# Variation of void ratio and permeability during consolidation in soft ground using vertical drain with heat injection

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**ABSTRACT**

To investigate the effect of heating through sand drain on the consolidation behavior of soft ground, a testing device which is able to control the temperature of sand drain is developed. Using the developed device, a series of consolidation test was conducted with and without heat injection and sand drain. During the consolidation of the model ground, the temperature distribution, the variation of void ratio, and permeability of soft ground were analyzed. Test results showed that the heat injection through sand drain increased final settlement and decreased the void ratio and the permeability of soft ground

**Keywords:** Heat injection, Vertical drain, Temperature distribution, Consolidation behavior, Void ratio, Permeability

## 1 INTRODUCTION

Temperature change affects the consolidation behavior of soft soil. Heat injection into vertical drains installed in a soft ground increases permeability of soft ground due to reduced viscosity of pore water, and generates additional excess pore water pressure of surrounding soil. Subsequently, these effects decrease the volume and void ratio of soft ground, and eventually increase vertical settlement for consolidation process. Therefore, if heating is used accompanying with a vertical drain and a pre-loading method, the improvement of soft ground can be achieved in an expeditious and efficient manner. The larger diameter of a vertical drain with an internal heat source also affects the heating volume of surrounding soil and, consequently, induce greater spatial variability of void ratio and permeability of soft ground.

A study on the mechanical property of soft soil with temperature change performed by Campanella and Mitchell (1968), Plum and Esrig (1969), Towhata et al. (1993). Abuel-Naga et al. (2006) and Bergado et al. (2007) studied the consolidation behavior of soft ground improved by prefabricated vertical drain with a heat exchanger in it. Park et al. (2012) investigated the effect of a vertical drain with heat injection on ultimate bearing capacity and trafficability of soft ground. Most of previous researches of the heat injection in soft ground have focused on consolidation settlement and strength due to the temperature change of soft ground. However, the spatial variability of void ratio and permeability in soft ground caused by heating hasn't been studied much.

In this study, to investigate the effect of heat injection not only on consolidation settlement but also on spatial variability of soft ground, a new testing device enabling the control of heating temperature and drain diameter was developed. Using the testing device, a series of consolidation test was performed with and without heat injection through the sand drain. During consolidation, vertical settlement and temperature at various locations inside the specimen were measured. After the consolidation test, the spatial variation of void ratio and permeability of the specimen were also estimated. Based on the test results, the temperature distribution, the consolidation behavior, and the variation of void ratio and permeability in soft ground were analyzed.

## 2 LABORATORY TEST AND CONDITIONS

### 2.1 Developed testing apparatus

Fig. 1 and 2 show the schematic illustration of the testing device for the consolidation of soft ground by vertical loading accompanying heating. The consolidation chamber has an inside diameter of 300 mm and a height of 485 mm. A rigid plate is placed on the top of the specimen to transmit air pressure controlled by a regulator as a vertical load upon the specimen. An electric heating rod located at the center of a sand drain is used to inject heating during the consolidation of the specimen. Fig. 3 shows the electric heating rod to simulate heat injection in soft ground. The heating rod has a diameter of 20mm and a height of 300mm. The vertical sand drain is installed using an open-ended mandrel made as a thin-wall tube to minimize smear around the sand drain. Two sizes of mandrel (40 mm and 60 mm in outside diameter) were manufactured to simulate various sizes of sand drain. During consolidation of the specimen under constant load, the temperature of the heating rod was also maintained constant by a temperature controller. Temperature sensors were used at several locations to measure the temperature inside the specimen during consolidation. Vertical displacement was measured by an LVDT.

