applied sciences

MDPI

Article

A Study on the Improvement Effect and Field Applicability of the Deep Soft Ground by Ground Heating Method

Mincheol Park

Kumoh National Institute of Technology, Gumi-si 39177, Korea; xlage0@kumoh.ac.kr; Tel.: +82-10-5123-8462

Received: 25 April 2018; Accepted: 21 May 2018; Published: 23 May 2018

Abstract: The soft ground in coastal areas should be treated when it needs to be used for the sustainably developed of urban or industrial complex constructions. The ground heating method for soft ground improvement was applied in Eastern Europe in the 1960s, but it was not widely used due to economic and environmental problems. The author developed a device for improving soft ground using an electric heating pipe. This paper investigates the improvement effect and field application of deep soft ground by the ground heating method using the electric heating pipe. Ground heating increases the temperature of the deep soft ground and increases the tip resistance of the static electronic piezo-cone penetration test. Additionally, the pressure of the pore water decreases because the pore water is evaporated due to the ground heating. As a result of the experiment, it was verified that there was an improvement in the effect of deep soft ground by the ground heating method. With ground heating for 96 h, the tip resistance was increased by 61% at a point 0.35 m horizontally away from the electric heat pipe, 22% at 0.97 m, and 2% at 1.31 m. As a result of the field test, it was found that there were no problems in the power supply of the diesel generator and the control panel. It was easy to install the electric heating pipes in the deep soft ground. However, due to boring, the ground was disturbed and water vapor was discharged through this gap. To minimize the discharge of water vapor, it is necessary to drive the electric heating pipe.

Keywords: sustainable coastal development; soft ground improvement; ground heating method; electric heating pipe; CPT test

---

1. Introduction

Development by civil engineers often places higher priority on safety and economic feasibility than on the environment, coexistence, and the sustainability of the Earth. In particular, soft ground with mud flats that serve as purifiers of seawater have lost their sustainability due to developments by civil engineers. Soft ground is made of clay and its strength varies depending on the water content [1–4]. Civil engineers remove the pore water in clay to increase its strength and then build buildings or roads on top of it. To remove pore water from clay, a large amount of sand is taken and loaded on top of it, and the water, deep under the ground, is drained through a sand spout by drilling a hole into the ground [5–12]. Therefore, if a reclamation project involves the development of clay ground, it requires a supply of sand. Usually, this involves cutting a mountain, collecting sand from it, and transporting it to a reclamation-site [13,14]. Such a development method can pose damage to mountains and roads. Instead of this, a way of removing pore water by clay heating can prevent the degradation of nature and ensure the sustainability of mud flats.

The typical soft ground improvement method is preloading with prefabricated vertical drains. Excess pore water pressure is generated by the preloading of the embankment in cases of low permeability soils. The pore water excess is drained by vertical prefabricated drains [2,15–17]. However, due to large settlements and/or filter clogging, the vertical prefabricated drain is blocked and excess pore water is not drained [18,19].

As an alternative, other ground improvement methods such as vacuum consolidation, jet grouting, deep mixing, and ground heating can be used.

The deep mixing method improves the soil by bonding and consolidating soil particles using a hardening agent [20]. It prevents the ground surface settlement and increases the soil strength. However, a precise on-site construction is required and the workplace should be large enough because of the equipment dimensions.

Vacuum consolidation is a method of making the ground soft under a vacuum state and using atmospheric pressure instead of the embankment load for preloading. The advantages of this method are the fact that the consolidation effect is assured up to deep depth, the shear fracture due to preloading can be prevented by using atmospheric pressure, and the construction period and workability are good. However, maintenance of the vacuum state due to airtightness is very important, so measurement management is required.

The jet grouting method is a method of injecting high-pressure injection material and air into the soft ground borehole and mixing the scoured soil and the injected material to form a solid cylindrical body. The advantage of this method is that the improvement effect is excellent.

The cost of the construction is high and, in areas affected by seawater, the hardening and improvement effects are poor. The material loss is high due to the high-pressure injection and the solid cylindrical body is not uniform. Moreover, this method is not applicable to peat soils and is less effective in clayey soils. Another ground improvement technique is the ground heating method.

There is an improved soft ground method utilizing ground heating. The ground heating method using fossil fuels was developed by Beles and Stănculescu [21] and Litvinov [22], as shown in Figure 1. The ground heating method, applied in the Soviet Union and in Romania, which is rich in fossil fuels, is a method of injecting and burning gaseous fuels mixed with air into soft ground. Because the pore water of the clay dissipates by burning fossil fuel, the water content of the clay decreases and the strength increases in a short time (about 10–20 days). Additionally, the color of the soil particles changes [23,24]. Most of the soil was non-plastic at 400–600 °C [25–31]. As a result, the strength of the clay sintered due to the rapidly increased ground heating, and the ground could be improved and utilized as a construction-site [1,22,23,29]. However, it this method was not widely used due to economic and environmental problems [17].

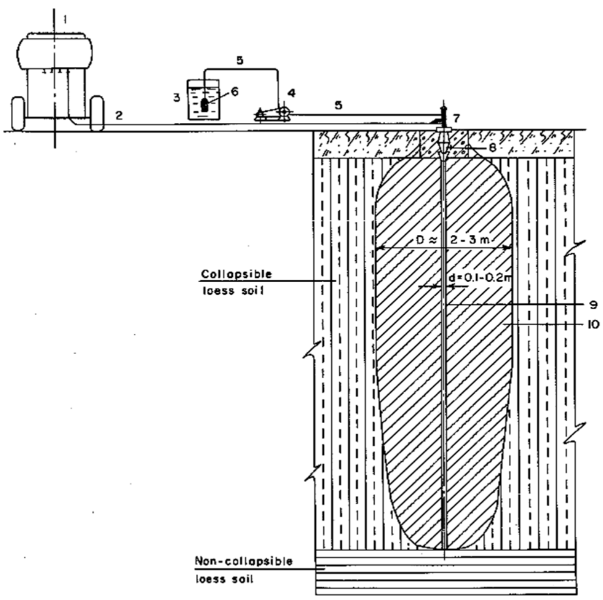

Figure 1. The conceptual diagram of the ground heating method using fossil fuel proposed by Litvinov [22].

Recently, a ground heating method using electric energy has been proposed in place of fossil fuel. Park, Im, Shin, and Han [17] developed an electric heating device that converts electric energy into thermal energy by the electric resistance method and improved the trafficability of the construction equipment on the soft ground. Additionally, an experimental study on the acceleration of consolidation using an electric heating device was conducted by Park, et al. [32] and they reported that the pore water was dissipated due to ground heating and that the acceleration of consolidation is excellent. Park, Lee, Jang, and Han [19] conducted a heat transfer analysis of silty sandy soil by electric heating and compared the temperature changes of the experiment using a linear heat source model and numerical analysis. Park [2] conducted two case experiments to investigate the temperature changes of the ground, depending on whether or not water vapor was discharged. The heat-transfer properties of the saturated ground changed according to the presence and absence of water vapor discharged by the heating. If water vapor was discharged, the temperature dropped dramatically due to heat loss. To apply the ground-heating method to actual field sites, it is necessary to restrain the discharge of water vapor, as reported by Park, Lee, Jang, and Han [19]. The theoretical solution and the numerical analysis method applied to the design of the ground heat exchanger were used to calculate the temperature change by ground heating. Compared with the conditions in which the water vapor was discharged, many differences appeared. This is because the phase change of the pore water and the heat-transfer process of the water vapor were not considered [2].

However, these studies [2,17,19,32] mainly focused on improving the surface soils of soft ground (less than 2.0 m). The ground heating method using fossil fuel performed by Beles and Stănculescu [4] and Litvinov [5] was successful in improving the soil at depths of up to about 20.0 m. The ground heating method using an electric heating tube must also be conducted at a deep depth to verify the improvement of the soft ground. Additionally, the thermal energy loss due to the discharge of water vapor occurred in the ground heating experiment conducted by Park [2]. At deep depths of soft ground, the loss of heat energy may not occur because the earth pressure cannot discharge the water vapor. Therefore, it is necessary to apply the ground heating method using an electric heating pipe at the deep soft ground. Additionally, existing studies carried out experiments on a laboratory scale [19,32]. Park, Im, Shin, and Han [17] have improved the shallow ground in the field, but have not been able to evaluate the power supply and the construction performance. For the ground heating method using electric heating pipes to be put to practical use, it is necessary to examine the practical application of the construction performance and power supply in the same deep soft ground. As proposed by Park [2], a design method is needed to estimate the heat transfer characteristics and strength improvement effects on the soft ground.

