planes and reduces permeability.

The above observation results are then compared with those of the conventional consolidation test. The results of the consolidation test suggested the following for leached sample compared to non-leached sample.

(1) The permeability of the leached clay is lower than the non-leached clay, and the leached clay take longer to consolidate than the non-leached clay.
(2) In the case of the lower consolidation pressure, the deformation of the leached clay continues over time after the completion of the main deformation, and it is assumed that the amount of the deformation is larger than the non-leached clay.

Regarding (1), the parallel array structure was observed in the leached sample. It was assumed that in the parallel array structure, the function of the water drainage is lowered. Therefore, it is suggested that the arrangement of clay particles reduces permeability. Regarding (2), in the case of the lower consolidation pressure, it was considered that the compressibility increases because clay particles become dispersed by the salt leaching. In addition, the deformation is considered to increase only in the lower

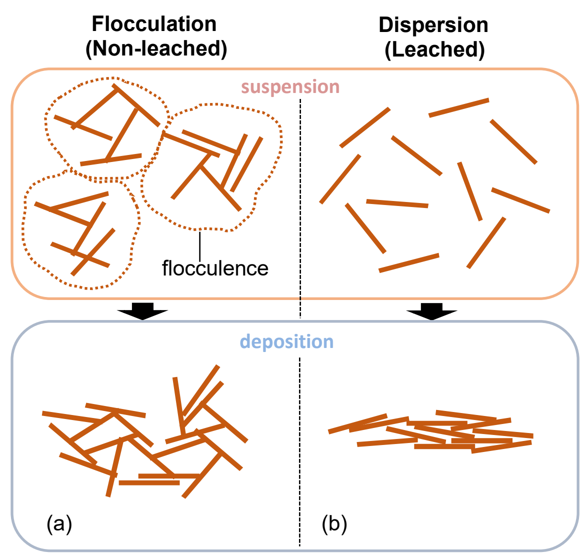

Figure 9. The models of non-leached and leached clays

consolidation pressure because the arrangement of clay particles changes to a dense state from dispersed state with increasing consolidation pressure.

Regarding the phenomenon of ground differential settlement, there are various possible causes, such as inhomogeneous loading, differences in permeability, and differences in grain size distribution and so on. In this work, the effect of salt leaching on the mechanical properties of clay was focused. From results of this study, it was confirmed that the leached Hachirogata clay has the delay of consolidation deformation, the decrease of permeability and the remarkable creep behavior. Therefore, it was indicated that the salt leaching affects the physicochemical and mechanical properties of the clay and is one of the factors that cause differential settlements in Hachirogata.

5 CONCLUSION

In this study, soil tests were conducted on the leached and the non-leached samples prepared from borehole sample and soil constants were compared in order to understand the effect of salt leaching on the consolidation and deformation properties of the Hachirogata clay. The microscopic structure was also evaluated using a scanning electron microscope (SEM).

From the consistency tests, it was confirmed that the liquid limit and plasticity index decreased after salt leaching, indicating that physicochemical property changed flowable property due to changes in the water content after salt leaching.

From the conventional consolidation tests, it showed that there was a delay in the settlement phenomenon of the leached sample at all consolidation pressure. The leached sample showed lower coefficients of consolidation and permeability, and higher coefficient of secondary consolidation in the lower consolidation pressure than the non-leached sample, suggesting that consolidation deformation continues a long time, and the compressibility increases in leached clay.

SEM images showed the random arrangement in the non-leached sample and the parallel array structure in the leached sample. The results suggested that the compressibility increases, and the permeability decreases because clay particles become dispersed and settle in a dense with a horizontal plane by salt leaching.

Therefore, it was inferred that the localized salt leaching is one of the factors that cause differential settlements from the above test results.

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