

Research Article

Development of Ground Freezing System for Undisturbed Sampling of Granular Soils

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The ground freezing technique was first invented for the undisturbed sampling of the granular soils. With increasing necessity of liquefaction evaluation under earthquake loading, there has been more research with high-quality granular samples, with ground freezing techniques in the world. However, there has been little research on the ground freezing techniques since Korea had no records of liquefactions until the Pohang earthquake in 2017. Since more than 10 places were reported with liquefaction phenomena, it is required to assess the liquefaction potential with high-quality samples of granular soils. Therefore, in order to obtain undisturbed samples of granular soils, a new local ground freezing equipment and an operating system were developed in this study. The applied coolant was liquid nitrogen and circulated through a double tube inserted in the ground. To evaluate the performance of the system, laboratory scale tests were performed with water only and saturated fine sands. In the laboratory evaluation, a frozen soil column of 60 cm diameter was made after 20 hours and the average freezing rate was approximately 12 mm/hr in radial direction. After laboratory evaluation, the freezing system was applied in the field and the performance was evaluated with the 2D electrical resistivity tomography. In the field evaluation, the frozen region was 4 m diameter with 6.5 m depth in a cylindrical shape.

1. Introduction

Understanding and evaluating soil behaviour, under seismic loading, is of extreme importance for a correct aseismic design of structures and earthworks. This requires, among the others, the availability of high-quality undisturbed samples. As far as clay soils are concerned, the sampling techniques developed by La Rochelle et al. [1] and Lefebvre and Poulin [2] are still up to date but not applicable to granular soils. On the other hand, sampling of granular soils can be accomplished by in situ freezing or the so-called “gel-pushing technique” (Umehara et al. [3], Taylor et al. [4]). Soil freezing is the oldest method for both undisturbed sampling of granular soils (e.g., Micheal et al. [5]) as well as for temporary support during underground excavations (Shuster [6], Gioda et al. [7]).

The Niigata and Alaska earthquakes in 1964 (Yoshida et al. [8], Sato et al. [9] and Sozen et al. [10]) raised the

extreme importance of evaluating the risk of liquefaction of saturated loose granular deposits. So far, liquefaction risk is evaluated by in situ testing and by using simplified approaches. On the other hand, research has been conducted in the laboratory on high-quality undisturbed samples since the mid-80s (Miyoshi et al. [11], Yoshimi and Goto [12]). In Canada, field application of frozen ground sampling was reported for the liquefaction evaluation and regular check-ups on the Duncan Dam (Sego et al. [13]).

Since there were concerns about the influence of freezing on the mechanical response of the ground, various research has been performed on the frozen soils. Regarding the frozen soil mechanics, years of research and design experience have been collected and published in Andersland and Ladanyi [14]. Furthermore, the effects of freezing on soils have been investigated by various researchers (e.g., Ghazavi and Rustaie [15], Konrad and Samson [16], Qi et al. [17], Wei et al. [18], Yang et al. [19], Mahzad et al. [20],

and Li and Fan [21]). Lo Presti et al. [22] summarized the frozen soil-sampling techniques and analysed the cooling methods. They suggested specific types of soils applicable to the freezing sampling, how to proceed with the freezing sampling such as the cooling rate to avoid the volumetric expansion, how to inserting the freezing pipes and its possible disturbance radius, and how to sample the soil from the frozen ground. Based on the previous research, undisturbed sampling method by freezing can become a proper method of undisturbed sampling on granular soils.

Local records in South Korea indicate that every year over 60 earthquakes occur in the country, where 36 of them are recorded near multipurpose dams. Most of those dams were constructed many years ago and may not adequately be designed for the expected earthquake loads; therefore, regular dam safety assessments to evaluate the current state of the dam and investigate the dam structure and foundation in planning for seismic retrofit are important. In addition, seismic performance of dams founded on sand and alluvium deposits should be assessed. It is well understood that the key to the analyses or evaluation is the quality of the samples. Due to this requirement from the industry, ground freezing technique has been considered by researchers in many countries to develop new ground freezing systems for undisturbed sampling of sand material.

In this study, a local ground freezing system was developed as a first step to establish undisturbed sampling system of granular materials, and the developed system was evaluated in laboratory-scale soil samples and further on field.

2. Development of Ground Freezing System

2.1. Design of Freezing Unit. The ground freezing technique can be categorized into two types based on the freezing agent: liquid nitrogen type and brine type. The liquid nitrogen-type ground freezing system freezes the target ground by continuous heat exchange between the ground and the double tube filled with liquid nitrogen. Generally, the tank lorry is used to carry the liquid nitrogen to the double tube to provide the injection of liquid nitrogen through the inner tube and the exhaustion of evaporated nitrogen through the outer tube.

The heat exchange occurs between the liquid nitrogen and adjacent ground, and after transmitting the heat, the liquid nitrogen evaporates and exhausts through the outer tube to the atmosphere. The liquid nitrogen-type ground freezing system has advantages in that the freezing system takes up relatively small space, is easy to control, and takes short time to freeze ground. Furthermore, it can be applied with an appropriate modification, where the groundwater flows at a relatively high speed compared with the brine type freezing system. However, the liquid nitrogen is not circulated, so it should be supplied continuously for the target ground temperature (Stoss and Valk [23]).