This paper is a study on the improvement effect and the field application of deep soft ground by a ground heating method using the electric heating pipe. An electric heating pipe was installed at a depth of 0.0–6.5 m and the effect of the temperature variation, the water vapor discharge, and the soil strength were verified by heating the ground. Powered by a diesel generator and control panel, the deep soft ground was heated using an electric heating pipe for 96 h, and the variation of the ground temperature and the vapor pressure of water vapor were measured using a thermometer and a pressure gauge. Additionally, the improvement effect of the deep soft ground before and after heating was verified by a static electronic piezo-cone penetration test (CPT). Finally, the field applicability was examined.

2. Ground Heating Method Using Fossil Fuels

2.1. Introduction

The ground heating method proposed by Beles and Stănculescu [21] and Litvinov [22] uses the thermal energy of fossil fuels. It is a method of drilling the ground and injecting fossil fuels mixed with air using a nozzle and burning it in the soft ground. Because the combustion process occurs directly in a closed borehole, it controls the chemical properties due to the control of the temperature and the soil combustion. The seepage of heated air into the pores due to the direct combustion of fuel and air causes a change in the properties of the soil. This method successfully improves the settlement characteristics and bearing capacity by heating yellow soil to the boring depth of 10–15 m during field construction.

Figure 1 is the conceptual diagram of the ground heating method proposed by Litvinov [22] that uses fossil fuels. It is a method of drilling the ground and injecting fossil fuels mixed with air using a nozzle and burning it in the soft ground. Because the combustion process occurs directly in a closed borehole, it controls the chemical properties due to the control of the temperature and the soil combustion. The seepage of heated air into the pores due to the direct combustion of fuel and air causes a change in the properties of the soil. This method successfully improves the settlement characteristics and bearing capacity by heating yellow soil to the boring depth of 10–15 m during field construction. The construction equipment used for the ground heating method is as follows: 1. Compressor; 2. Pipeline; 3. Container for liquid fuel; 4. Pump for supplying fuel under pressure into the borehole; 5. Fuel pipeline; 6. Filters; 7. Nozzle; 8. A combustion chamber with a cover; 9. Borehole; 10. A zone of thermic stabilization of the soil. Fossil fuel mixed with air was forced into the borehole without a discharge hole and the yellow soil was heated to a radius of two to three meters. The diameter of the heating hole is 15–20 cm, the depth is about 8–10 m, and the heating time is about 8–10 days. If the time of the thermal treatment is increased, it is possible to treat the ground of about 100 m^3 at a depth of 3–15 m.

2.2. Problems in Practical Use

However, the ground heating method using fossil fuel proposed by Litvinov [22] has a complicated heating system and environmental and economic problems (Figure 2). A device for mixing fossil fuel and air in the gaseous state, a nozzle for injecting said gas into the boring hole, a pipe, and a generator are required. The boring hole should be sealed so that the mixed fuel and air does not escape to the surface. Because fossil fuels are burned in the ground, environmental problems arise and as the cost of fossil fuels is high, the economic efficiency is low.

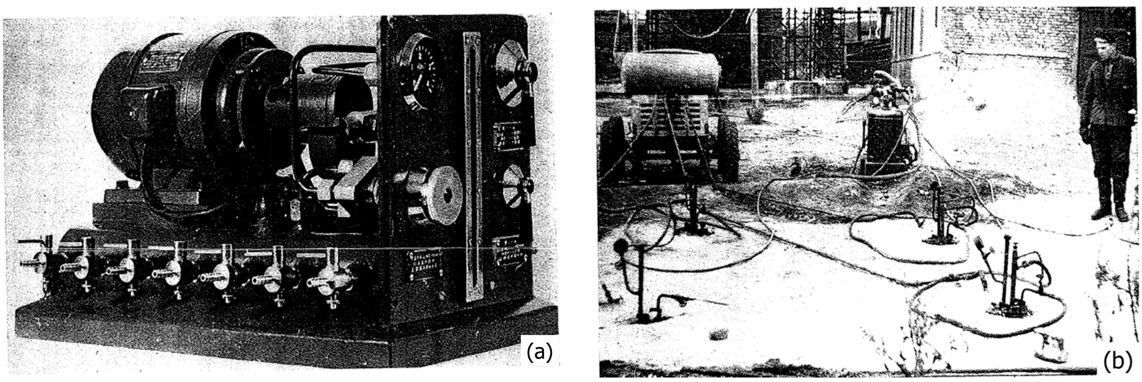

Figure 2. Photos of the ground heating equipment and application proposed by Litvinov [22]. (**a**) The equipment for mixing fossil fuel and air; (**b**) a photo of the construction the soil heating method.

3. Field Ground Heating Experiment

3.1. An Electric Heat Pipe for the Experiment

In this study, an electric heating pipe, the same device developed by Park et al. in 2012, was used to improve the deeper soft ground. The electric heating pipe was made of nickel-chrome, the protective tube was made of stainless steel (SUS 304), and the heat transfer medium was made of magnesia (MgO) (Figure 3a). It was designed and manufactured to maintain the surface temperature at 450 °C due to the heat generation of the nickel-chromium wires using a current of 3 kW (1 kW/m) [33]. Figure 3b is an image of an electric heating pipe manufactured for the experiment. The total length of the electric heating tube was 4.0 m, the heating part was 3.0 m, the non-heating part was 1.0 m, and the diameter was 22.7 mm. In the indoor experiments performed by Park [2], the lead wire of the electric heating pipe for the supply of electric power snapped due to the ground heating. This is because the lead wire was covered in PVC (polyvinyl chloride). Therefore, to prevent the lead wire from snapping due to the ground heating, the length of the non-heating part was made to be 1.0 m.

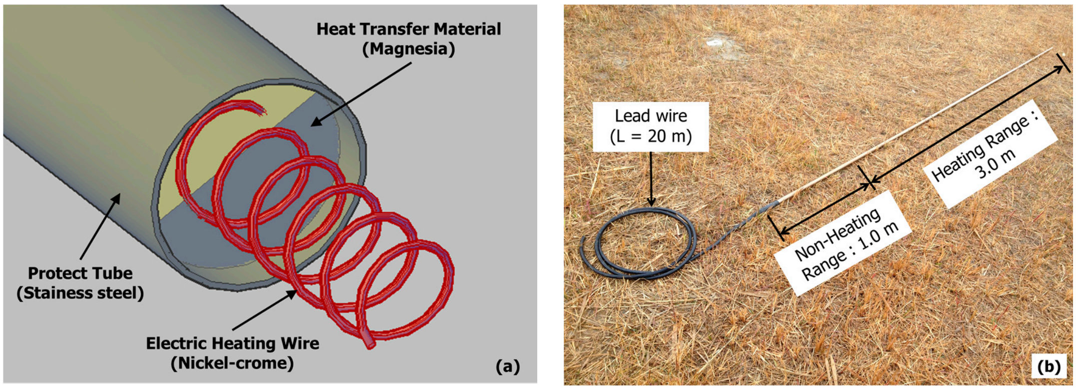

Figure 3. The electric heat pipe in the file test. (**a**) Section view; (**b**) Overall view.

3.2. Experimental Site and Ground Condition

The experimental site is Hwaseong City, in the Gyeonggi Province, located in the West Sea area in the Republic of Korea. This area has a difference of 8.0 m between the rise and fall of the tide and the marine clay is widely composited. The surface layer of the experimental site is about 1.0–1.5 m in the over-consolidated clay and marine clay at a depth of 6.0–14.0 m below it. The area used in the experiment is 900 m^2, with a width of 30 m, and a length of 30 m.

Table 1 shows the soil profile of the site and the results of the standard penetration test (SPT). In the left column of Table 1, BH means Borehole. The upper part of the soil profile of the experimental site is composed of marine clay, and the area below it is composed of weathered soil (WS), weathered rock (WR), and soft rock (SR). The marine clay is very soft with the N value of the standard penetration test being between 0/30 and 5/30.

Table 1. The soil profile and the result of standard penetration test (SPT).