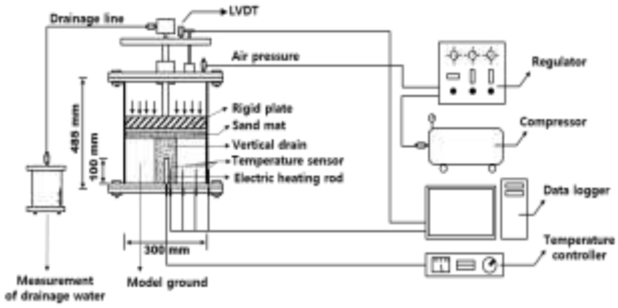



Fig. 1. Schematic diagram of test setup

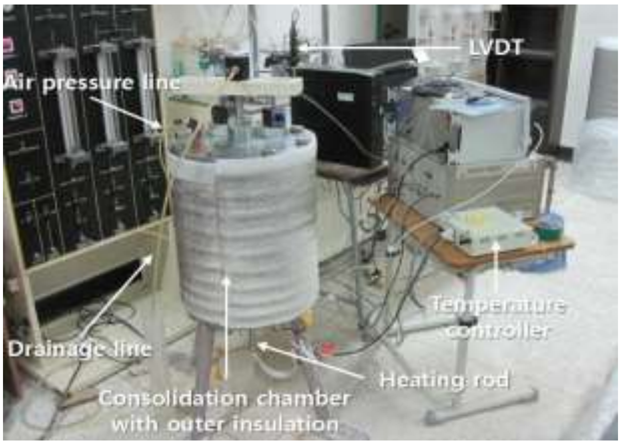



Fig. 2. Testing device.

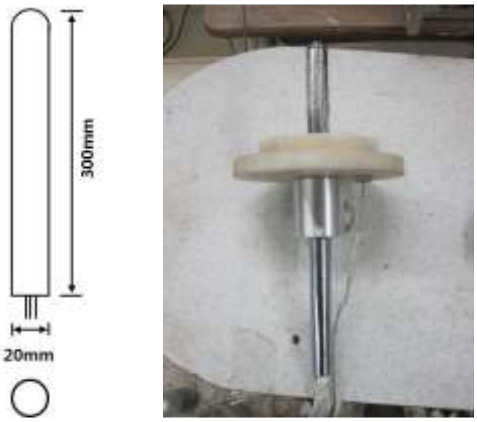



Fig. 3. Electric heating rod.

## 2.2 Test procedure and condition

Reconstituted kaolin was used to simulate soft ground. Kaolin powder was placed in a mixing chamber with water content of 110%, more than twice the samples liquid limit of kaolin. The index properties of kaolin are summarized in Table 1. The kaolin slurry was stirred constantly by a mixing blade for about 24 hours. During the mixing, a vacuum was applied to remove air bubbles trapped in the slurry. Once the mixing under the vacuum was completed, the kaolin slurry was placed into the consolidation chamber, and then 40 kPa of pre-consolidation pressure was applied for approximately 10 days. After the reconstitution of the specimen, the consolidation chamber was located at the center of a mandrel-inserting device. After that, the mandrel was pushed into the center of the specimen to make a central hole for the installation of a sand drain. And then the heating rod was inserted through the bottom plate of the chamber into the central hole. After the insertion of a heating rod, sand was poured into the central hole and the top of the specimen to make a vertical sand drain and a sand mat. Temperature sensors were installed at intervals of 50mm from the heating rod. The heating was injected by the heating rod. After all the parts were assembled as shown in Fig. 1, the specimen was consolidated by increasing the vertical load incrementally in two stages (100kPa and 200kPa). The temperature of the heating rod was maintained at 53°C for the consolidation. During the consolidation, temperature, settlement, and the amount of drained water were measured. After the consolidation tests, the spatial variation of void ratio and permeability of the specimen were estimated. Five tests were performed according to the heat injection and the varying diameter of the sand drain. Test conditions are summarized in Table 2.

Table 1. Index properties of kaolin

| | LL(%) | PL(%) | PI(%) | Gs | Passing ratio (#200) | U.S.C.S. |
|---|---|---|---|---|---|---|
| EPK kaolin | 55.60 | 18.93 | 36.67 | 2.51 | 99.46 | MH |

Table 2. Test conditions

| Drainage direction | Diameter of sand drain (mm) | Heating condition | Designation |
|---|---|---|---|
| Vertical | - | Without heating | V |
| Vertical and Radially inward | 40 | Without heating | R-40 |
| | 60 | Without heating | R-60 |
| | 40 | With heating | RH-40 |
| | 60 | With heating | RH-60 |

## 3 ANALYSIS OF TEST RESULTS

### 3.1 Temperature change

Fig. 4 shows the temperature change in the soft ground according to the heating time. The temperature in the soft ground was measured at 50 mm, 100 mm, and 150 mm from the heating rod. After the heat injection, the temperature increased from the center and stabilized after 10,000 minutes at all locations. The increasing diameter of the sand drain increased the temperature of the soft ground. In order to investigate the equilibrium time of the temperature in radial distance from the center, the time for the steady state of temperature for RH-40 and RH-60 was plotted as shown in Fig. 5. The larger drain diameter required more time for the temperature equilibrium and the time for the steady state of RH-60 was 2.68 times longer than RH-40 in average.

