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Quick measurement of soil temperature by means of IR thermometer

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Synopsis

In waterfront soil mechanics for tidal flat, the subsurface soil temperature distribution at depths where suction develops above groundwater is one of the most important parameters in describing the soil dynamics. In addition, the subsurface temperature is important for managing curing temperature of cement treated soil in cold regions. These require the measurement of subsurface temperature over a wide area, so an efficient measurement method is required. In recent years, new methods such as microbial solidification have also been studied, and it is possible that temperature control in the soil will become more important. Various types of thermometers are available today, and many of which can be used to measure soil temperatures. In this study, a method that can avoid the problems of damage to the sensor and shorten the standing-by time required for thermal equilibrium was developed and investigated its applicability to a quick soil temperature measurement. Specifically, instead of conventional contact thermometers, infrared (IR) thermometer which is a noncontact thermometer recently developed was attempted to measure soil temperature quickly. A casing pipe with a spacer made of polyvinyl chloride was penetrated from the ground surface to a target depth. After removing the spacer, the IR thermometer was set into the casing pipe, and then, soil temperature was measured quickly in about 5 seconds. A stable measurement was successively conducted. It was confirmed that measured temperature using IR thermometer is sufficiently accurate based on a comparison with the temperature measured by self-recording thermistor thermometer. Both measuring methods using the narrow view angle type IR thermometer setting at the top of the casing pipe with a longer distance from the target depth and the wide view angle type IR thermometer setting inside of the casing pipe with a shorter distance from the target depth can measure soil temperature with sufficient accuracy. Because the linearity between the actual temperature and the displayed temperature possibly tends to be lost particularly in a low temperature range, it is necessary to pay attention to the measurable temperature range of the IR thermometer by calibration. As it was confirmed in this study, because IR thermometer can efficiently/quickly and reliably measure soil temperature, this new thermometer is applicable to construction management requiring temperature control, e.g., placement of cement treated soils in winter season in cold region.

Key Words: Soil temperature, thermometer, infrared

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赤外線温度計を用いた地中温度計測

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要　　旨

干潟を対象とした水辺の土質力学において，地下水位より上にサクションが発生する深度における地中温度分布は，土質力学において最も重要なパラメータの一つである．また，寒冷地におけるセメント処理土の養生温度管理においても，地中温度の把握は重要である．この場合，広域の地中温度を計測する必要があり，効率的な測定方法が求められる．また，近年では微生物固化などの新しい手法について研究が進められており，地盤中の温度管理がより重要になる可能性が高い．現在，様々なタイプの温度計が販売されており，その多くが地中温度測定に利用可能である．本研究では，センサーの破損の問題を回避し，熱平衡に達するまでの時間を短縮できる方法を開発し，迅速な地中温度測定への適用性について検討した．具体的には，従来の接触型温度計の代わりに，近年開発された非接触型温度計である赤外線（IR）温度計を用いた地中温度の迅速測定方法について検討した．

ポリ塩化ビニルでできたスペーサー付きのケーシングパイプを地表から目標深さまで貫入し，スペーサーを取り外した後，ケーシングパイプに IR 温度計をセットして地中温度を約 5 秒で素早く測定したところ，安定して温度測定をすることができた．自記録式サーミスタ温度計による測定温度との比較から，高い精度で IR 温度計による測定が可能であることを確認した．測定対象深度からの距離が長く，ケーシングパイプ上部に設置する狭視野タイプの IR 温度計と，測定対象深度からの距離が短く，ケーシングパイプ内部に設置する広視野タイプの IR 温度計のいずれの測定方法でも十分な精度で地中温度を測定することができた．しかし，特に低温域においては，実測温度と表示温度との直線性が損なわれることがあるため， IR 温度計の測定可能温度範囲に注意し，必要に応じてキャリブレーションを実施する必要がある．本研究で確認されたように，IR 温度計は効率的・迅速かつ高精度に地中温度を計測できるため，寒冷地における冬季のセメント処理土の打設など，温度管理が必要な施工管理にも適用できるといえる．

キーワード：地中温度，温度計，赤外線

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1. Introduction

In waterfront soil mechanics for tidalflat, the subsurface soil temperature distribution at depths where suction develops above groundwater is one of the most important parameters in describing the soil dynamics. In addition, the subsurface temperature is important for managing curing temperature of cement treated soil in cold regions. Temperature control (heating system) is required in placement of cement treated soils in winter season in cold region because cement treated soil does not harden under very cold temperature. These require the measurement of subsurface temperature over a wide area, so an efficient measurement method is required.

Soil temperature from ground surface to about 500 mm depth is an important parameter for evaluating the activity environment of microbes that contribute to the decomposition of organic matters in the soil[1]. In recent years, new methods such as microbial solidification have also been studied, and it is possible that temperature control in the soil will become more important.

Various types of thermometers are available today[2),3),4)], and many of which can be used to measure soil temperatures[5]. In the previous days, mercury-in-glass thermometers had been mainly used to measure soil temperatures. Although the measurement accuracy of the mercury-in-glass thermometer is very high, the glass tube is easily damaged, and it takes a standing-by time for thermal equilibrium after the start of measurement. Therefore, electrical measurement with thermistor thermometers and thermocouple thermometers, which are easier to handle and require a shorter standing-by time than mercury-in-glass thermometers, are now widely used. In many cases of these electrical measurement thermometers, the sensor itself is protected by a thin metal sheath, which is easily damaged. In addition, because the length of the sensor is as long as 200 mm (mostly 100 to 150 mm), it is necessary to excavate the ground to an appropriate depth to measure a temperature at a target depth deeper than the length of the sensor.

Considering the background mentioned above, in this study, a method that can avoid the problems of damage to the sensor and shorten the standing-by time required for thermal equilibrium was developed and investigated its applicability to a quick soil temperature measurement. Specifically, instead of conventional contact thermometers, infrared (IR) thermometer which is a noncontact thermometer recently developed was attempted to measure soil temperature quickly in about 5 seconds after the start of measurement using a hole pre-drilled to a target depth.