Borehole No.	Marine Sediments (m)		WS (m)	WR (m)	SR (m)
	Clay	Sand			
BH-9	6.0	-	1.0	-	1.5
BH-10	14.0	6.5	-	-	1.5
BH-12	10.2	8.8	1.0	2.5	-
SPT N	0/30–5/30	3/30–50/20	50/28–50/14	50/5–50/4	-

The test site is BH-10 and Figure 4 shows the physical and engineering properties of the clay. Figure 4a shows the over-consolidation ratio (OCR) profile. The OCR from the surface and down to 5 m was 2.06 on average, while the OCR below 5 m is, on average, 1.57. Figure 4b shows the Casagrande plasticity chart, in which CL was judged to be clay and showed a low compressibility with a liquid limit of no more than 50%. Figure 4c shows the natural water content, with an average of 40.2% from the ground surface down to 5.0 m, and an average of 37.1% below 5.0 m in depth. Figure 4e represents the compression index, an indicator of the compressibility of the clay. The compression index was 0.43–0.44 down to 10.0 m in depth. Figure 4f shows the undrained shear strength of the clay. The physical and engineering properties of the ground in the experimental site shown in Figure 4 are almost similar to the engineering characteristics of marine clay in the West Coast of Korea investigated by Park [34]. These marine clays were transported and deposited by seawater and exist at depths of about 10–15.0 m in the Gyeonggi Province in the west coast of Korea. The liquid limits of these clays are between 30 and 50%. The unit weight of the clay is approximately equal to 17.7 kN/m^3.

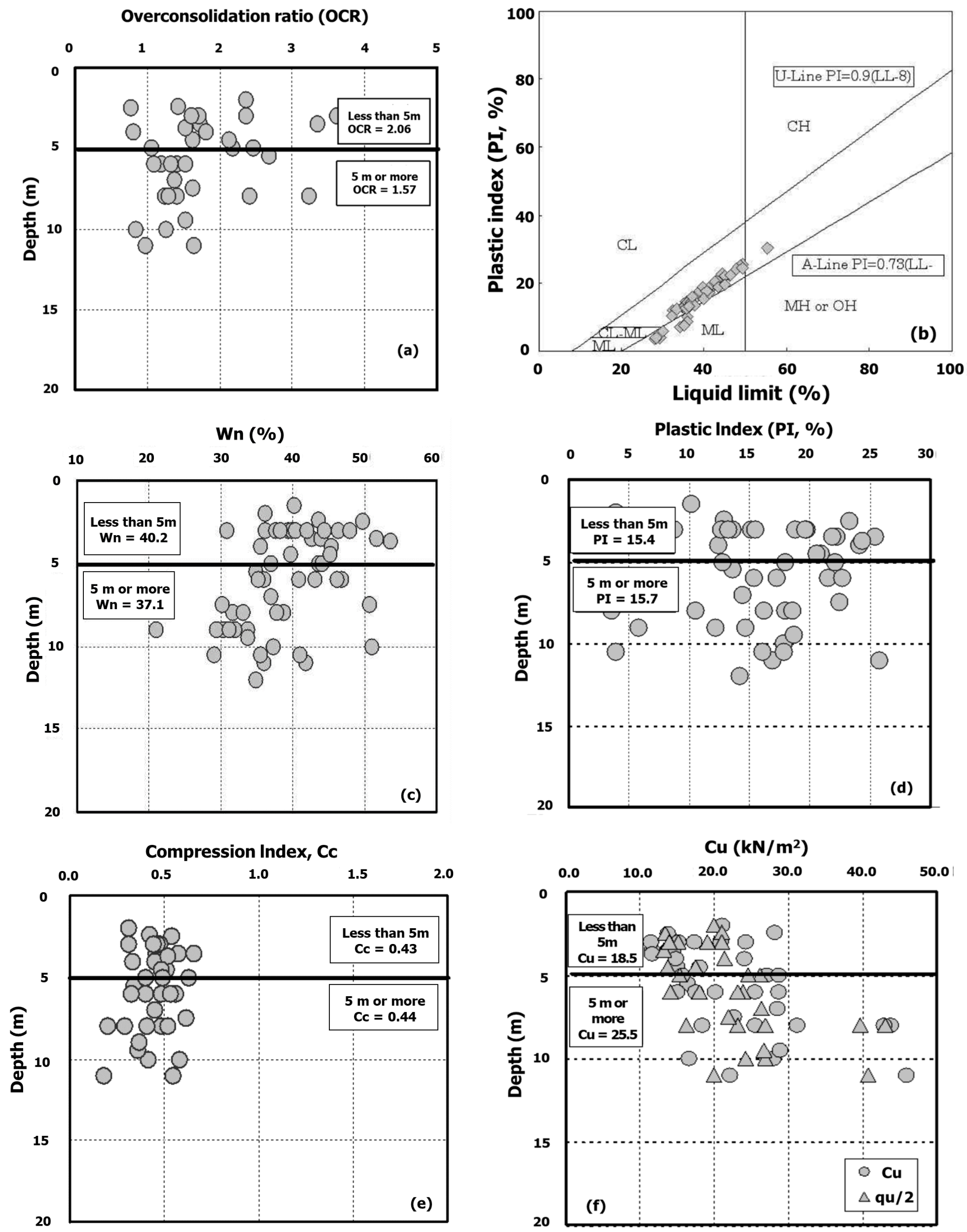

Figure 4. The geotechnical and physical properties of clay. (**a**) over-consolidation ratio; (**b**) plasticity chart; (**c**) natural water content; (**d**) plasticity index; (**e**) compression index; (**f**) undrained shear strength.

3.3. Installation of Experimental Equipment

The ground was drilled to install an electric heating pipe. The depth of the installation of the electric heating pipe was 3.5–6.5 m. The rod type of the drill machine is the NX size, as given in the diamond core drill manufacturers association drill rod specification in ASTM D2113-99 [35]. After the casing was pulled out, the internal cavity was filled with bentonite. Finally, a lead wire was connected to the electric heating tube and protected by a heat shrink tube and silicone.

The measurement system consisted of sensors and data loggers. The sensors used in the experiment are a thermometer that measures the temperature of the ground due to the ground heating and a pressure gauge that measures the vapor pressure generated by the phase change of pore water to water vapor. Considering the characteristics of the heating experiment, sensors operating at a maximum operating temperature of 400 °C were used. All the sensors were connected to a multiplexer and a data logger.

A Resistance Temperature Detector (RTD) was used to measure the temperature change between 0 °C and 400 °C, and the pressure was measured using Melt Pressure Transducer (MPT 124-111) which can measure the pressure change between 0.0 MPa and 1.0 MPa (Figure 5a). The sensors were placed in a steel protection tube with a diameter of 5.0 cm and installed at a depth of 5.0 m. The measurements for the experiment were performed at 30-min intervals using a multiplexer (NCTSS-1632) and a data logger (CR-1000), as shown in Figure 4b.

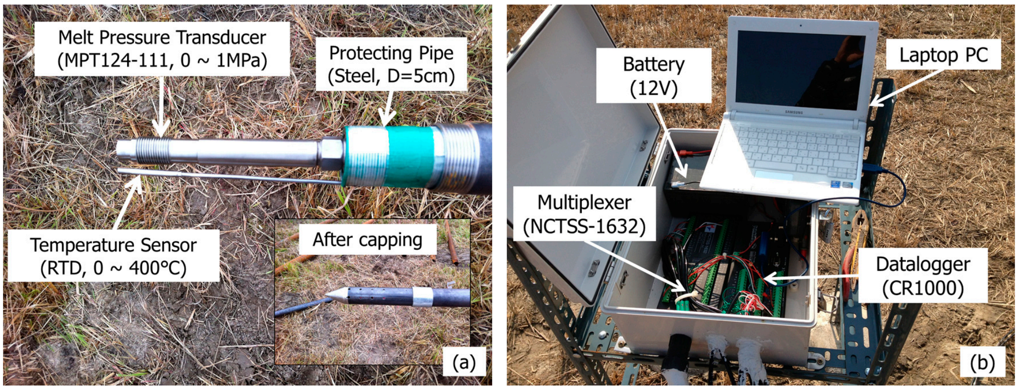

Figure 5. The installation process of the sensors and the measurement systems. (**a**) Installed sensors; (**b**) measurement system.

