

APPLICABILITY OF OPTICAL FIBER SENSOR ON TEMPERATURE DISTRIBUTION ESTIMATION AND LEAKAGE DETECTION OF IMPERMEABLE LINER IN SOLID WASTE LANDFILL

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1. INTRODUCTION

In Japan, Basic Act on Establishing a Sound Material-Cycle Society has promoted the recycling of waste, and the volume of final waste disposal has been greatly reduced. However, technological and economic constraints inevitably result in the generation of waste that is difficult to recycle. Solid waste landfills will continue to be an indispensable social capital to receive such waste.

11 criteria must be met when decommissioning general waste landfills and industrial waste managed landfills¹⁾. One of the items listed is that "the interior of the landfill is not abnormally hot compared to the temperature of the surrounding area.

The methods proposed for monitoring the temperature inside the landfill include measuring the temperature inside the gas vent pipe and the temperature of leachate, and measuring the temperature of a pore hole drilled about 1 m deep from the ground surface as a method that is not affected by air temperature²⁾. However, all of these temperature measurements were taken at limited points on the landfill site. It is not easy to properly select representative points in a landfill with a large area, huge landfill capacity, and heterogeneous landfill waste. It is desirable to determine the temperature inside the landfill in area and even in three dimensions.

Optical fiber sensors are capable of measuring the distribution of temperature, strain, etc. in the linear direction of an optical fiber by using the optical fiber itself as the measuring section, utilizing the fact that the intensity, frequency, etc. of scattered light incident on the optical fiber varies with the temperature, strain, etc. of the optical fiber^{3) 4) 5) 6)}.

In the temperature monitoring of landfill sites, it is thought that by wiring optical fibers to the impermeable liner at the boundary between the landfill site and the surrounding ground in a mesh pattern or at regular intervals, the temperature distribution at the boundary of the landfill site can be grasped from an areal perspective,

and is expected to contribute to the determination of the abandonment of landfill sites. It is also expected to estimate the three-dimensional temperature distribution inside a landfill by inverse analysis based on the temperature distribution at the bottom and on the slope of the landfill.

Given that temperature distribution can be measured by optical fiber sensors, there is a possibility that leachate leakage due to the breakage of the impermeable liner can be detected as an abnormal temperature distribution by wiring optical fibers under the impermeable liner.

In this study, optical fibers were wired to a model of the slope of a landfill with an impermeable liner, and the reproducibility of the temperature distribution of the impermeable liner and the possibility of detecting water leakage were examined using temperature measurement data from the optical fiber sensor.

2. METHODS

2-1 Optical Fibers and Measuring Instruments

In this study, general-purpose single-mode optical fibers coated with resin were used for optical fiber (0.9 SM(PAPB)-NH, Sumitomo Electric Industries, Ltd., 0.9 mm outside diameter). This optical fiber is capable of distribution measurement and can act as a measurement section at any position along the entire length of the optical fiber.

An optical fiber sensor was formed by connecting an optical fiber to an instrument to measure temperature. Temperature was measured in two ways. A method for measuring temperature from the amount of frequency shift of Brillouin scattered light (Brillouin Optical Correlation Domain Analysis (BOCDA))³⁾ and a method for measuring temperature from the intensity of Raman scattered light (Raman Optical Time Domain Reflectometry (ROTDR)). For the former measurement, a Brillouin instrument (custom-made, Yokogawa Electric Corp., 5 cm spatial resolution, 2.5 cm measurement interval) was used, and for the latter, a

Raman instrument (OPThermo FTR3000X, Sumitomo Electric Industries, Ltd., Spatial resolution 100 cm, measurement interval 25 cm) was used. The measurement interval is the distance between the temperature measurement points, and the spatial resolution is the average value of the temperature over a length of meters centered on the temperature measurement point.

In the Brillouin measurement, the amount of frequency shift of Brillouin scattered light depends on changes in strain and temperature. In this study, however, no external force was applied to the optical fiber, and the temperature was determined assuming that the amount of frequency shift depends only on changes in temperature.

2-2 Experimental Device

Two impermeable liners and two nonwoven geotextile were laid alternately on the slope using an impermeable liner laying trestle (W272cm×D300cm×H150cm) consisting of concrete panels with a slope of 1:2. Figure-1 shows a photograph of a slope model with impermeable liners laid.