2. Soil temperature measurement method

The procedure of the quick temperature measurement attempted in this study is shown in Figure 1. The casing pipe used to hold the predrilled hole was a polyvinyl chloride pipe (VP30) with an inner diameter of 31 mm and an outer diameter of 38 mm, with a length of 900 mm. A polyvinyl chloride cylindrical spacer (polyvinyl chloride round rod with an outer diameter of 30 mm) having a polyvinyl chloride conical tip with an angle of 60° (or tip angle of 30° in a case of stiff soil) was

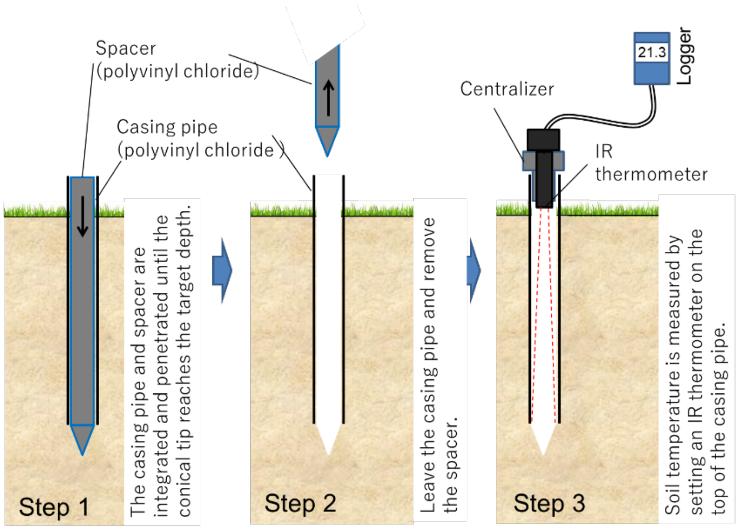

Figure 1. Procedure for quick soil temperature measurement using an IR thermometer

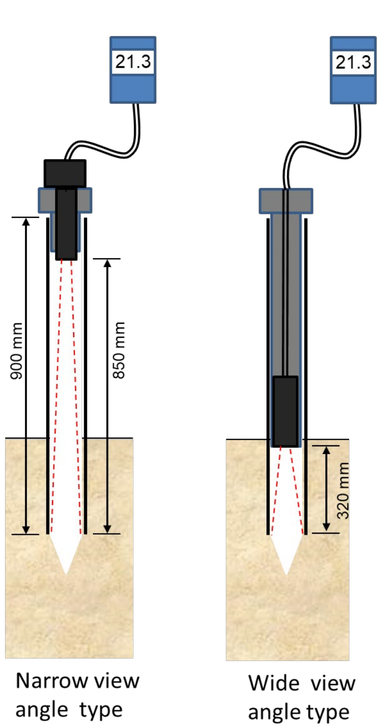

Figure 2. Distance between IR thermometer and target soil surface
Left: Narrow view angle type
Right: Wide view angle type

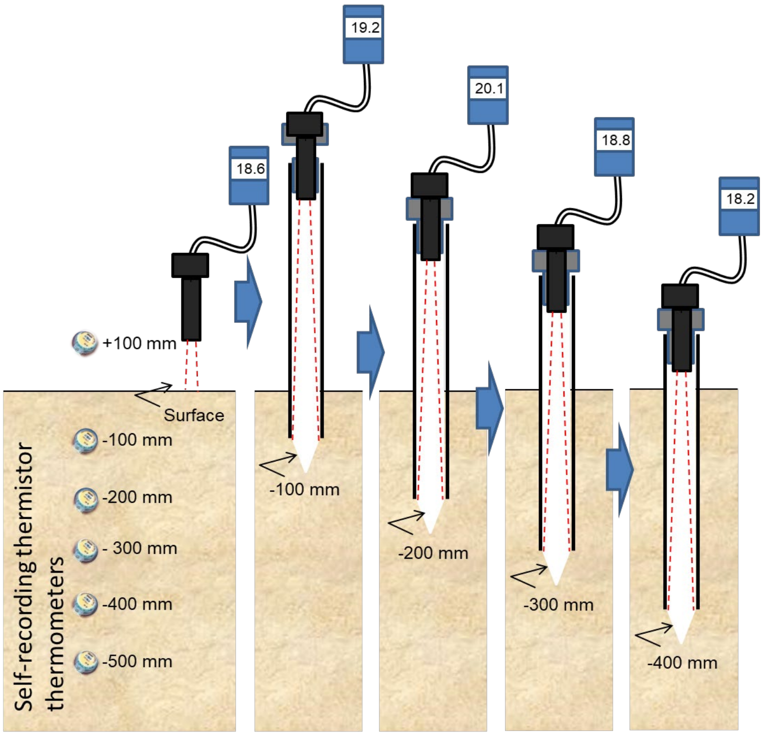

Figure 3. Depths of self-recording thermistor thermometers and measurement of IR thermometer

inserted into the casing pipe. The outer of the threaded connection between the cylindrical spacer and the conical tip was tapered for setting of an O-ring, and when tightened the connection, the attached O-ring is pushed outward. This mechanism was designed for preventing sand particles from entering the clearance between the casing pipe and the spacer; however, the soil used in this study did not require this mechanism. The tip of the casing pipe was also tapered to match the conical shape of the spacer tip with cone angle of 60°. The material of the spacer was polyvinyl chloride, which has low thermal conductivity, so that the temperature of the target soil would not change before the temperature measurement.

The IR thermometer mainly used in this study was a type with a narrow view angle (HORIBA IT-450F), which can focus on the thermal radiation from a distanced target. It was not affected by the casing pipe wall even if the sensor and the target have a distance. The IR thermometer was set with a socket placed on the top of the casing pipe to centralize the view direction. When the IR thermometer was mounted on a 900 mm long casing pipe, it had a target distance of 855 mm and a field of view diameter of 32.4 mm. This means that the casing pipe wall with an inner diameter of 31 mm was slightly included in the field of view; however, it had been confirmed that this condition did not affect the soil temperature measurement. Another type of IR thermometer (Sato Keiryoki Mfg. Co., Ltd, SK-8210) with a wide view angle was also used in this study. In a case of IR thermometers with a wide view angle, it was necessary to place the sensor close to the target. Therefore, the sensor was inserted to the casing pipe and placed close to the target depth. The sensor with outer diameter of 23 mm was attached inside the tip of a plastic pipe with an outer diameter of 27 mm and a wall thickness of 2 mm. And then, it was inserted into the casing pipe with the length of 900 mm, resulting in the distance of 320 mm between the tip of the casing pipe and the sensor. In this condition, the field of view has a diameter of 30.3 mm, which means that the measurement is performed on almost the entire surface of the opening at the tip of the casing pipe. The difference in temperature measurement methods between using narrow view angle type and wide view angle type IR thermometers is illustrated in Figure 2. Both the IR thermometers have a measurement resolution of 0.1°C.