3.4. Experiment Case

Figure 6 shows the conceptual diagram of the field experiments conducted in this study. There are a total of eight experimental conditions. Cases 1 and 2 are constructed with an electric heating pipe and a temperature sensor. The temperature sensor was installed at a point 0.5 m horizontally from the electric heating pipe. In Case 2, four discharge holes for water vapor were installed at a distance of 0.5 m. Case 2 was to investigate the temperature variation of the ground due to the ground heating, depending on whether or the water vapor was discharged. In Case 3, three sensors were installed at 0.3 m, 0.6 m, and 1.2 m in the horizontal direction from the electric heating pipe to investigate the heat transfer characteristics of the ground heating. In Case 4, the cone penetration test (CPT) was performed at 0.35 m, 0.67 m, and 1.31 m in the horizontal direction from the electric heating pipe to verify the improvement effect of the soft ground by ground heating. CPTs were carried out three days after the ground heating was completed. A CPT was conducted at 9 am at a point 0.35 m horizontally distanced from the heat source. Then, another CPT was carried out at the remaining points at intervals of about 3 h. In Cases 5 and 6, only the electric heating pipe was installed. The CPTs in Cases 5 and 6 were performed after the completion of the CPT in Case 4. Experiments were performed 4 days after the ground heating was completed.

In Case 7, the installation depth of the electric heating pipe was 0.0–3.0 m and 3.0–6.0 m. In Case 8, one electric heating pipe and one sensor were installed, and the CPT was performed at a horizontal distance of 0.45 m from the electric heating pipe. The experiment was carried out in the autumn of Korea. The temperatures ranged from 15 degrees during the day to 7 degrees during the night. However, because the heated ground is 3.5 to 6.5 m below the ground surface, it was not affected by the atmosphere.

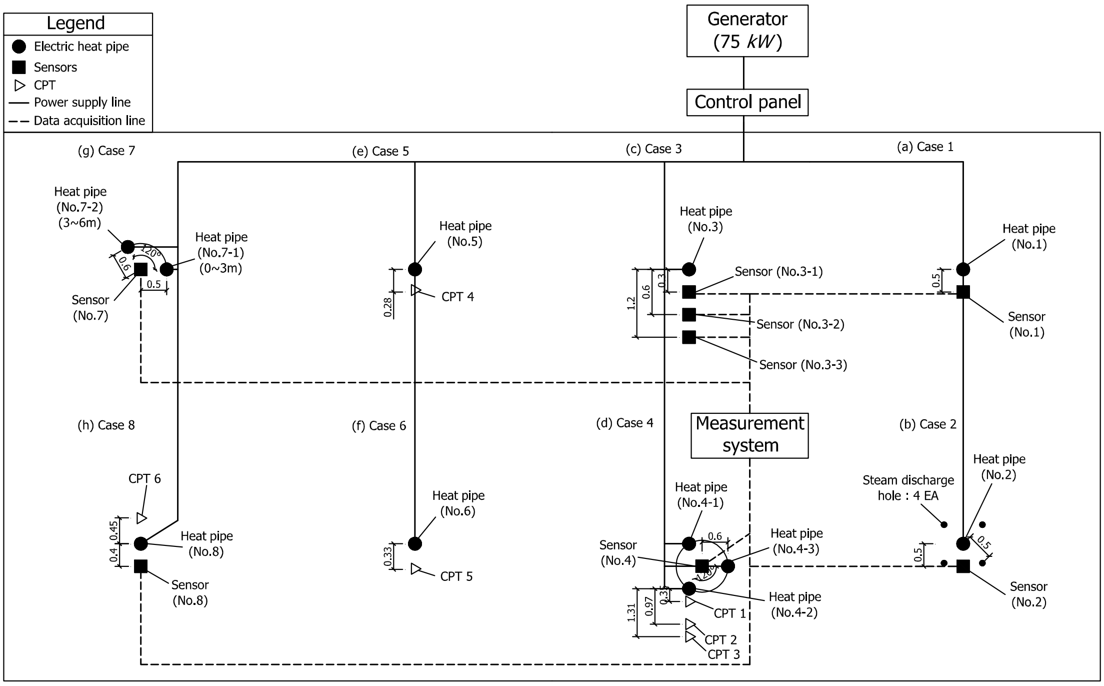

Figure 6. The conceptual diagram of the field experiments performed in this study.

4. Results of Ground Heating Method

4.1. Heat Transfer Characteristic

Figure 7 shows the variation of the ground temperature due to ground heating. Figure 7a shows the whole sensor. The temperature of the ground was increased by heating twice for 48 h. The pattern in which the temperature was decreased after the heating was finished was also similar. Figure 7b compares the variation in the ground temperature due to the installation of the steam discharge hole. As in the study by Park [2], the heat energy was lost due to the discharge of the water vapor. However, in the secondary heating, the electric heating pipe of Case 1 was lost and it was not heated. The electric heating pipe has a weak connection with the lead wire supplying the electric power. Therefore, for practical use, it is necessary to improve the connection part. The temperature of the ground in Case 4, which is 3 degrees in the 120-degree direction, was increased up to 86.0 degrees.

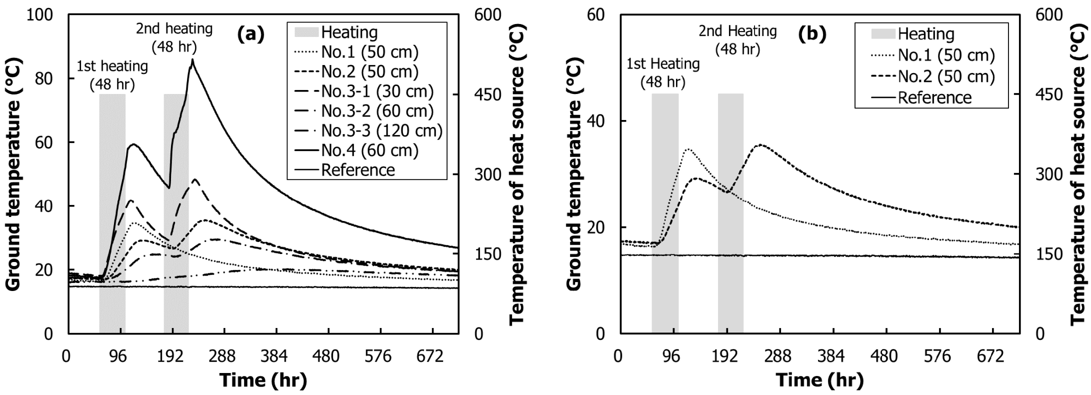

Figure 7. The variation of the ground temperature due to ground heating. (**a**) Overall sensor; (**b**) comparison of the temperature variation due to the installation of the steam discharge hole.

The test results first examined the temperature change by the ground heating. Table 2 and Figure 8 show the temperature measured in the Case 1 experiment. Table 2 shows the initial temperature of each sensor, the maximum temperature due to heating, and the temperature gradient (dT/dt) at the first heating (48 h). The initial temperature was increased from 18.0 °C to 48.43 °C at a point 0.3 m away from the electric heating pipe with an exothermic temperature of 450.0 °C. The temperature gradient was 0.413 °C/h at 30 cm and decreased with the increase in the distance from the heat source.

Table 2. The temperature variation due to ground heating (Case 3).

Sensor	D (m)	T_i (°C)	T_{max} (°C)	dT/dt (°C/h)
3-1	0.3	18.00	48.43	0.413
3-2	0.6	17.18	29.56	0.141
3-3	1.2	16.01	20.21	0.018

D: Horizontal distance from the heat source; T_i: Temperature before heating; T_{max}: Maximum temperature after heating; dT/dt: Temperature gradient.