On the other hand, the brine-type ground freezing system utilizes the solution of calcium chloride or magnesium chloride, which is called "brine" for the freezing ground. A refrigerating machine controls brine at $-20\sim-40^{\circ}\text{C}$ and the temperature-controlled brine is circulated through the

freezing pipe. After the heat exchange between low-temperature brine and ground, the temperature of the brine is lowered by the refrigerating machine. Compared with the liquid nitrogen-type ground freezing machine, where the liquid nitrogen is not recycled, the brine-type ground freezing system recycles the brine by controlling the temperature by the refrigerating machine. Compared with the previously mentioned liquid nitrogen type, the brine type system is more suitable for a large-scale construction site for long construction duration due to its large facilities including refrigerating machine and storage for the brine. It has disadvantages such as longer time required to freeze a certain area of ground than the liquid nitrogen type and is not suitable for the high-velocity groundwater flow.

Based on the comparison of the two above mentioned freezing systems, the liquid nitrogen-type ground freezing system has more advantages than the brine type in that the system takes relatively small space and the freezing duration is relatively short. Therefore, this study utilized the liquid nitrogen to develop a freezing system as shown in Figure 1.

The developed ground freezing system consisted of control part, freezing tube and necessary tube, and sensors. The freezing tube was made with double tube, where the liquid nitrogen was provided via the inner tube and the evaporated nitrogen exhausts through the outer tube. The diameter of the outer tube was designed and manufactured as 73 mm to utilize the conventional boring machine for NX size sampling tube. On the surface of the outer freezing tube, the multitemperature sensors were attached to measure the temperature of the freezing tube during the ground freezing operations. The injected amount of freezing agent, liquid nitrogen, was manually controlled based on the feedback data of liquid flux, temperature, and pressure in the current system. Eventually, the control program would be developed to automatically control the injection of freezing agent.

As a last step of the development of the ground freezing system, a stainless steel cylindrical chamber for the artificial soil deposit was manufactured to evaluate the freezing system. The structure was made with double-shell system to accommodate artificial soil deposit in the inside chamber ($\Phi = 597$ mm) and water in the outer chamber ($\Phi = 800$ mm). With these double chambers, the groundwater level could be controlled freely.

3. Laboratory Evaluation of Developed Freezing System

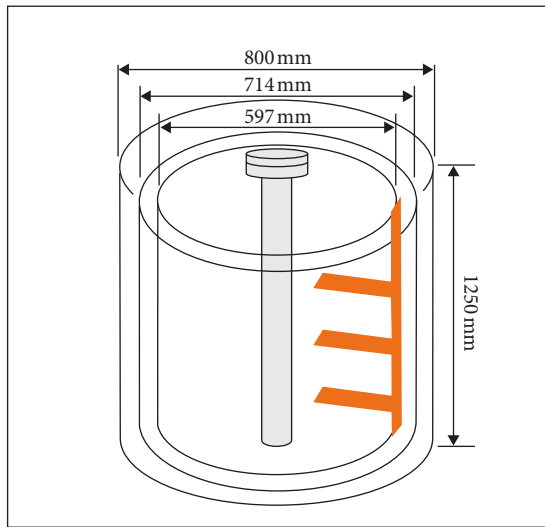
Experimental evaluations were performed twice on the previously described ground freezing system. As a preliminary test, the ground freezing system was filled with tap water at 5°C to check up the configuration and the core unit of the system at the first test. At the second test, the ground freezing system was evaluated with saturated fine sands. As shown in Figure 2, temperature sensors were installed at the top, middle, and bottom of the inner cell. Moreover, jigs were installed at those three points to accommodate many sensors for radial monitoring the temperature inside the inner chamber. Particularly, at the middle point of the freezing pipe,



FIGURE 1: Developed ground freezing system.

12 temperature sensors were installed at every 20 mm distance from the outer freezing pipe to evaluate the freezing of soil or water at the middle point of the freezing pipe.

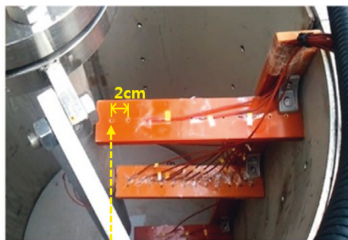
3.1. *Water Freezing Experiment.* For this experiment, the liquid nitrogen was injected with 60 Nm³/h (cf. 1 Nm³/h = 1.28 kg/h) to the chamber filled with tap water. Since the



(a)



(b)



(c)

FIGURE 2: Installation of temperature sensors. (a) Schematic diagram of freezing chamber, (b) installed temperature sensor, and (c) temperature sensors on jigs.

main purpose of the water freezing experiment was to ensure the performance of the core unit of the freezing system, the injection of the liquid nitrogen was stopped when the freezing of water was observed (Figure 3).

After 55 min of injection of liquid nitrogen, the water in the chamber was drained and the formed ice was investigated. Based on the visual observation, the ice forms, in a relatively uniform cylindrical shape, are shown in Figure 4. However, the diameter of the upper ice column was a little bit smaller than that of the lower because the water surface is in contact with the atmosphere, where the temperature was relatively higher than that of the water inside the chamber.

The average freezing rate was measured as 26.2 mm/h (24 mm/55 min), which was much faster than the reported freezing rate of soils 2–7 mm/h. The convection flow of the water cooled down the whole water inside the chamber while the convective flow could not be expected in the pore water



FIGURE 3: Water freezing experiment.

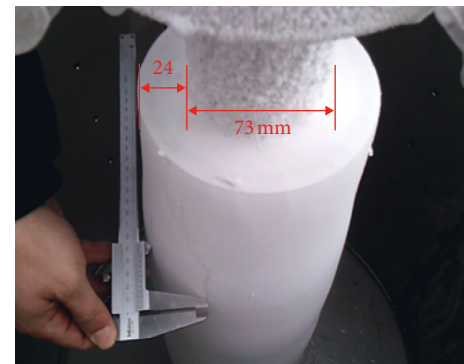


FIGURE 4: Ice column after 55 min injection of LN₂.

in the soil mass. Due to this difference, the direct comparison of freezing rate between the water and saturated soils was not meaningful.