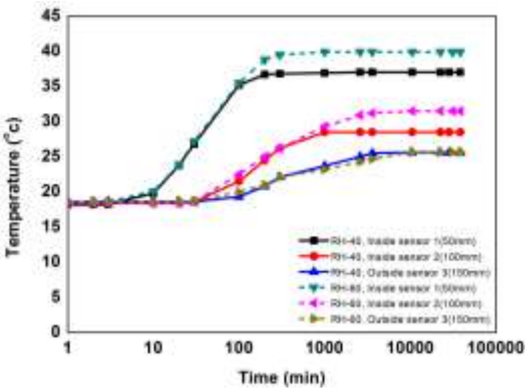



Fig. 4. Temperature in the soft ground sample

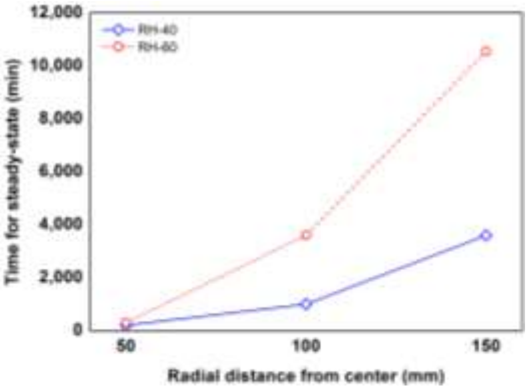
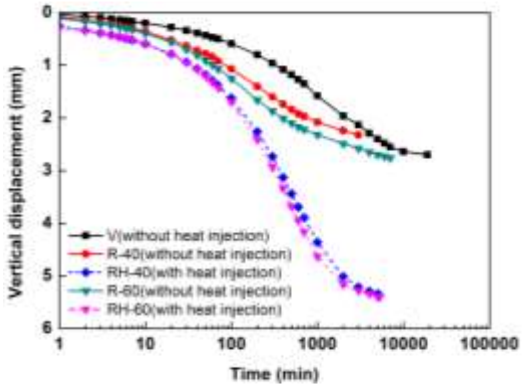


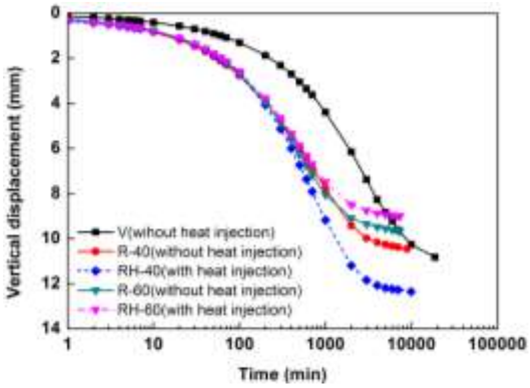

Fig. 5. Parallel time of temperature

### 3.2 Consolidation settlement

Fig. 6 shows the consolidation settlement measured in two stages of loading (100kPa and 200kPa). Based on the measured settlement data, the final settlement in each test condition was estimated at 95% of the consolidation ratio by hyperbolic method as summarized in Table 3. In fig. 6, the sand drain accelerated the consolidation rate, and the heat injection increased the final settlement. In Fig. 6 and Table 3, the vertical drain accelerated the consolidation rate, but had a negligible effect on total settlement, at 100 kPa of loading (OC state) . On the other hand, heat injection clearly increased the final settlement about 85%. At the loading stage of 200 kPa (NC state), however, heat injection did not affect the total consolidation settlement, while the vertical drain accelerated the consolidation rate and had a negligible effect on the total settlement same as the 100 kPa loading.




(a) 100kPa loading (OC state)




(b) 200kPa loading (NC state)

Fig. 6. Consolidation settlement.