The procedure of quick soil temperature measurement illustrated in Figure 1 is described below. In Step 1, the casing pipe with inserted spacer was penetrated the soil until the center

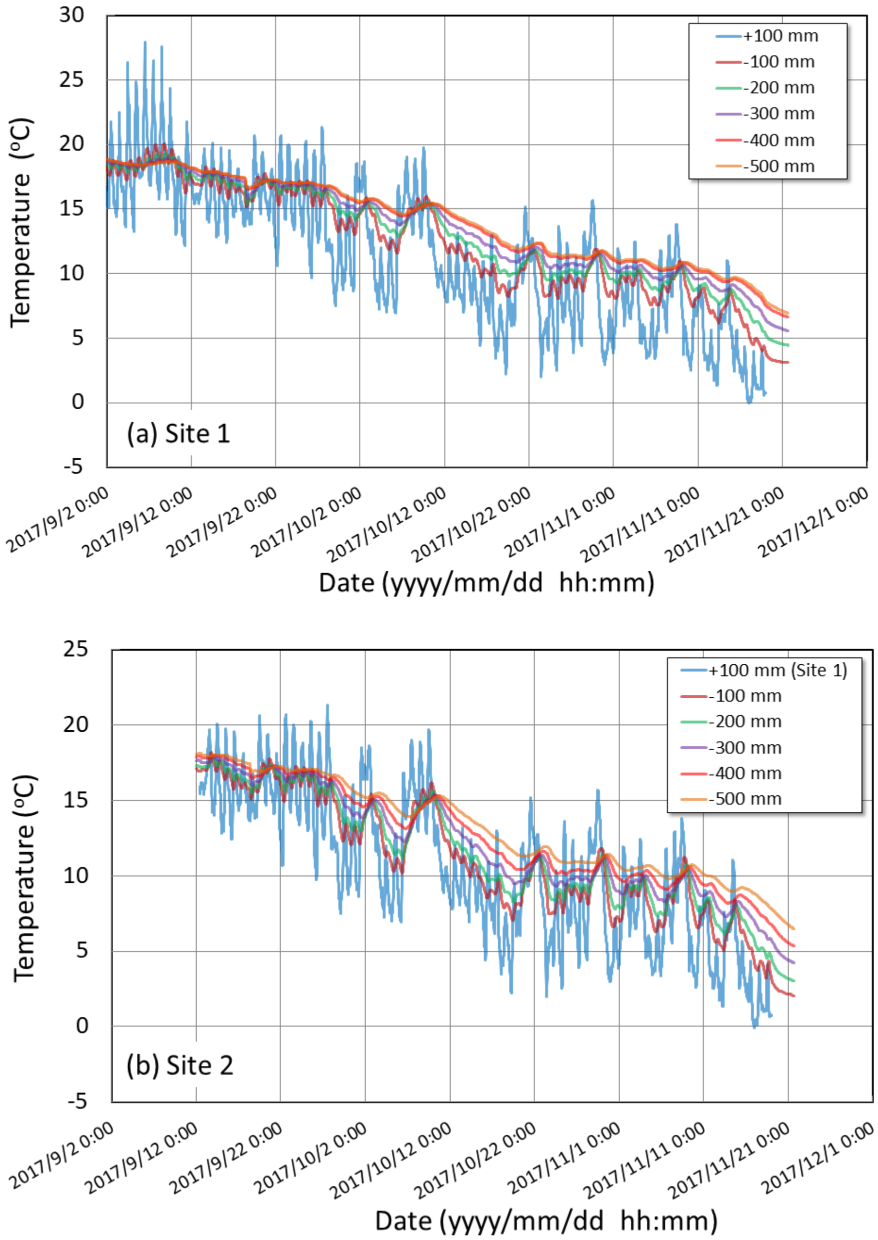

Figure 4. Temporal variations of air and soil temperatures measured by self-recording thermistor thermometers.

depth of the conical tip of the spacer reached the target depth. When the soil was too hard for the spacer to be penetrated by hand pushing, the upper part of the spacer was lightly tapped with a shockless hammer for penetration. In Step 2, only the spacer was extracted from the casing pipe, which was remained in the soil, and then in Step 3, the IR thermometer was quickly set inside the casing pipe and the soil temperature was measured.

Temperature measurements were conducted from early September to mid-November in 2017 at two field locations (Site 1 and Site 2) on the west side of the Faculty of Engineering, Hokkaido University, Japan. The two sites are approximately 110 m apart. Site 1 was in the shadow of a building and receives little sunlight, but Site 2 received plenty of sunlight. In order to measure the soil temperature at multiple depths at the same point, the measurement depth was increased step by step using the same drilled hole as illustrated in Figure 3. The measurement depths were the ground surface (GL ±0 mm), GL –100 mm, GL –200 mm, GL –300 mm, and GL –400 mm, and the above procedures from Step 1 to Step 3 were repeated at each measurement depth. In order to compare with the soil temperature quickly measured by the IR thermometer, self-recording thermistor thermometers (ONSET TidbiT v2 UTBI-001) were installed at GL –100 mm, GL –200 mm, GL –300 mm, GL –400, and GL –500 mm to record continuous temperature

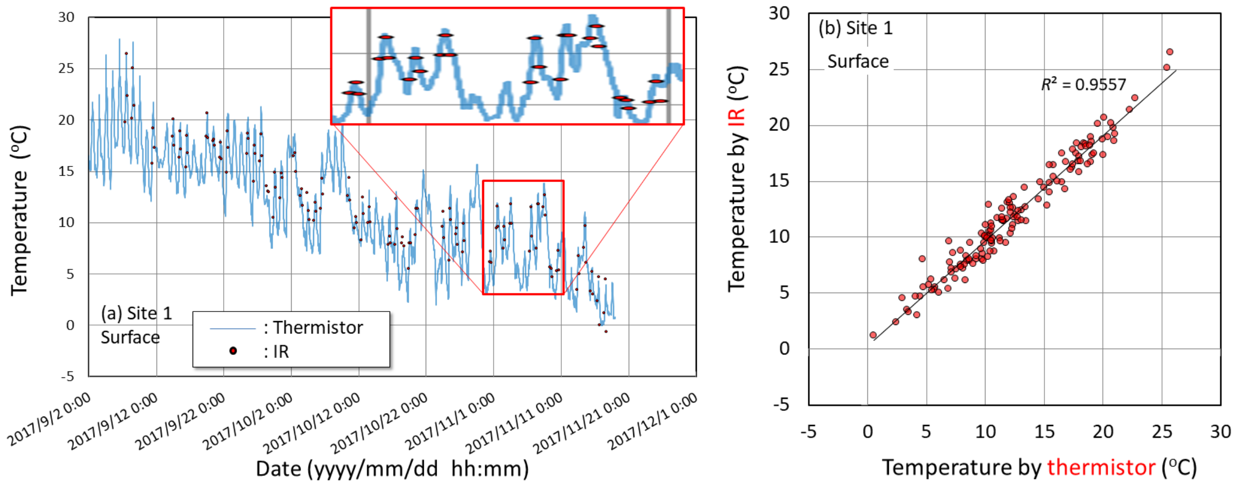

Figure 5. Measurement results of narrow view angle type IR thermometer on the ground surface at Site 1: (a) the IR thermometer measurement values superimposed on the temporal variation of measured values with the self-recording thermistor thermometers, (b) Comparison between the IR thermometer and thermistor thermometer measurements.

variations. When the self-recording thermistor thermometers were installed, gravel particles larger than 5 mm in the surrounding soil including the measurement range of the IR thermometer were removed, so as not to obstruct the penetration of the casing pipe with spacer. Measurements with the IR thermometer were basically conducted three times a day, in the morning, at noon, and in the evening. Note here that the temperature on the ground surface was not measured at Site 2.