3.2. Saturated Sand Freezing Experiment. The second test was performed on a saturated sand sample. For the full saturation, the sand was compacted at every 30 cm thick layer in the inner chamber and the outer chamber was filled with water flowing upward to the inner chamber. The full saturation was ensured with visual inspection when the water level of the inner chamber became similar to that of the outer one. As shown in Figure 5, the freezing process could be observed from the surface of the sands. When the freezing started, the liquid nitrogen was continuously injected to the inner pipe of freezing pipe for 20 hrs. After that, the minimum amount of liquid nitrogen was applied to maintain the frozen state for 4 hrs. A total 24 hrs was elapsed and about 1800 kg of liquid nitrogen, average 69.2 kg/h, was consumed. Figure 5 shows progress of freezing on top of the sand sample.

However, the freezing process was not as smooth as expected as the atmospheric temperature was not controlled, liquid nitrogen tank was exchanged frequently, and the amount of the injected freezing agent was manually controlled. The effect of unsmooth freezing process is shown in Figure 6.

A frozen soil column with 350 mm diameter including 50 mm thick ice was obtained after 24 hrs of freezing. The average freezing rate was calculated as 12 mm/h.



FIGURE 5: Progress of freezing on top of the sand sample.

Figure 7 shows the extraction of frozen soil sample and the measurement of surface temperature of the frozen sample. The surface temperature was measured at -8.1°C , which was 4°C higher during the freezing due to the elapsed time of extraction.

4. Field Evaluation of Developed Freezing System

4.1. Site Condition. To evaluate the applicability of the developed ground freezing system and to improve the ground freezing system for the field application, the system was installed in the field site located in the southern part of

Andong city at Gyeongsang-Buk Province in Korea. Two borings were performed to investigate the stratigraphic profile. The sand layer was encountered at the depth of $3.4\sim 3.7\text{ m}$ from the ground level and 4.4 m -thick sand with gravel layer was located under the sand layer. Below the sand with gravel, the sandy gravel layer was found. The groundwater level was located at the depth of 3.5 m from the surface level. The targeted freezing depth was around 10 m from the ground surface, including the top sand layer, sand with gravel, and sandy gravel.

4.2. Field Installation of Ground Freezing System. In the laboratory evaluation, the liquid nitrogen was manually controlled in the injection to the freezing pipe. Prior to the field application, an automatic injection module of freezing agent was developed to minimize the use of freezing agent. The automated open-close valves were installed on the LN_2 supply system. The valve was closed if the temperature of the freezing pipe was below the specified temperature, and the valve was open if the temperature was above the specified one so that the temperature of the freezing pipe was maintained in a certain range. For the efficient exchange of the heat between the freezing pipe and adjacent ground, the pressure of the supply LN_2 was controlled below 1 kg/cm^2 . By maintaining the minimum pressure difference between LN_2 supply and atmosphere, the flow rate of the freezing agent was controlled low enough to have sufficient time for heat exchange.

The ground freezing system was installed on the site by the following order as shown in Figure 8. First, to evaluate the ground freezing based on the electrical resistivity characteristics, two holes were bored at 3 m distance from the freezing pipe for the tomography tests prior to the freezing pipe installation. Two holes with 1.5 m spacing were bored for the freezing pipes. After inserting the 8.5 m long freezing pipe, the liquid nitrogen (hereafter denoted as LN_2) tank was connected to the freezing pipe and the exposed portion of the pipe system was insulated. After the setup of the freezing system, the freezing agent, LN_2 was supplied continuously for 72 hours . For the continuous supply, LN_2 was recharged with the tank lorry once a day, twice in total.

As soon as the LN_2 was injected, the temperature change of the exhausted gaseous nitrogen (hereafter GN_2) confirmed the heat of the LN_2 was exchanged with the ground. Within 30 minutes , after the injection of LN_2 , the internal temperature of the freezing pipe became below zero degree and approximately after 2 hours , the internal temperature of the freezing pipe was around -50°C and that of the exhausted GN_2 was around -116°C . The amount of the exhausted GN_2 was stabilized as $150\text{ Nm}^3/\text{hr}$. Once the fluent injection was confirmed, the injected amount of LN_2 was controlled automatically. The automatic injection was controlled by the temperature of the exhausted GN_2 at -120°C . By controlling the temperature at the exhausted GN_2 , the temperatures of freezing pipes were maintained in the range between -60 and -80°C and the injected amount of LN_2 in the range between 80 and $170\text{ Nm}^3/\text{hr}$.

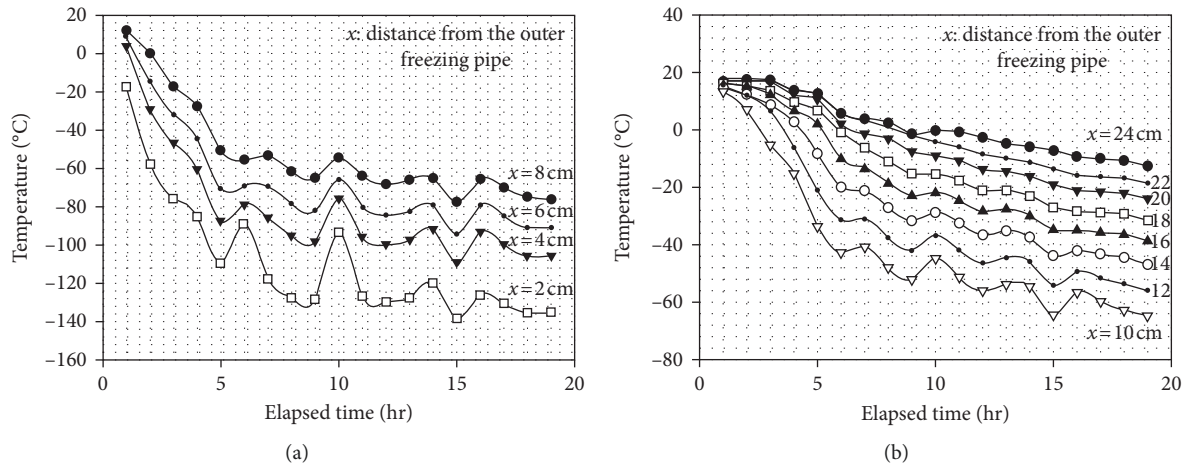


FIGURE 6: Temperature with elapsed time at various locations from the freezing pipe.