Table 3. Comparison of final settlement.

| Test | 100kPa loading | | 200kPa loading | |
|---|---|---|---|---|
| | S (mm) | Ratio | S (mm) | Ratio |
| V | 2.91 | 1.00 | 10.82 | 1.00 |
| R-40 | 2.35 | 0.81 | 10.45 | 0.97 |
| R-60 | 2.76 | 0.95 | 9.66 | 0.89 |
| RH-40 | 5.36 | 1.84 | 12.35 | 1.14 |
| RH-60 | 5.40 | 1.86 | 9.00 | 0.83 |

### 3.2 Spatial variability of void ratio and permeability

Fig. 7 shows the spatial distribution of void ratio after consolidation together with the temperature distribution during consolidation. The increased temperature by the heat injection decreased the void ratio in the soft ground. Clearly, the higher the temperature increases inside the specimen, the lower the void ratio becomes. The increasing diameter of the sand drain also increased the temperature because of the higher thermal conductivity of sand. This trend can be observed more distinctly in Fig. 8 which shows the void ratio and permeability ratio to the initial value. Table 4 summarizes the comparison of the void ratio and the permeability ratio for all tests. The heat injection through the sand drain reduced both the void ratio and permeability ratio and they decreased by 6% and 13%, respectively. As the results, it is quite clear that higher heating temperature and larger diameter of the sand drain induced lower void ratio and permeability of soil. Therefore, the consolidation behavior was affected not only by the heating temperature but also by the diameter of the sand drain.

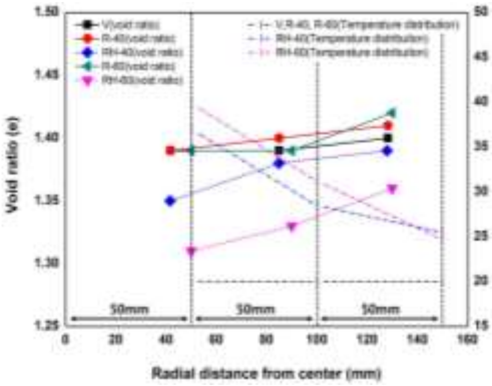



Fig. 7. Void ratio according to the varying temperature distribution

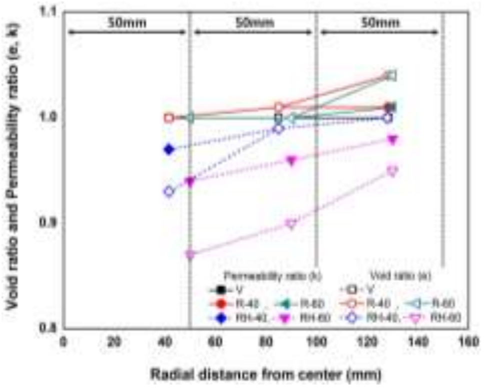



Fig. 8. Void ratio and Permeability ratio

Table 4. Comparison of void ratio and permeability ratio

| Test | Void ratio | | Permeability ratio | |
|---|---|---|---|---|
| | Range (e) | Ratio | Range (k) | Ratio |
| V | 1.39~1.39 | 1.00 | 0.82~0.82 | 1.00 |
| R-40 | 1.39~1.41 | 1.00~1.01 | 0.82~0.85 | 1.00~1.04 |
| R-60 | 1.39~1.41 | 1.00~1.01 | 0.82~0.85 | 1.00~1.04 |
| RH-40 | 1.35~1.39 | 0.97~1.00 | 0.76~0.82 | 0.93~1.00 |
| RH-60 | 1.31~1.36 | 0.94~0.98 | 0.71~0.78 | 0.87~0.95 |

## 3 CONCLUSION

In order to investigate the consolidation behavior with varying temperature and the diameter of the sand drain, a testing device to simulate soft ground with heat injection and various drain diameter was developed. Using the testing device, a series of consolidation tests with heat injection through the sand drain were conducted. During consolidation, vertical settlement and temperature at various locations inside the specimen were measured. After the consolidation test, the spatial variation of void ratio and permeability ratio in soft ground was also estimated. Based on the test results, the temperature distribution, the consolidation behavior, and the variation of void ratio and permeability in the soft ground according to temperature were analyzed. Test results showed that the increasing diameter of the sand drain with an internal heat resource expands the heating area. The increased temperature by heat injection increased the final settlement and decreased the void ratio and the permeability ratio of soft ground.

## ACKNOWLEDGEMENTS

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