In addition, from mid-October 2021 to mid-December 2021, quick soil temperature measurements using a soil container with 295 mm in diameter and 345 mm in height was also conducted. Six plastic containers filled with soil, in which self-recording thermistor thermometers were installed on the surface of the soil layer and at depths of 100 mm and 200 mm, were prepared. Then, 5 plastic containers were placed in 5 different locations with different temperatures, respectively, inside the building of the Faculty of Engineering, Hokkaido University, and 1 plastic container was placed outside the building (in winter, it was moved to the windbreak room of the building entrance to prevent it from freezing). The soil temperature was quickly measured irregularly with the IR thermometer. Temperature measurements were conducted on the soil surface using the narrow view angle type and at depths of 100 mm and 200 mm using both the narrow and wide view angle types.

The holes used for measurement with the IR thermometer were not left in open but were buried by breaking up the surrounding soil. In addition, since the soil was gradually compacted due to repeated measurements in a limited area, the soil around the measurement point is dug up and buried again every one to two weeks to ensure that the soil as the target of temperature measurement is homogenous.

In the following, due to space limitations, the field temperature measurement results obtained using the narrow view angle type IR thermometer will be mainly described with details. The field temperature measurement results obtained using the wide view angle type IR thermometer and the soil temperature measurement results obtained in the soil containers will be shown briefly.

Main specifications of each thermometer used in this study is described below:

HORIBA, IT-450F

- Measuring range: –50 to 500°C (correction is required below 0°C)
- Output: 4 to 20 mA corresponding to 0 to 500°C
- Accuracy: ±(3°C+0.1% of output range) or smaller (emissivity 1.000)
- Measured wavelength: 8 to 16 μm
- Response time: 0.4 s (95%)
- Operation ambient: 0 to 55°C, 35 to 85%rh without condensing

Sato Keiryouki Mfg. Co., Ltd, SK-8210

- Measuring range: 0 to 400°C
- Accuracy: ±2°C or ±2%rdg, whichever is larger (emissivity 0.95)
- Response time: 0.300 s (90%)
- Detector: Thermopile
- Measured wavelength: 8 to 14 μm
- Output: 4 to 20 mA corresponding to 0 to 400°C

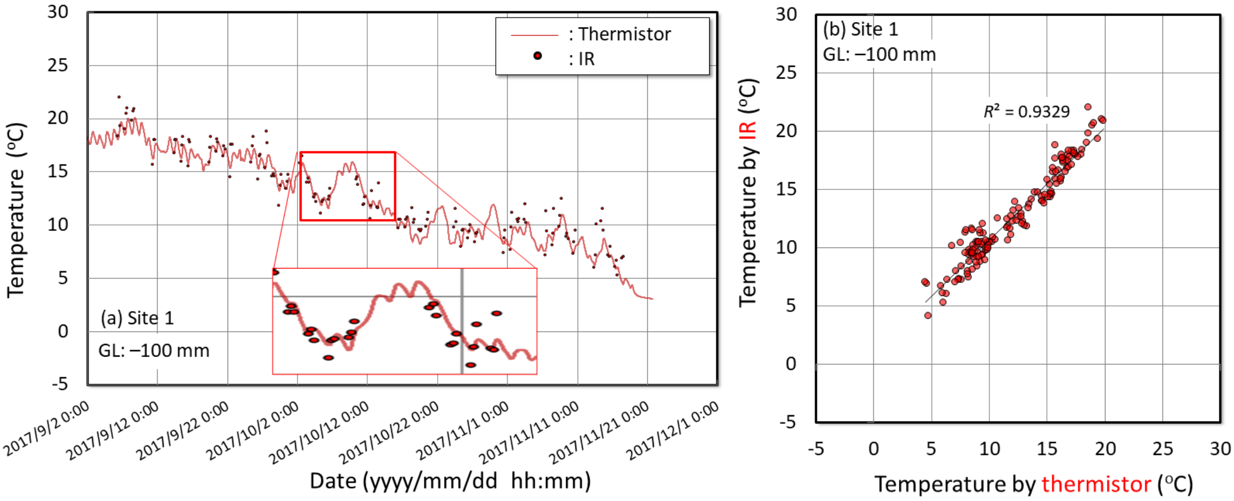

Figure 6. Measurement results of narrow view angle type IR thermometer at GL –100 mm at Site 1: (a) the IR thermometer measurement values superimposed on the temporal variation of measured values with the self-recording thermistor thermometers, (b) Comparison between the IR thermometer and thermistor thermometer measurements.

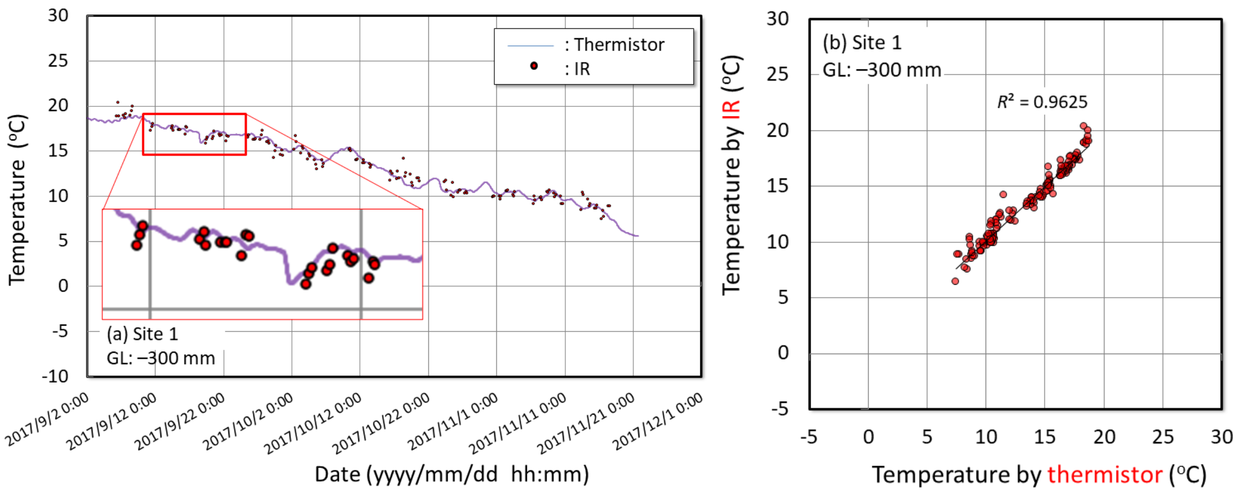

Figure 7. Measurement results of narrow view angle type IR thermometer at GL –300 mm at Site 1: (a) the IR thermometer measurement values superimposed on the temporal variation of measured values with the self-recording thermistor thermometers, (b) Comparison between the IR thermometer and thermistor thermometer measurements.