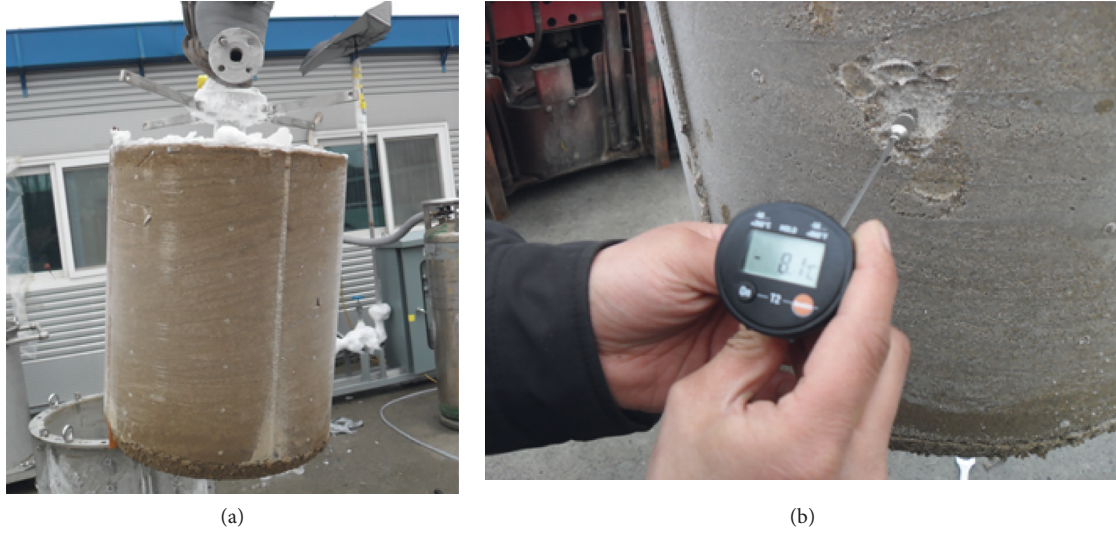


FIGURE 7: Extraction of frozen sand sample and measurement of surface temperature.



FIGURE 8: Continued.



FIGURE 8: Ground freezing system installation procedure. (a) Freezing pipe insertion, (b) inserted freezing pipe, (c) installation of LN₂ supply system, (d) LN₂ supply connected to freezing pipe, (e) pipe insulation, (f) LN₂ supply, (g) automated control panel, and (h) freezing pipe after LN₂ supply.

After 72 hours of injection, the ground surface was frozen with a diameter of 700~800 mm with visual inspection.

4.3. *Evaluation of Developed Freezing System by Electrical Resistivity Tomography Test.* To assure the performance of the developed freezing system on the field, it is required to determine the freezing region properly. In the laboratory scale experiments, it could be measured with the buried

thermometers but another method should be used in the field application. Even though it is artificially frozen ground, those site investigation techniques on the permafrost can be applied to evaluate the performance of the developed systems. Various geophysical methods were researched on the permafrost regions due to the practical difficulties on the frozen ground.

The effectiveness of the geophysical methods on the frozen ground has been reported by many researchers

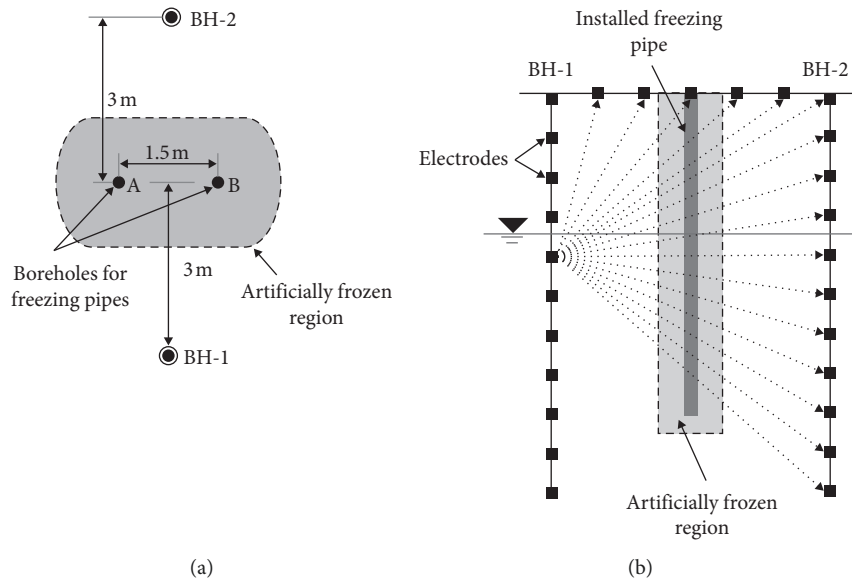


FIGURE 9: (a) Schematic diagram of the plan and (b) section views of the ground freezing and tomography boreholes.