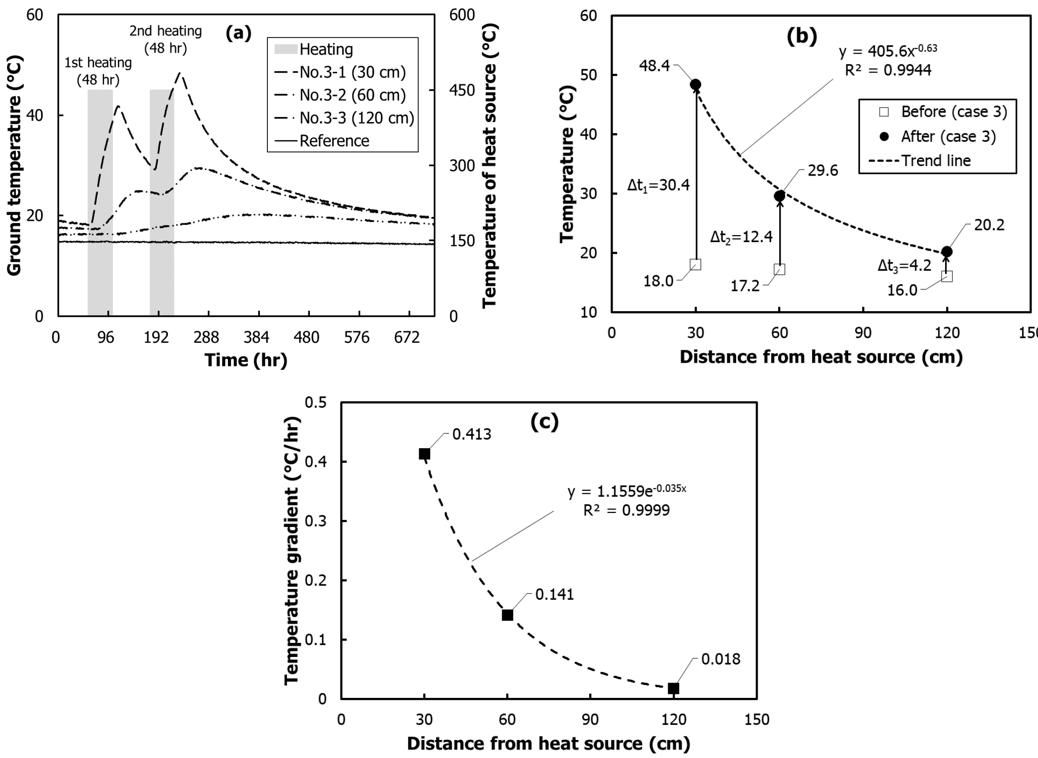

Figure 8. The temperature variation by ground heating using an electric heat pipe. (**a**) The temperature variation of all the sensors; (**b**) the variation of the temperature curve; (**c**) the temperature gradient according to the distance from the surface of the electric heat pipe.

The temperature changes shown in Table 2 and Figure 8a were considered as the temperature change curves according to the horizontal distance from the heat source. As shown in Figure 8b, it was expressed as a power function of $y = 405.6x^{-0.63}$. In addition, the temperature gradient along the horizontal distance was in the form of an exponential function: $y = 1.1559e^{-0.035x}$ (Figure 8c).

Figure 9a shows the change of the underground vapor pressure due to ground heating. The vapor pressure sensor was installed at the same point as thermometer No. 2 and No. 3-3. The vapor pressure increased by about 20 kPa due to the ground heating and the pore water evaporated into water vapor. As shown in Figure 9b, it was confirmed that the air bubbles leaked to the surface of the ground and the water vapor generated by the heating was discharged to the surface because the sensor was not shielded.

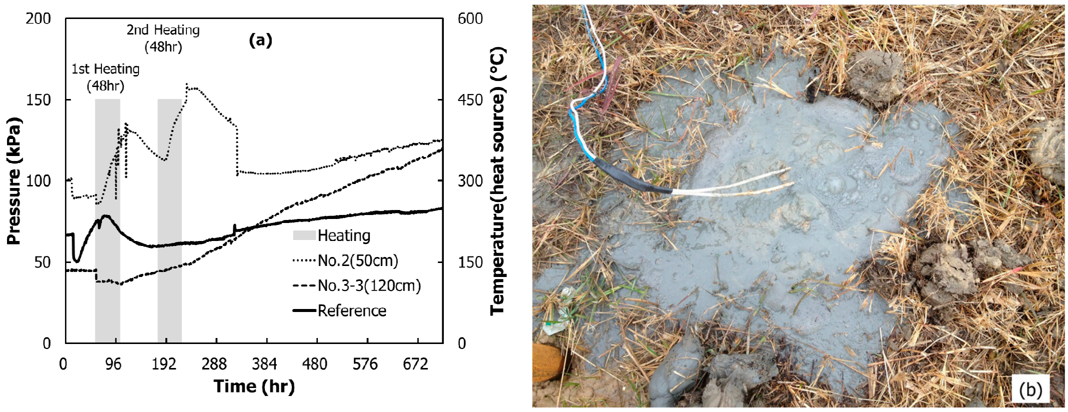

Figure 9. The variation of the vapor pressure by ground heating using an electric heat pipe. (**a**) The variation of the vapor pressure; (**b**) the bubbles on the ground surface.

4.2. Soil Improvement Effect

A static electronic piezo-cone penetration test (CPT) was carried out to verify the effect of soil improvement (ASTM D 5778, 2000). The cone had a measuring range of 100 MPa, a tip area of 10 cm^2, a sleeve area of 150 cm^2, and the electric resistance sensor of the strain gauge type. It is a cone type cone and its aspect ratio is 0.8. The tip resistance of the CPT depends on the water content of the soil [36–38]. In this study, the strength of the sintered ground due to ground heating was verified by the CPT test. The soil classification index (I_c) profile of the clay was estimated as described in References [38,39] based on the CPT tests data. Figure 10 shows the comparison between the soil classification index (I_c) profile obtained before (reference CPT test) and after heating. The soil classification index had slightly decreased after ground heating because the soil resistance increased and the pore water pressure decreased due to the ground heating.

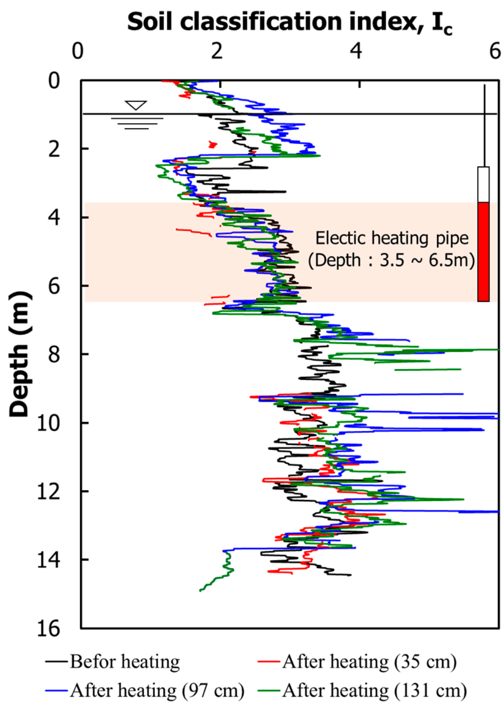

Figure 10. The Soil Classification Index obtained by the CPT tests data (before and after ground heating).

Because the CPT was only possible belowground at a temperature of 50 °C, the test was performed three days after ground heating was terminated. The strength of the ground before ground heating was measured by performing the CPT in advance. After ground heating, the test was performed for a total of four times at 0.35 m, 0.97 m, and 1.31 m from the heat source in the horizontal direction.

Figures 11 and 12 show the result of the measurement of the tip resistance from the CPT. Since the purpose of this study was to understand the change of the soil strength due to electric heating, only the results of 3.5–6.5 m, where the electric heating pipe was installed, are shown in the graph. In Figures 11 and 12, the tip resistances after heating were increased from before heating.

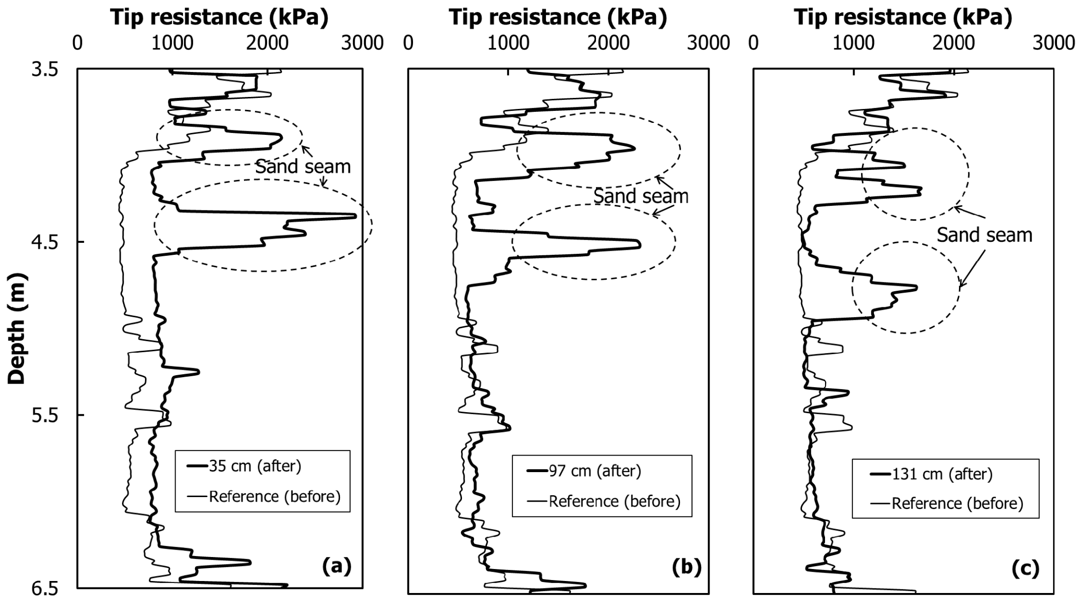

Figure 11. The variation of the tip resistance due to ground heating using an electric heat pipe (Case 4), (**a**) a point 35 cm in the horizontal direction; (**b**) 97 cm; (**c**) 131 cm.