- Operation ambient: 0 to 70°C, less than 90%rh without condensing

ONSET TidbiT v2 UTBI-001

- Measuring range: –20 to 70°C
- Accuracy: ±0.21°C
- Resolution: 0.02°C
- Response time: 5 minutes in water; 12 and 20 minutes in air moving 2 m/sec and 1 m/sec, respectively (90%)

3. Measurement results in the field

3.1 Results of continuous measurements

Temporal variations in air temperature and soil temperatures measured with a self-recording thermistor thermometer are shown in Figure 4. Here, Figure 4(a) is for Site 1, and Figure 4(b) is for Site 2. Because the air temperature was not measured at Site 2, the air temperature measured at Site 1 is shown as a reference value. From the end of summer to the beginning of winter, temporal variations of soil temperatures in response to seasonal and diurnal variations of air temperature in Sapporo are successfully captured. The soil temperatures tend to decrease with the change of seasons from autumn to winter. When the air temperature decreases significantly as a diurnal variation, the deeper the soil temperature measurement depth, the slower the response in soil temperature. At the depth of GL –100 mm, the response of soil temperature with diurnal temperature

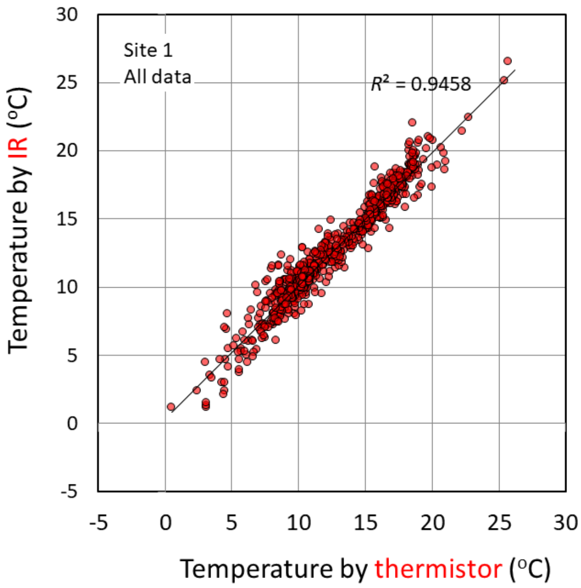

Figure 8. Comparison between the data observed by the IR thermometer (narrow view angle type) and the data observed by the thermistor thermometers (all data from Site 1)

fluctuations can be seen; however, at the depths of GL –200 mm and GL –300 mm, the diurnal variation gradually decreased, and below GL –400 mm, only little diurnal variation was observed.

3.2 Results of narrow view angle type IR thermometer

3.2.1 Results at Site 1

Measurement results of the ground surface temperature at Site 1 is shown in Figure 5. Figure 5(a) shows the results of the ground surface temperature measured by the IR thermometer superimposed on the temporal variation of air temperature measured stationarily by the thermistor thermometer at GL +100 mm. The data for the middle 12 days are shown in the inset by enlarging the horizontal axis, and the measured values using the IR thermometer correspond to the significant diurnal temperature fluctuation. The comparisons between the measured value of the IR thermometer and the measured value of the self-recording thermistor thermometer are plotted in Figure 5(b). The data were plotted around a straight line with a slope of almost 45°, and a high determination coefficient (R^2 value) of 0.9557 was calculated. This indicates that the quick soil surface temperature measurement using the IR thermometer was sufficiently reliable compared to the measured value of the continuous measurement of air temperature with the self-recording thermistor thermometer.

The measured soil temperature at GL –100 mm at Site 1 is shown in Figure 6. Figure 6(a) shows the results of soil temperature measured by the IR thermometer superimposed on the temporal variation of the soil temperature measured stationarily by thermistor thermometer buried at GL –100 mm. At this depth, the soil temperature is also fluctuating under the influence of the diurnal variation of air temperature. The data for the middle 12 days are shown in the inset by enlarging the horizontal axis, and the measured values using the IR thermometer correspond to the diurnal temperature fluctuation stationarily measured by the thermistor thermometer. The comparisons between the measured value of the IR thermometer and the measured value of the self-recording thermistor thermometer are plotted in Figure 6(b). The data were plotted around a straight line with a slope of almost 45°, and a high determination coefficient (R^2 value) of 0.9557 was calculated. This indicates that the quick soil temperature measurement at a depth with the IR thermometer was sufficiently reliable compared to the measured value of the continuous measurement of soil temperature with the self-recording thermistor thermometer.

The measured soil temperature at GL –300 mm at Site 1 is shown in Figure 7. Figure 7(a) shows the results of soil temperature measured by the IR thermometer superimposed on the temporal variation of the soil temperature measured stationarily by thermistor thermometer buried at GL –300 mm. At this depth, the soil temperature shows almost no effect of diurnal variation of air temperature. The data for the middle 12 days are shown in the inset by enlarging the horizontal axis, and the measured values of the IR thermometer correspond to the