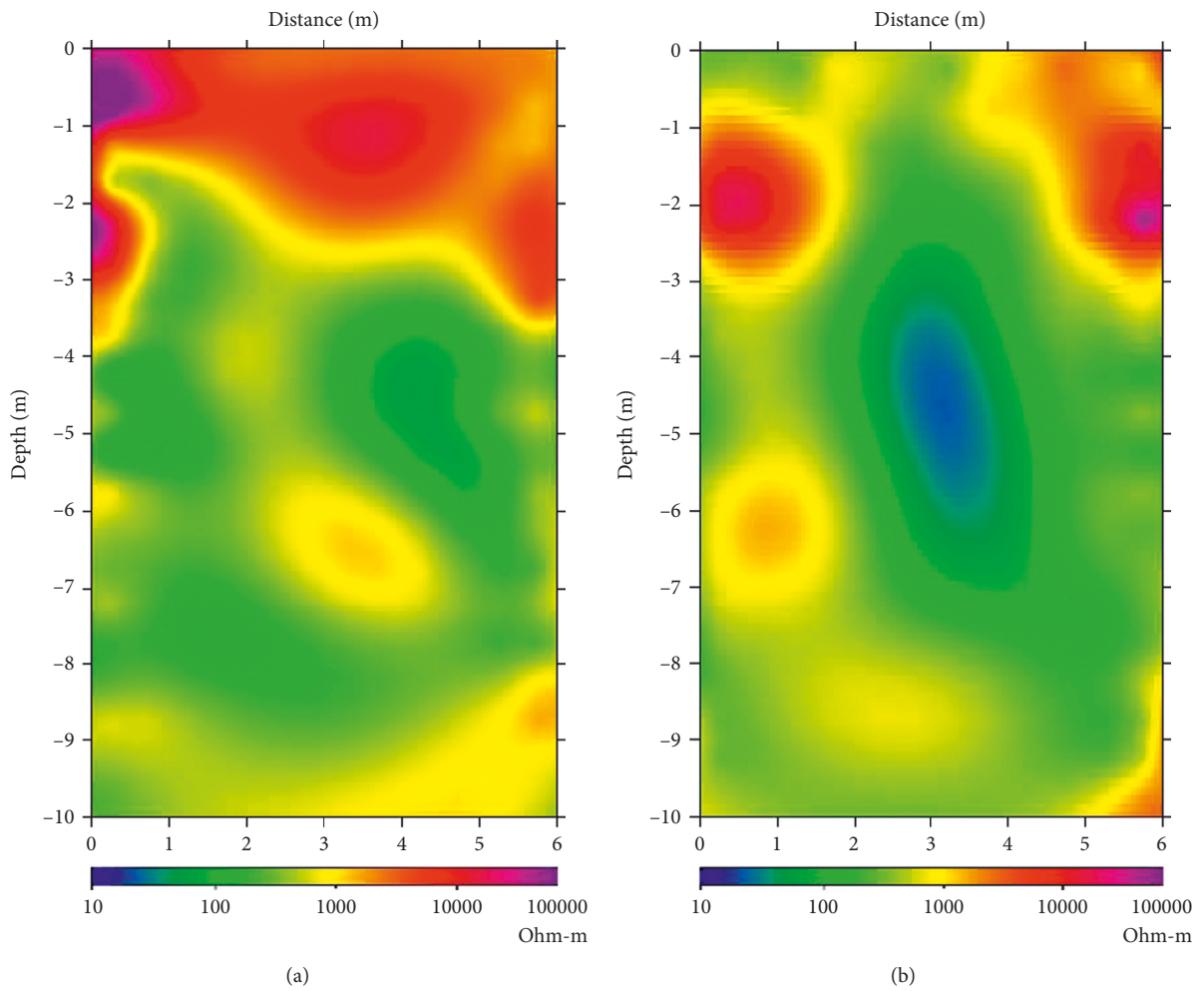


FIGURE 10: Electrical resistivity contours of 1st test (a) and 2nd test (b).

(e.g., Hoekstra and McNeill [24], Scott et al. [25], Kneisel [26], Kneisel et al. [27], Christ and Park [28], and Kim et al. [29]). Among various geophysical survey methods, the wave propagation characteristics can be useful to identify the frozen and unfrozen state of the soils but it is hard to define the frozen area in the field. Therefore, the electrical resistivity with tomographic analysis is used to evaluate the performance of the developed system by defining the frozen region.

The electrical resistivity tomography tests are originated from the electrical resistivity tests at surface. The electrodes are installed surrounding the target area at boreholes and on surfaces, and tomography can be obtained by the measured electric potentials generated from the underground electric currents. The electrical resistivity tomography test shows higher resolution and resolving power than the conventional electrical resistivity by installing electrodes in the boreholes surrounding the target area (Shima and Sakayama [30]).

For the evaluation of the artificial ground freezing, two boreholes down to 10 m depth were made perpendicular to the ground freezing direction for the 2D tomography. Figure 9 shows the schematic diagram of the plan and section views of the ground freezing and tomography boreholes. The freezing pipes for the ground freezing were installed with 1.5 m spacing and the boreholes, BH-1 and BH-2, for the tomographic evaluation were installed to the depth of 10 m with 3 m spacing perpendicular to the line of freezing pipes. The electrodes of each borehole and on the surface were installed with 1-m spacing for both borehole/borehole data and borehole/surface data acquisition. Total number of the installed electrodes was 27. Eleven electrodes were installed in each borehole and 5 electrodes on the surface.