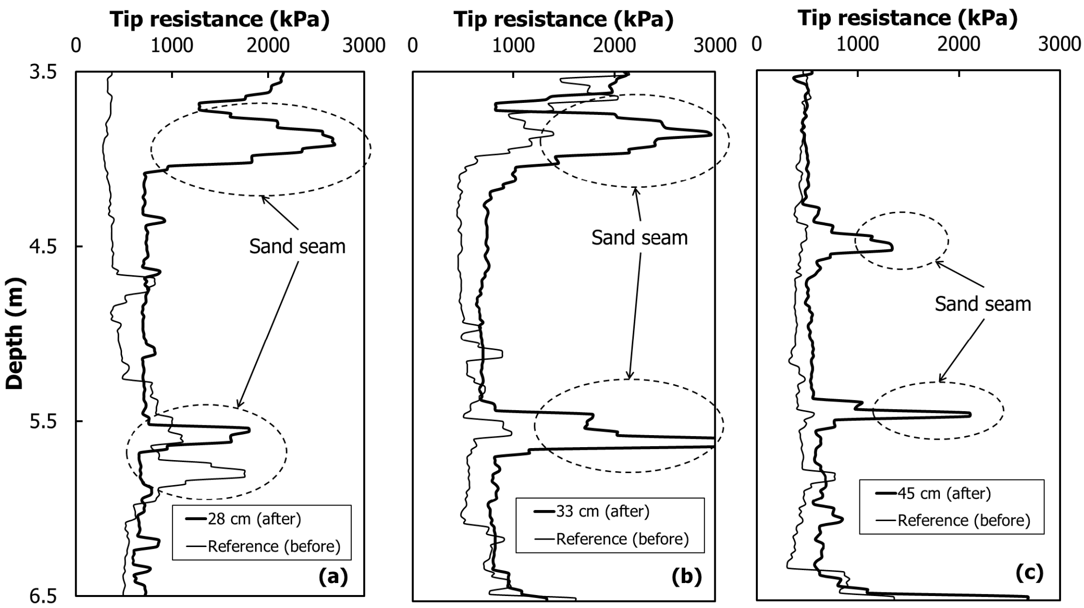

Figure 12. The variation of the tip resistance due to ground heating using an electric heat pipe (Cases 5, 6, and 8), (**a**) a point 28 cm in the horizontal direction; (**b**) 33 cm; (**c**) 45 cm.

It is difficult to quantify the increase in the strength due to ground heating only by the tip resistance graphs shown in Figures 11 and 12, so the average tip resistance of the heating zone was calculated. In this case, the section where the tip resistance is irregularly increased due to the sand seam was excluded.

Table 3 shows the change of the average tip resistance due to the ground heating for a total of 96 h. The average tip resistance change at the point 1.31 m away from the heat source was increased by two percent at 540.0 kPa before heating and at 555.0 kPa after heating.

Table 3. The variation of the average tip resistance due to ground heating using an electric heat pipe.

Case	D (m)	q_i (kPa)	q_h (kPa)	$\frac{(q_h - q_i)}{q_i} \times 100$ (%)
4	0.35	540.0	870.0	61
	0.97	540.0	660.0	22
	1.31	540.0	555.0	2
5	0.28	435.0	710.0	63
6	0.33	540.0	730.0	35
8	0.45	452.5	530.0	17

D: Horizontal distance from the heat source; q_i: Tip resistance before heating; q_h: Tip resistance after heating.

Figure 13 shows the change of the tip resistance according to the horizontal distance as a result of the CPT of Case 4 shown in Table 3. The change of the tip resistance according to the horizontal distance from the heat source was estimated by the linear function of $y = -3.2942x + 983.79$. It was heated up to 120 cm in the horizontal direction from the electric heating pipe which was the heat source, and the tip resistance had also slightly increased.

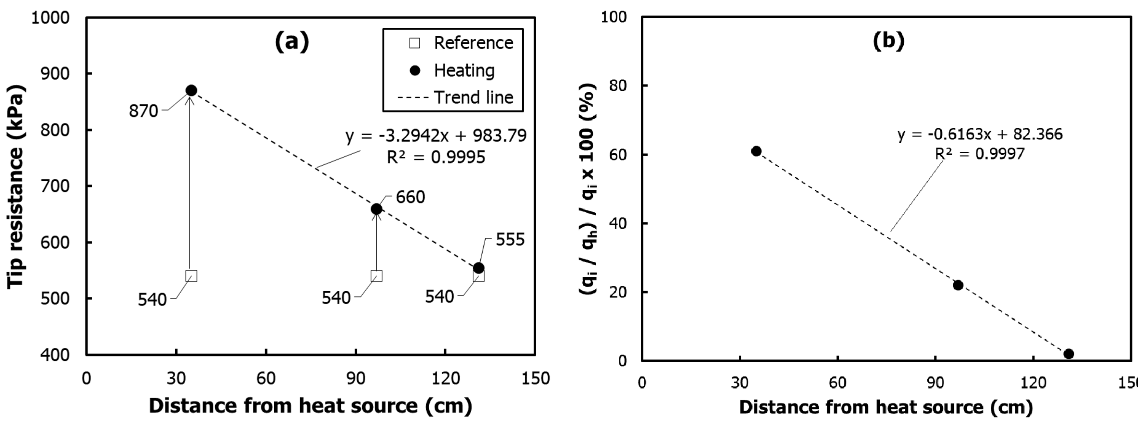

Figure 13. The variation of the tip resistance according to the distance from the surface of the electric heat pipe (Case 4); (**a**) the comparison of the variation in the tip resistance before and after heating; (**b**) the comparison of the increased rate of tip resistance after heating.

Figure 14 shows the change of the tip resistance according to the horizontal distance as a result of the CPTs in Cases 5, 6 and 8, shown in Table 3. Unlike Case 4 in Figure 13, the increase in strength concerning the horizontal distance from the electric heating pipe was not calculated as a linear equation. This is because Figure 14 shows the result of Cases 5, 6 and 8 according to the horizontal distance from the electric heating pipe. The reason for why the increase in the strength due to ground heating is relatively smaller than Case 4 is that the sand seam is distributed at 5.5 m of the electric heating pipe (Figure 12). The heat energy in the ground due to ground heating is transmitted in a vertical direction rather than in a horizontal direction. Therefore, because there is a sand seam at the mid-point of the electric heating pipe, the heat is not transferred to the upper part and the water vapor is discharged to the sand seam.

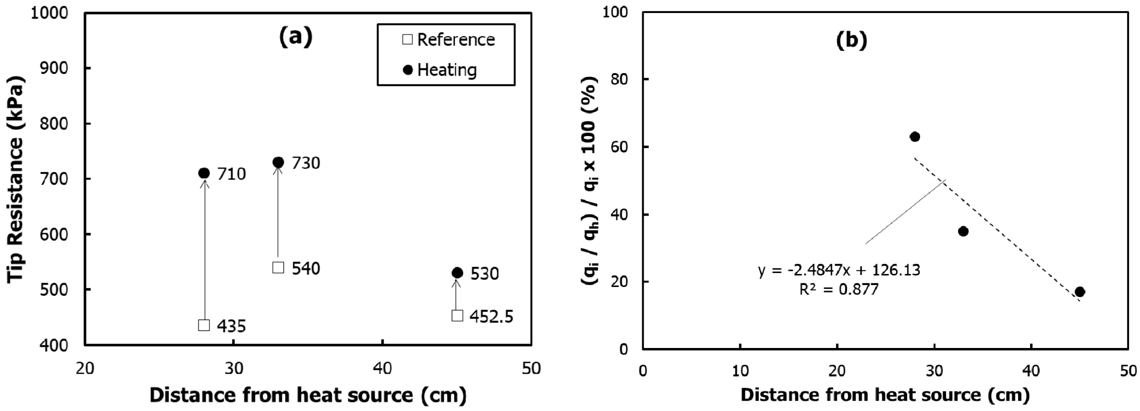

Figure 14. The variation of the tip resistance according to the distance from the surface of the electric heat pipe (Cases 5, 6 and 8), (**a**) the comparison of the variation in tip resistance before and after heating; (**b**) the comparison of the increased rate of tip resistance after heating.