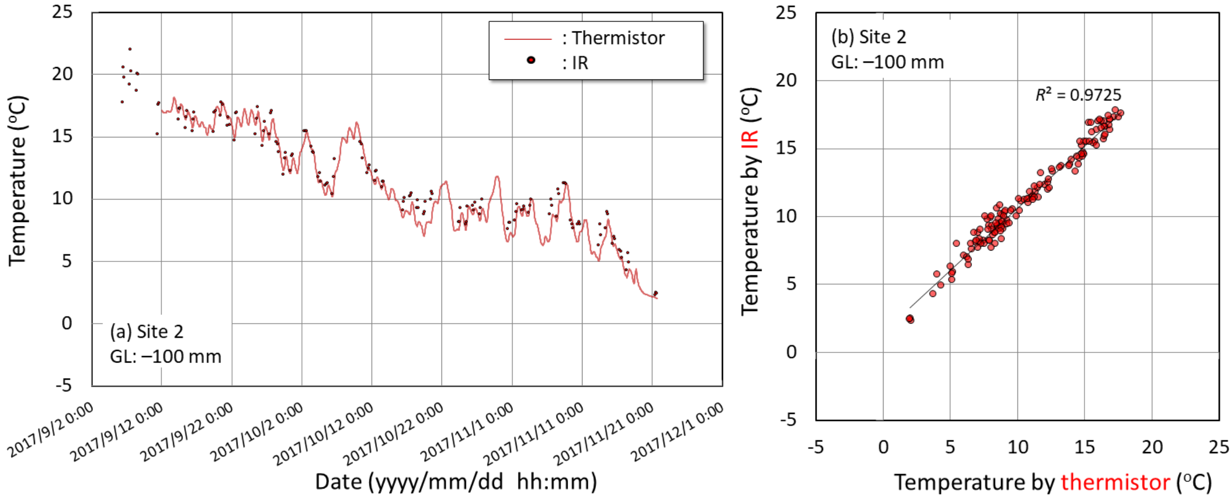

Figure 9. Measurement results of the narrow view angle type IR thermometer at GL –100 mm at Site 2: (a) the IR thermometer measurement values superimposed on the temporal variation of measured values with the self-recording thermistor thermometers, (b) Comparison between the IR thermometer and thermistor thermometer measurements.

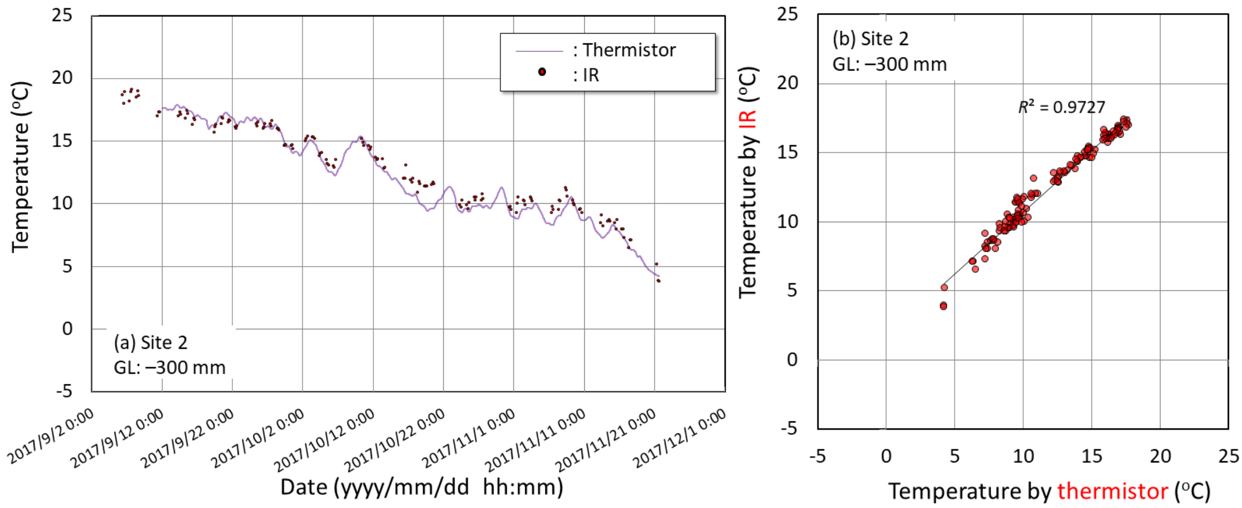

Figure 10. Measurement results of narrow view angle type IR thermometer at GL –300 mm at Site 2: (a) the IR thermometer measurement values superimposed on the temporal variation of measured values with the self-recording thermistor thermometers, (b) Comparison between the IR thermometer and thermistor thermometer measurements.

diurnal temperature fluctuation stationarily measured by the thermistor thermometer at the depth of GL –300 mm. The comparisons between the measured values of the IR thermometer and the measured values of the self-recording thermistor thermometer are plotted in Figure 7(b). The data were plotted around a straight line with a slope of almost 45°, and a high determination coefficient (R^2 value) of 0.9625 was calculated. This indicates that the quick soil temperature measurement with the IR thermometer at depths deeper than that of Figure 6 was also sufficiently reliable, compared to the measured value of the continuous measurement of soil temperature with the self-recording thermistor thermometer.

The comparison between measured values of the IR thermometer and the measured values of the self-recording thermistor thermometer consisting of 743 data recorded on the ground surface and at the depths of GL –100 mm, GL –200 mm, GL –300 mm, and GL –400 mm at Site 1 is shown in Figure 8. The data were plotted around a straight line with a slope of almost 45°, and a high determination coefficient (R^2 value) of 0.9458 was calculated. The standard deviation (SD) of the measured values of the IR thermometer against the approximated relationship corresponding to the measured values of the thermistor thermometer is 0.934 °C. In the range where the temperature did not fall below 0°C, the quick soil

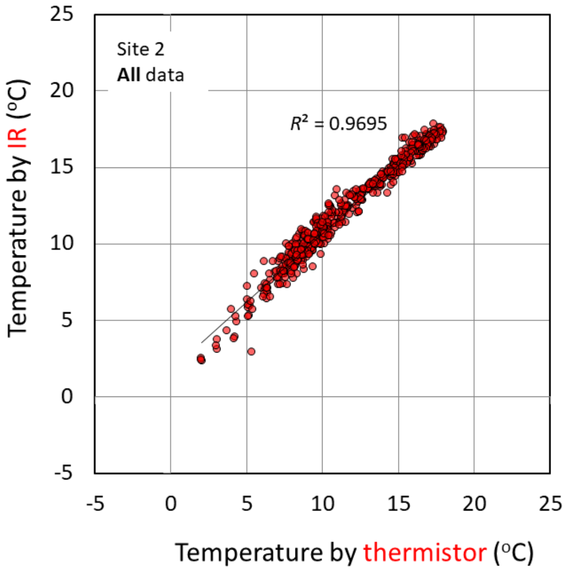

Figure 11. Comparison between the data observed by the IR thermometer (narrow view angle type) and the data observed by the thermistor thermometers (all data from Site 2)