For the installation of the electrodes, the boreholes were made to the depth of 10 m with a casing. The 30 mm diameter of PVC pipes where the electrodes were attached with 1 m spacing were inserted in the casing. After extruding the casing, the gap between the PVC pipes and boreholes were backfilled with in situ soils to minimize the contact resistance between the electrodes and ground.

The tomography tests were performed 4 times in total, to evaluate the effects of ground disturbance of pipe installation and ground freezing. The first test was performed before installing freezing pipes, the second test after the freezing pipes installation to evaluate the ground disturbance due to pipe installation, and the third and fourth tests after 30 hours and 50 hours, respectively, of nitrogen injection to evaluate the ground freezing.

4.4. Evaluation by Tomography Tests. Figures 10(a) and 10(b) show the electrical resistivity contours before the ground freezing. Figure 10(a) is the electrical resistivity contours back-calculated from the first tomography tests before the freezing pipe installation and Figure 10(b) shows those from the second tests after the freezing pipe installation to evaluate the disturbance effect due to the pipe installation.

At the first tomography test, there could be some effects of disturbance due to the injected water for the electrode

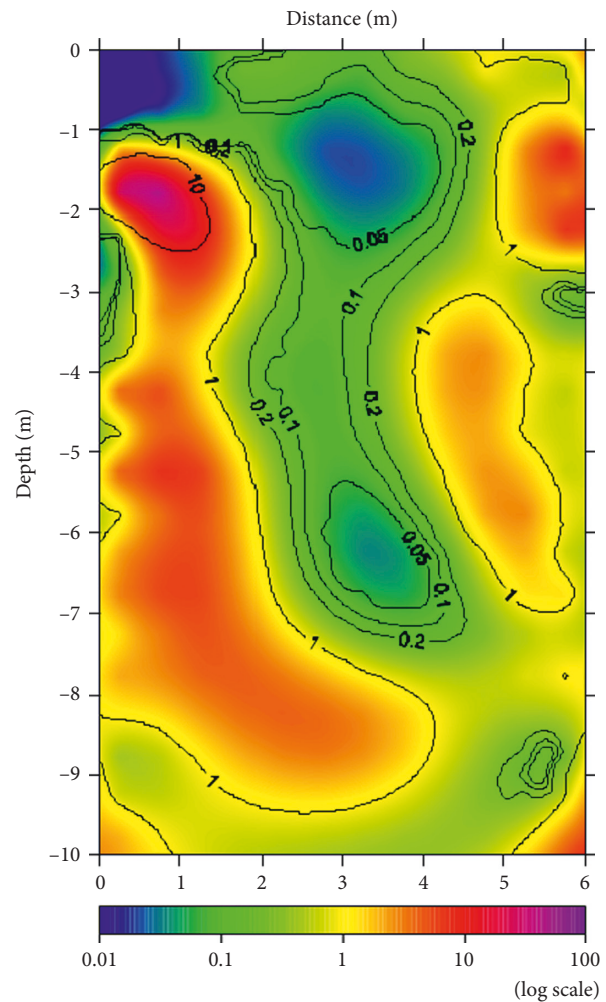


FIGURE 11: Electrical resistivity ratio contours of 2nd test over 1st test.

installations. Particularly, the electrodes installed above the groundwater showed very high electrical resistivity depending on the backfilling conditions. As shown in Figure 10(a), up to several thousands of electrical resistivity are detected down to the depth of 3.5 m, above the groundwater level, and electrical resistivity values are lower than 1000 ohm-m below groundwater level. Based on the electrical resistivity results, the sand and sand with gravel layer can hardly be detected while the groundwater level can be clearly observed.

At the second tomography test, the disturbance due to the injected water affected the results more distinctly. The installations of the freezing pipes and the effects of the injected water clearly lowered the electrical resistivity values near the surface as shown in Figure 10(b). Furthermore, the lower values of electrical resistivity are observed in the middle where the 200 mm diameter metal freezing pipes are installed.

Figure 11 shows the ratio contour of electrical resistivity between the first and second tomography tests to evaluate the effects of steel casing installation and ground disturbance due to pipe installation. The ratio of 1 represents no change