Figure 15 is the variation of the pore pressure according to the horizontal distance from the electric heat pipe (Case 4). As a result of the measurement of the pore water pressure, there was a section where the pore water pressure was estimated to be small due to the sand seam present in the clay layer. This section is identical to the section where the cone resistance value is estimated to be high in Figure 11. The change of the pore water pressure due to ground heating was reduced by heating up the horizontal distance of 35 cm as shown in Figure 15a. However, little change occurred at the lateral distance of 97 cm and 131 cm in Figure 15b,c.

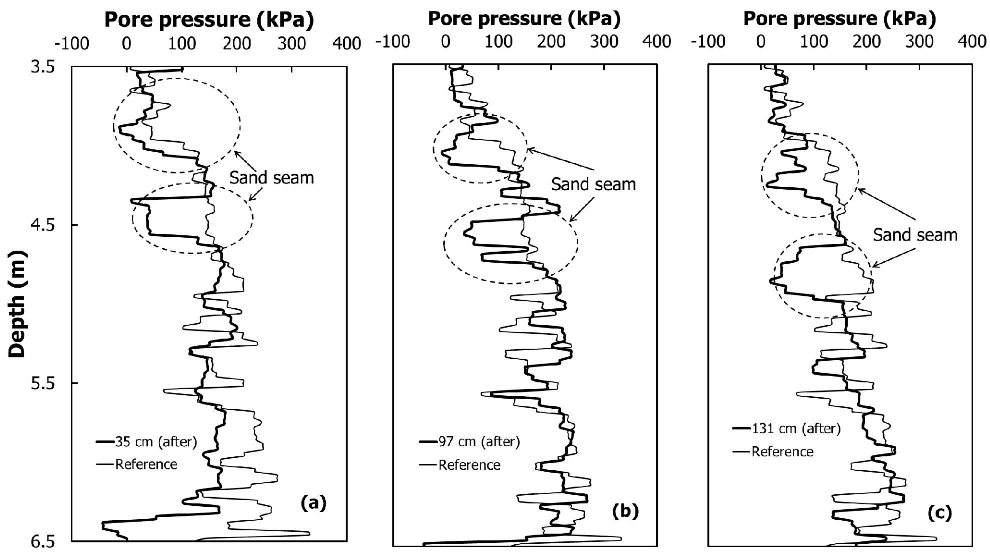

Figure 15. The variation of the pore pressure according to the horizontal distance from the electric heat pipe (Case 4), (**a**) a point 35 cm in the horizontal direction; (**b**) 97 cm; (**c**) 131 cm.

Figure 16 is the variation of the pore pressure according to the horizontal distance from the electric heat pipe (Cases 5, 6 and 8). As shown in Figure 15, there was a section where the pore water pressure was estimated to be small due to the sand seam. The pore water pressure due to the ground heating did not decrease when the distance from the electric heating pipe was about 45 cm in the horizontal direction.

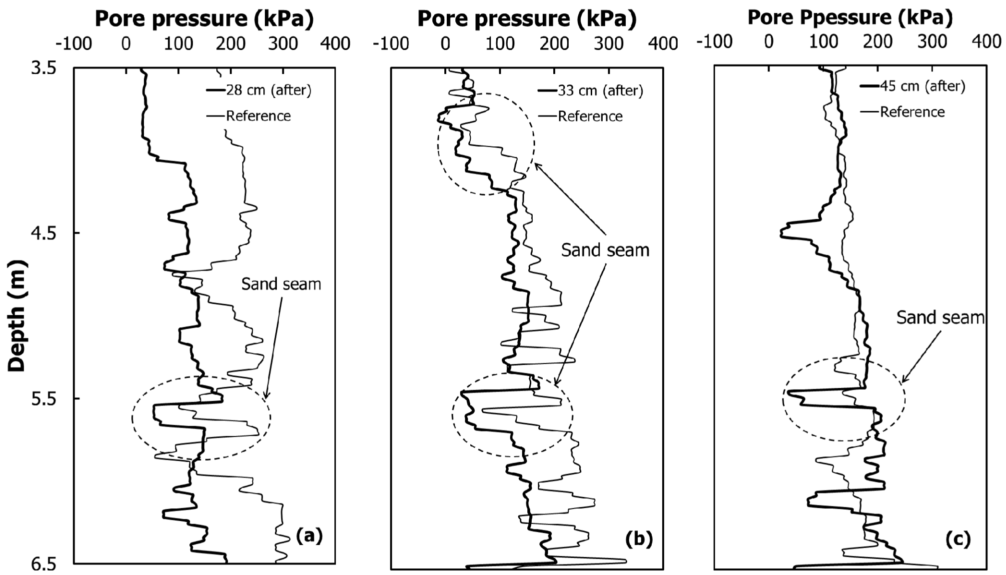

Figure 16. The variation of the pore pressure according to the horizontal distance from the electric heat pipe (Cases 5, 6 and 8), (**a**) a point 28 cm in the horizontal direction; (**b**) 33 cm; (**c**) 45 cm.

5. Discussion

As a result of the measurement of the temperature change of the ground due to ground heating, it was confirmed that it reduced to the power function according to the horizontal distance from the heat source. The underground temperature distribution of the energy pipe for utilizing geothermal energy uses the linear heat source model by Kelvin (1882). In this model, the temperature decreases from the heat source in the form of an exponential function and the tendency is similar to the decreasing function determined from the experimental results of this study.

The phase change of the pore water due to ground heating occurred through the generation of the pressure gauge and the bubble. This phenomenon means that the heat transfer characteristic due to the ground heating is very complicated. This is because the phase change of the pore water and the heat transfer due to the water vapor occurred simultaneously. On the other hand, the leakage of the water vapor to the surface also means the loss of heat energy. Litvibov (1960) [22] even knew that heat would be lost if the water vapor was evacuated. A sealing device was applied to solve this problem. The heat transfer characteristics by ground heating needed to be further investigated through laboratory experiments and numerical analysis.

The increase in the tip resistance of the heated ground by the CPT was up to 1.2 m from the heat source and the improvement of the soil strength was reduced to the first order linear equation. It has been experimentally verified that the temperature and the strength of the soil increase together through the heat transfer from the electric heating pipe. However, it was difficult to clarify the relationship between the heat transfer and the strength improvement of the soft soil due to the inhomogeneity of the ground.

Additionally, the discharge of the water vapor in the indoor ground heating experiment performed by Park [2] means a loss of heat energy. At deep depths, the loss of heat energy may not occur because the earth pressure suppresses the discharge of water vapor. However, as a result of the experiment, the ground was not homogeneous and it was disturbed by the boring for the installation of the heating pipe. The water vapor was discharged through these gaps and, consequently, a loss of heat energy occurred.

As a result of applying the ground heating method to the deep soft ground, it was easy to install the electric heating pipe after boring. However, although the borehole was filled with bentonite, this gap served as a passage through which the water vapor was discharged. Therefore, it was necessary to increase the strength so that an electric heating pipe can be inserted into the soft ground of the site.

In the secondary heating, the electric heating tube of Case 1 was lost and could not be heated. The electric heating tube was weak on the part of the connection with the lead wire supplying electric power. Therefore, it is necessary to improve the connection part of the electric heating pipe for practical use.

6. Conclusions

This paper studied the improvement effect and field application of deep soft ground by a ground heating method using an electric heating pipe. The ground heating increased the temperature of the deep soft ground and increased the tip resistance of the CPT. After ground heating for 96 h, the tip resistance was increased by 61% at a point 0.35 m horizontally away from the electric heat pipe, 22% at 0.97 m away from the pipe, and 2% at 1.31 m away from the pipe. Additionally, the pore water pressure decreased because the pore water evaporated due to the ground heating. As a result of the experiment, the improvement effect of the deep soft ground by the ground heating method was verified.