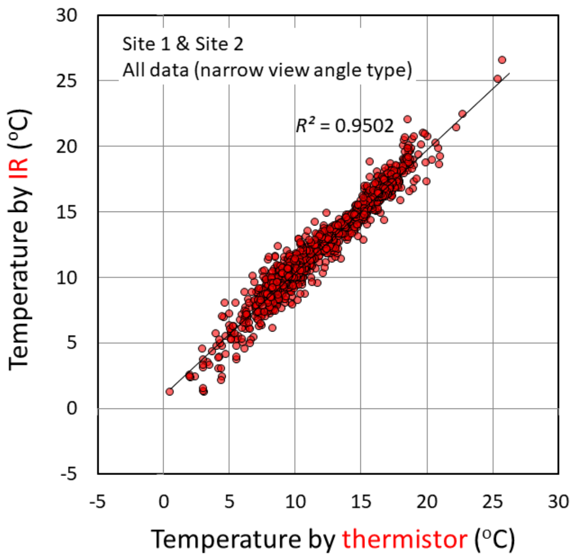

Figure 12. Comparison between the data observed by the IR thermometer (narrow view angle type) and the data observed by the thermistor thermometers (all data from both Site 1 and Site 2)

temperature measurement with the IR thermometer was sufficiently reliable to be comparable to the stationarily measured value of self-recording thermistor thermometer.

3.2.2 Results at Site 2

The measured soil temperature at GL –100 mm at Site 2 is shown in Figure 9. Figure 9(a) shows the results of soil temperature measured by the IR thermometer superimposed on the temporal variation of the soil temperature measured stationarily by thermistor thermometer buried at GL –100 mm. As shown in Figure 6(a) for Site 1, the measured values of the IR thermometer correspond to the diurnal temperature fluctuation stationarily measured by the thermistor thermometer.

The measured soil temperature at GL –300 mm at Site 2 is shown in Figure 10. Figure 10(a) shows the results of soil temperature measured by the IR thermometer superimposed on the temporal variation of the soil temperature measured stationarily by the thermistor thermometer buried at GL –300 mm. As shown in Figure 7 for Site 1, although the soil temperature shows almost no effect of diurnal variation of air temperature at this depth, the measured values of the IR thermometer correspond to the diurnal temperature fluctuation

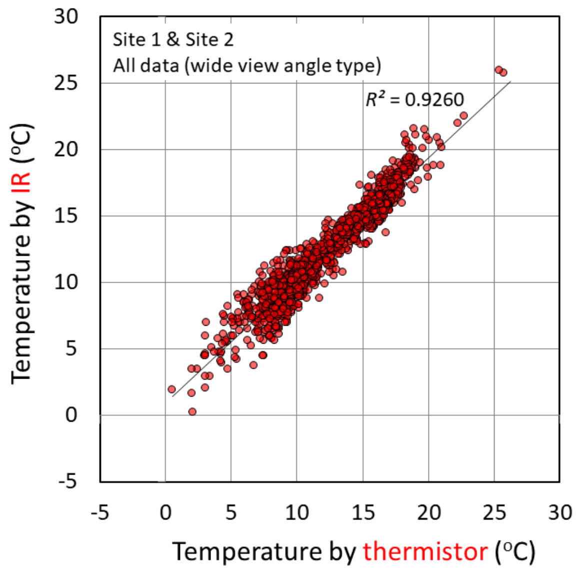

Figure 13. Comparison between the data observed by the IR thermometer (wide view angle type) and the data observed by the thermistor thermometers (all data from both Site 1 and Site 2)

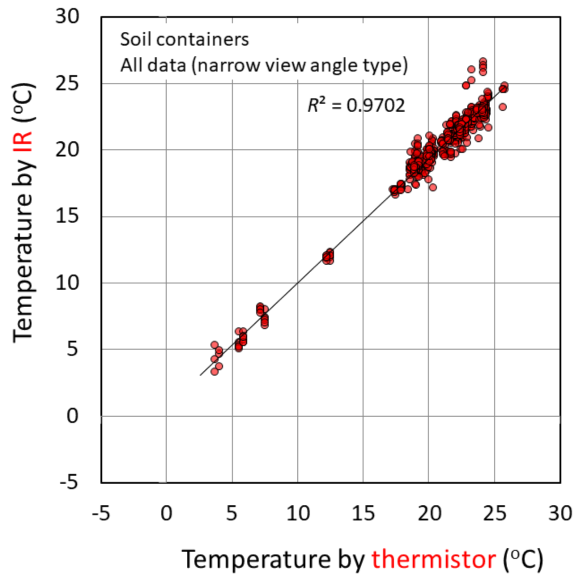

Figure 14. Comparison between the data observed by the IR thermometer (narrow view angle type) and the data observed by the thermistor thermometers (all data from the 6 soil containers)

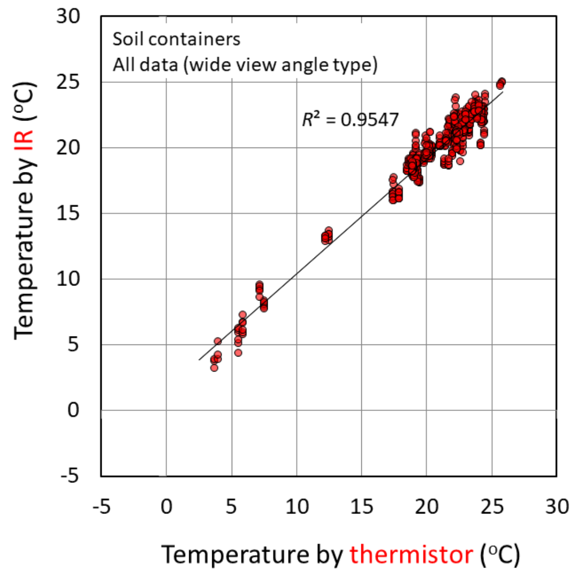

Figure 15. Comparison between the data observed by the IR thermometer (wide view angle type) and the data observed by the thermistor thermometers (all data from the 6 soil containers)

stationarily measured by the thermistor thermometer. The comparisons between the measured value of the IR thermometer and the measured value of the self-recording thermistor thermometer are plotted in Figure 10(b). The data were plotted around a straight line with a slope of almost 45°, and a high determination coefficient (R^2 value) of 0.9727 was calculated. Even the quick soil temperature measurement with the IR thermometer at deeper depths than that of Figure 9 was sufficiently reliable, compared to the measured value of the continuous measurement of soil temperature with the self-recording thermistor thermometer.

The comparison between measured value of the IR thermometer and the measured value of the self-recording thermistor thermometer consisting of 551 data recorded at depths of GL –100 mm, GL –200 mm, GL –300 mm, and GL –400 mm at Site 2 is shown in Figure 11. The data were plotted around a straight line with a slope of almost 45°, and a high determination coefficient (R^2 value) of 0.9695 was calculated. In the range where the temperature did not fall below 0°C, the quick soil temperature measurement with the IR thermometer was sufficiently reliable to be comparable to the stationarily measured value of the continuous measurement with the self-recording thermistor thermometer.