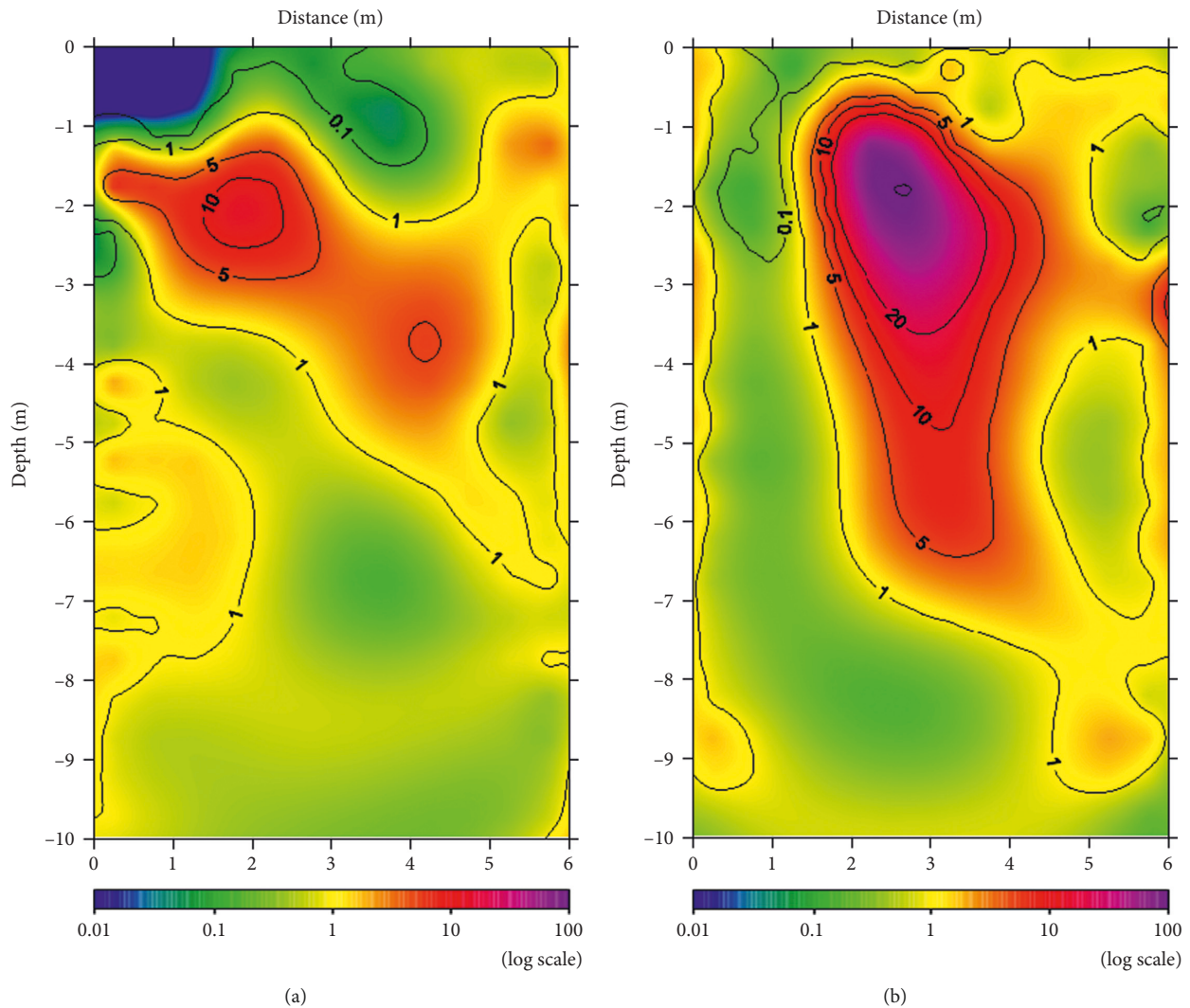


FIGURE 12: Electrical resistivity ratio contours of the 3rd test over 1st test (a) and (b) 3rd test over 2nd test.

in ground conditions and the ratio of 10 and 0.1 represent 10 times increase and 10 times decrease, respectively. By plotting the ratio between the first and second tomography tests, the aforementioned lower electrical resistivity area due to the metal freezing pipe is clearly observed in Figure 11.

There might be errors due to ignorance of the freezing pipe installation if the first tomography test result is considered as the only control group. On the contrary, if the second tomography test result is considered as the only control group, the frozen area can be overestimated due to the lower electrical resistivity values of the metal pipes. Therefore, both the first and second tomography test results are considered as control group to analyse the freezing effects from the third and fourth tomography tests.

Figures 12(a) and 12(b) show the ratio of electrical resistivity after 30 hours of nitrogen injection and the first and the second tomography tests, respectively. Although Figure 12(a) does not clearly show the effect of frozen area, Figure 12(b) shows a distinct frozen area in the middle, where the electrical resistivity increases more than 5 times. This indicates the vicinity of the freezing pipe is getting

frozen, resulting in increase of the electrical resistivity at the time of the third tomography tests. Based on Figure 12(b), the frozen area in the horizontal direction is less than 2 m from the freezing pipes and the freezing depth is about 6.5 m from the surface.

Figures 13(a) and 13(b) show the ratio of electrical resistivity after 50 hours of nitrogen injection and the first and the second tomography tests, respectively. Figure 13(a) still does not clearly show the effect of frozen area but Figure 13(b) more clearly shows the frozen area than Figure 12(b) with electrical resistivity increase more than 20 times. However, the frozen area is not extended from the third tomography tests. The horizontal area is still within 2 m from the frozen pipes and the frozen depth, where the ratio is greater than 5, is still about 6.5 m. This implies that the 50 hours of nitrogen injection results approximately in 2 m horizontally from the freezing pipe and 6.5 m with the 8.5 m of freezing pipe.

Unlike the lab scale evaluation, the heat loss in the field condition presumably prevents the development of freezing face deeper and wider. Thus, the longer duration of nitrogen injection from 30 hours to 50 hours does not extend the