As a result of the field test, it was found that there was no problem in the power supply by the diesel generator and the control panel. It was easy to install the electric heating pipes on the deep soft ground. However, due to boring, the ground was disturbed and water vapor was discharged through this gap. To minimize the discharge of the water vapor, it was necessary to drive the electric heating pipe. For this purpose, the strength of the electric heating pipe must be increased. If the soil is not homogeneous and the sand is present, the efficiency of the ground heating may decrease.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lambe, T.W. *A Mechanistic Picture of Shear Strength in Clay*; Research Conference on Shear Strength of Cohesive Soils; ASCE: Boulder, CO, USA, 1960; pp. 555–580.
2. Park, M. A Study on Heat-Transfer Characteristics by a Ground-Heating Method. *Sustainability* **2018**, *10*, 412. [CrossRef]
3. Das, B.M. *Advanced Soil Mechanics*; CRC Press: Boca Raton, FL, USA, 2013.
4. Sakr, M.A.; Shahin, M.A.; Metwally, Y.M. Utilization of lime for stabilizing soft clay soil of high organic content. *Geotech. Geol. Eng.* **2009**, *27*, 105. [CrossRef]
5. Bergado, D.; Alfaro, M.; Balasubramaniam, A. Improvement of soft Bangkok clay using vertical drains. *Geotext. Geomembr.* **1993**, *12*, 615–663. [CrossRef]
6. Kirsch, F.; Kirsch, K. *Ground Improvement by Deep Vibratory Methods*; CRC Press: Boca Raton, FL, USA, 2014.
7. Gaafer, M.; Bassioni, H.; Mostafa, T. Soil Improvement Techniques. *Int. J. Sci. Eng. Res.* **2015**, *6*, 217–222.
8. Indraratna, B.; Rujikiatkamjorn, C.; Balasubramaniam, A.; McIntosh, G. Soft ground improvement via vertical drains and vacuum assisted preloading. *Geotext. Geomembr.* **2012**, *30*, 16–23. [CrossRef]
9. Long, P.; Nguyen, L.; Bergado, D.; Balasubramaniam, A. Performance of PVD improved soft ground using vacuum consolidation methods with and without airtight membrane. *Geotext. Geomembr.* **2015**, *43*, 473–483. [CrossRef]
10. Ye, G.-B.; Xu, Y.; Zhang, Z. Performance Evaluation of PVD-Reinforced Soft Soil with Surcharge and Vacuum Preloading. *Int. J. Civ. Eng.* **2018**, *16*, 421–433. [CrossRef]
11. Rujikiatkamjorn, C.; Indraratna, B. Environmental Sustainability of soft soil improvement via vacuum and surcharge preloading. In Proceedings of the Geo-Congress 2014: Geo-characterization and Modeling for Sustainability, Atlanta, GA, USA, 23–26 February 2014; pp. 3658–3665.
12. Lo, D.; Feng, T.; Ajlouni, M.; Mesri, G. Surcharging of soft ground to reduce secondary settlement. In *Soft Soil Engineering*; Routledge: Abingdon, UK, 2017; pp. 55–65.

13. Bergado, D.; Chai, J.; Alfaro, M.; Balasubramaniam, A. *Improvement Techniques of Soft Ground in Subsiding and Lowland Environment*; A.A. Balkema Pubulishers: Brookfield, VT, USA, 1994.
14. Indraratna, B.; Rujikiatkamjorn, C.; Nimbalkar, S.; Zhong, R.; McIntosh, G.W. *Ground Improvement for Enhancing the Performance of Road, Rail, and Port Infrastructure*; University of Wollongong: Wollongong, Australia, 2015.
15. Kim, T.; You, S. Settlement analysis considering sand mat induced initial settlement in soft ground improved by PBD. *Int. J. Civ. Eng.* **2015**, *13*, 146–152.
16. Han, J. *Principles and Practice of Ground Improvement*; John Wiley & Sons: Hoboken, NJ, USA, 2015.
17. Park, M.; Im, E.; Shin, B.; Han, H. Improvement of shallow soil using electric heating equipment. *J. Korean Geotech. Soc.* **2012**, *28*, 41–54. [CrossRef]
18. Kim, B.I.; Kim, D.H.; Kim, S.S.; Han, S.J. Consolidation characteristics of soft ground in suction drain method. *J. Korean Soc. Civ. Eng.* **2009**, *29*, 287–294.
19. Park, M.; Lee, K.; Jang, J.; Han, H. Thermal Analysis of Silty Sand Soil by Pipe Heater Installed in the Ground. *J. Korean Geoenviron. Soc.* **2013**, *14*, 5–13.
20. Kim, Y.-S.; Choo, J.-H.; Cho, Y.-S. Applicability Study on Deep Mixing for Urban Construction. *J. Korea Acad. Ind. Cooper. Soc.* **2011**, *12*, 500–506. [CrossRef]
21. Beles, A.; Stănculescu, I. Thermal treatment as a means of improving the stability of earth masses. *Geotechnique* **1958**, *8*, 158–165. [CrossRef]
22. Litvinov, I. *Stabilization of Settling and Weak Clayey Soils by Thermal Treatment*; Highway Research Board Special Report; Highway Research Board: Washington, DC, USA, 1960; pp. 94–112.
23. Litvinov, I.; Rzhanitzin, B.; Bezruk, V. Stabilization of soil for Constructional Purposes. In Proceedings of the Fifth International Conference on Soil Mechanics and Foundation Engineering, Paris, France, 17–22 July 1961; pp. 775–777.
24. Michot, A.; Smith, D.S.; Degot, S.; Gault, C. Thermal conductivity and specific heat of kaolinite: Evolution with thermal treatment. *J. Eur. Ceram. Soc.* **2008**, *28*, 2639–2644. [CrossRef]
25. Wintermyer, A. Percentage of water freezable in soils. *Public Roads* **1925**, *5*, 5–8.
26. Van der Lingen, G.; Biesenbach, J. Investigations on the heat treatment of subsoils and gravels. *S. Afr. Ind. Chem.* **1949**, *3*, 70–74.
27. Bose, S. *Stabilization of Certain Clayey Soils in India by Thermal Treatment*; Indian Road Congress: New Delhi, India, 1953.
28. Chandrasekharan, E.; Boominathan, S.; Sadayan, E.; Narayanaswamy, S.K. Influence of heat treatment on the pulverization and stabilzation characteristics of typical tropical soils. *Highw. Res. Board Spec. Rep.* **1969**, *103*, 161–172.
29. Wang, M.; Benway, J.M.; Arayssi, A.M. The effect of heating on engineering properties of clays. In *Physico-Chemical Aspects of Soil and Related Materials*; ASTM International: West Conshohocken, PA, USA, 1990.
30. Tang, A.-M.; Cui, Y.-J.; Barnel, N. Thermo-mechanical behaviour of a compacted swelling clay. *arXiv*, 2008.
31. Yilmaz, G. The effects of temperature on the characteristics of kaolinite and bentonite. *Sci. Res. Essays* **2011**, *6*, 1928–1939.
32. Park, M.; Im, E.; Lee, K.; Han, H. Experimental Study for Consolidation by Electric Heating Systems. *J. Korean Geoenviron. Soc.* **2012**, *13*, 43–53.
33. Kanthal, A.B. *Heating Alloys for Electronic Household Appliances*; Kanthal: Hallstahammar, Sweden, 2003.
34. Park, K.-R. *Engineering Properties of Sea Deposit Clay of West Coast in Korea Peninsula*; Graduate School of Engineering, Konkuk University: Seoul, Korea, 2001.
35. ASTM. Standard practice for rock core drilling and sampling of rock for site investigation. In *ASTM D2113-99*; ASTM International: West Conshohocken, PA, USA, 1999.
36. Cosanti, B.; Squeglia, N.; Lo Presti, D. Evaluation of the degree of compaction of levees by a CPT-based method. In Proceedings of the 5th International Conference on Geotechnical Engineering for Disaster Mitigation and Rehabilitation, Taipei, Taiwan, 13–14 September 2017; Meei-Ling Lin: Taipei, Taiwan, 2017; pp. 193–206.
37. Yang, H.; Russell, A.R. Cone penetration tests in unsaturated silty sands. *Can. Geotech. J.* **2015**, *53*, 431–444. [CrossRef]

38. Lo Presti, D.; Stacul, S.; Meisina, C.; Bordoni, M.; Bittelli, M. Preliminary Validation of a Novel Method for the Assessment of Effective Stress State in Partially Saturated Soils by Cone Penetration Tests. *Geosciences* **2018**, *8*, 30. [CrossRef]
39. Robertson, P. Soil classification using the cone penetration test. *Can. Geotech. J.* **1990**, *27*, 151–158. [CrossRef]

© 2018 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).