As described above, regarding the data measured at Site 1 and Site 2, it was shown that the values measured quickly by the IR thermometer are highly correlated with the values stationary measured over time by the buried thermistor thermometer. Some data deviate from the straight line with a slope of 45° degree. This is because the installed position of the thermistor thermometers and the measurement positions of the IR thermometer are not the same. In addition, the diurnal variation of soil temperature was significant at shallower depths. Here, all the data, including the data corresponding to this large variation are plotted, resulted in some deviation from the regression line. The coefficient of determination was close to R^2 = 0.95, even though some of the data show deviation. The standard deviation (SD) of the measured values of the IR thermometer against the approximated relationship corresponding to the measured values of the thermistor thermometer is 0.586 °C.

3.3 Comparison between the narrow and wide view angle types

The comparison between the measured values of the IR thermometer (narrow view angle type) and the measured values of the self-recording thermistor thermometer consisting of 1294 data recorded at both Site 1 and Site 2 is shown in Figure 12. The data were plotted around a straight line with a slope of almost 45°, and a high determination coefficient (R^2 value) of 0.9502 was calculated. The standard deviation (SD) of the measured values of the IR thermometer against the approximated relationship corresponding to the measured values of the thermistor thermometer is 0.925 °C.

The comparison between the measured values of the IR thermometer (wide view angle type) and the measured values of the self-recording thermistor thermometer consisting of 1294 data recorded at both Site 1 and Site 2 is shown in Figure 13. Similar to the data measured by the narrow view angle type IR thermometer described above (Figures 4 to 12), the data were plotted around a straight line with a slope of almost 45°; however, because of a large data variation, determination coefficient (R^2 value) calculated for this is 0.9263, which is rather small. In addition, the standard deviation (SD) of the measured values of the IR thermometer against the approximated relationship corresponding to the measured values of the thermistor thermometer is 1.307 °C, which is rather large. This is a matter of the recommended temperature range (–50 to 500°C for narrow view range type and 0 to 400°C for wide view range type) for the IR thermometers, rather than the effect of the view angle itself. The narrow view angle type IR thermometer used in this study maintained a linear relationship even when the temperature approached down to 0°C, whereas the wide view angle type IR thermometer used in this study shows larger variation when the temperature was below 10°C.

The measurement using both the narrow view angle type and the wide view angle type are available even round 5°C or a little below that. This fact indicates that these measurement techniques are useful in temperature management for cement treated soils placed in winter season in cold region, because cement treated soils do not harden under very cold temperature. At the beginning stage of curing before the mixture of soil and cement is hardened, temperature measurement using IR thermometer can be conducted. Also, even if the target depth is in a deeper portion, temperature measurement with wide view angle type IR thermometer can be conducted using a longer casing pipe and spacer, and a longer rod connecting to the wide range type IR thermometer as well, because the wide range type IR thermometer can be inserted to the casing pipe.

3.4 Measurement results in the soil containers

The comparison between measured values of the IR thermometer (narrow view angle type) and the measured values of the self-recording thermistor thermometer consisting of 659 data recorded in the 6 soil containers is shown in Figure 14. Similar to the data measured by the narrow view angle type IR thermometer described above (Figure 12), the data were plotted around a straight line with a slope of almost 45°, and a high determination coefficient (R^2 value) of 0.9702 was calculated. The standard deviation (SD) of the measured values of the IR thermometer against the approximated relationship corresponding to the measured values of the thermistor thermometer is 0.664 °C.

The comparison between the measured values of the IR thermometer (wide view angle type) and the measured values of the self-recording thermistor thermometer consisting of 594 data recorded in the 6 soil containers is shown in Figure 15. Similar to the measured data with the wide view angle type IR thermometer described above (Figure 13), the measured value in voltage was converted to the temperature by approximating it with a non-linier quadratic function based on the calibration results. Regardless the type of IR thermometer, the data measured by the wide view angle IR thermometer were plotted around a straight line with a slope of almost 45°, and a high determination coefficient (R^2 value) of 0.9547 was calculated. The standard deviation (SD) of the measured values of the IR thermometer against the approximated relationship corresponding to the measured values of the thermistor thermometer is 0.775 °C.

Note here that the data set shown in Figures 14 and 15 are plotted in two groups: one is around 20 to 25°C corresponding to locations inside the building, and the other is lower than 20°C corresponding to outside of the building from autumn (mid-October 2021) to winter (mid-December 2021).

3.5 Summary of measurement results

As described above, each temperature measured with IR thermometer was compared with the temperature measured with thermistor thermometer buried near the target depth of the IR thermometer, resulted in a good agreement with a high determination coefficient (R^2 value) of 0.95 or higher (except 0.92 for a case of data including temperature below 5°C. Although the accuracy of IR thermometers written in their specification is larger than 2 or 3°C, quickly measured temperature with IR thermometer shows practically sufficient accuracy compared to stationary measurement very accurate temperature with thermistor thermometer (accuracy of 0.21°C with resolution of 0.02°C).

4. Conclusions

In this study, aiming to develop a quick soil temperature measurement method applicable to efficient and accurate measurement at multiple depth at each investigation point over a wide area avoiding damage to the thermometer body and problems of a long time for thermal equilibrium, a quick soil temperature measurement with an infrared radiation thermometer (IR thermometer) using a predrilled hole up to the target depth was attempted. The findings from this study are written hereunder.

1) A casing pipe with a spacer made of polyvinyl chloride was penetrated from the ground surface to a target depth. After removing the spacer, the IR thermometer was set into the casing pipe, and then, soil temperature was measured quickly in about 5 seconds. A stable measurement was successively conducted. Although the measured temperature with the IR thermometer does not have the accuracy of a mercury-in-glass thermometer, which takes time in measurement for thermal equilibrium, it was confirmed that it is sufficiently accurate based on a comparison with the temperature measured by self-recording thermistor thermometer.
2) Both measuring methods using the narrow view angle type IR thermometer setting at the top of the casing pipe with a longer distance from the target depth and the wide view angle type IR thermometer setting inside of the casing pipe with a shorter distance from the target depth can measure soil temperature with sufficient accuracy.
3) Because the linearity between the actual temperature and the displayed temperature possibly tends to be lost particularly in a low temperature range, it is necessary to pay attention to the measurable temperature range of the IR thermometer by calibration.

These findings are useful in temperature measurement of cement treated soils placed in winter season in cold region where temperature control (heating system) is often required if necessary because cement treated soils do not harden under freezing temperature (it should be taken care at temperatures below 5°C).

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