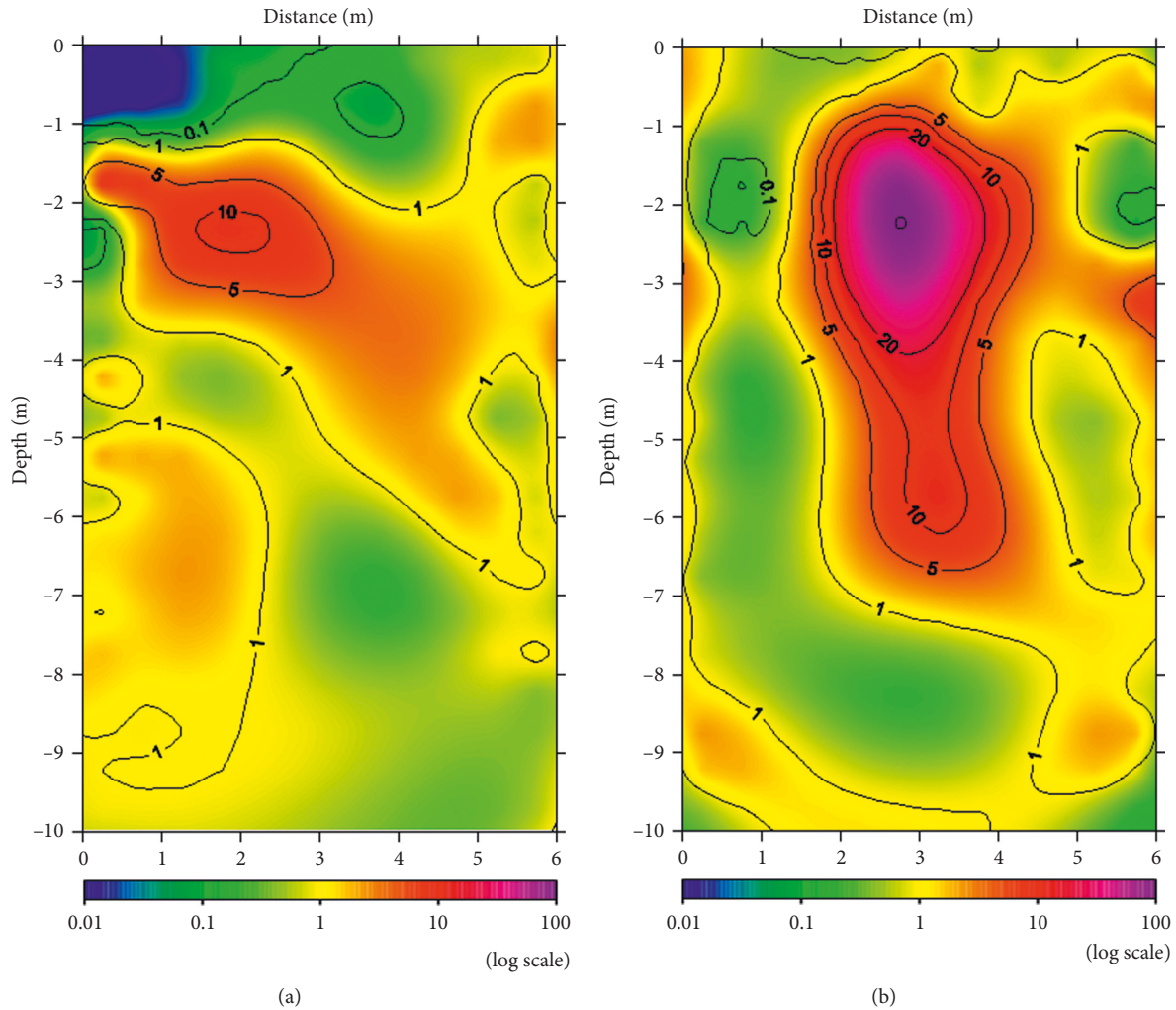


FIGURE 13: Electrical resistivity ratio contours of 4th test over 1st test (a) and (b) 4th test over 2nd test.

frozen area but enhances the already frozen area increasing the electrical resistivity more.

5. Conclusions

In this research, a local ground freezing system was developed for undisturbed soil sampling of granular soil. The system was developed as a prototype and core equipment was evaluated in a laboratory scale. The developed system is modified to be applied to the field evaluations.

Based on the laboratory experimental results, an average freezing rate of 12 mm/h was observed when the freezing pipe was fully filled with liquid nitrogen. The average freezing rate showed that the undisturbed sampling could be performed on the frozen ground after approximately 24 hours. In addition, it was observed that the freezing face was uniformly developed cylindrically from the freezing tube.

The tomography tests can effectively detect the ground condition changes due to pipe installation, ground disturbance and ground freezing. However, care should be taken

to choose a control group to analyse the freezing area in that the tomography results are sensitive to the ground condition not only due to the freezing, but also ground disturbance by boring and installing pipes.

The field evaluation of the developed ground freezing system showed that the electrical resistivity of the frozen area increased about 5 times compared with the unfrozen one. The frozen region was about 4 m diameter and 6.5 m depth in an approximate cylindrical shape. Based on the limited test data of LN₂ injection for less than 50 hours, the freezing face was not further developed but the already frozen area was becoming harder presumably because of the lower unfrozen water contents.

Based on the lab and field evaluation, the freezing system developed herein can effectively freeze the targeted area. However, since the main purpose of the developed system is to obtain the undisturbed granular soil samples, the mechanical behaviour or liquefaction potential should be evaluated compared from the samples obtained both by conventional sampling method and the developed freezing system. Furthermore, the correlation between the electrical resistivity results and the

liquefaction potential should be investigated with more field and lab test results.

Data Availability

All the data used in this research are provided in the manuscript and numeric data can be provided upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

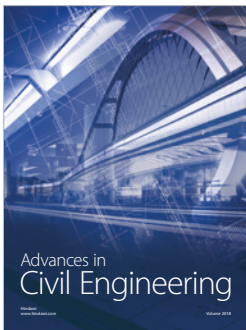
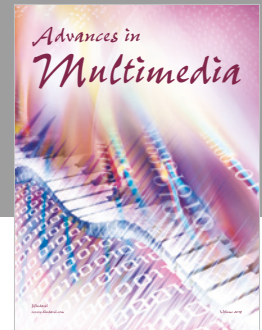
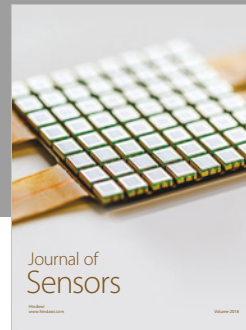
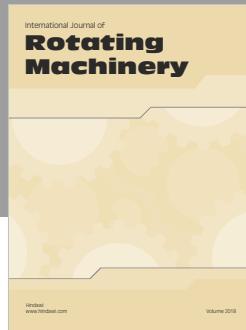
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