Figure-2 shows a schematic cross-section of the slope where the impermeable liner was laid. On the upper surface of the lower nonwoven geotextile, a rubber heater was placed as a heat source and an aluminum plate was placed for heat diffusion and fixed with curing tape. Optical fiber cables were placed on the top surface of the upper nonwoven geotextile and fixed with curing tape. Two optical fiber cables were placed in parallel adjacent to each other to enable simultaneous temperature measurement at the same position by the Brillouin and Raman instruments.

Figure-3 shows a wiring diagram of an optical fiber cable. The upper end of the figure is the shoulder and the lower end is the butt of the cable. The fiber optic cable routing started at the left end of the slope shoulder and was routed in a single stroke, with longitudinal wires running from left to right at 50 cm intervals, followed by horizontal wires running from top to bottom at 50 cm intervals, then crossing the center of the slope from right to left and returning to the left end of the slope shoulder. The total length of one fiber optic cable on the slope was 41,360 mm.

The surface temperature distribution of the upper impermeable liner was photographed by a thermal infrared camera.

2-3 Experimental Conditions

Two experiments were conducted: Experiment 1 and Experiment 2.

The objective of Experiment 1 was to understand the reproducibility of the two-dimensional temperature distribution of the impermeable liner using the measurement data from the optical fiber sensor. First, temperatures were measured at room temperature by

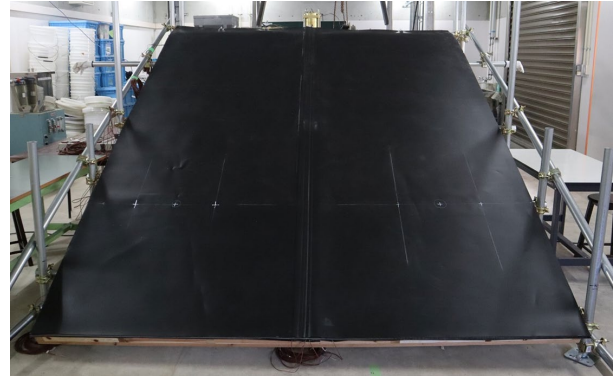


Figure-1 Slope Model with Impermeable Liner Laid

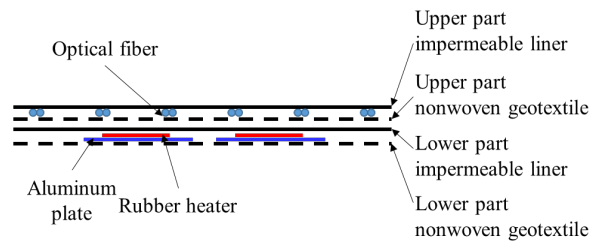


Figure-2 The Structure of The Impermeable Liner and The Fiber Optic Cable and Location of Heat Sources

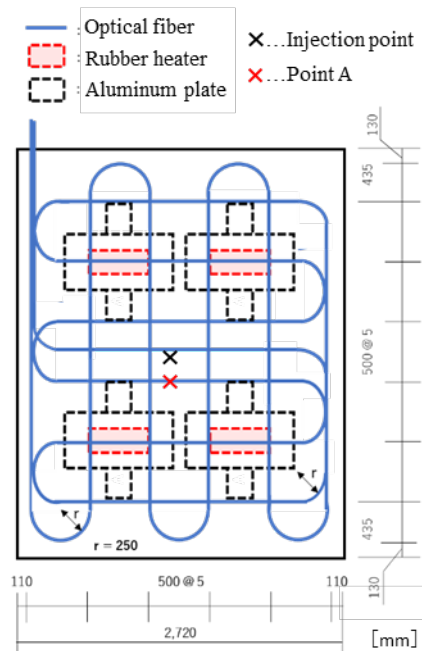


Figure-3 Arrangement of Fiber Optic Cables, Heat Sources and Water Injection point

optical fiber sensors using Brillouin and Raman instruments and a thermal infrared camera. After that, the temperature of the rubber heater was set to 80°C, and the temperature distribution of the upper impermeable liner was confirmed to be normal by a thermal infrared camera, and then the temperature was measured by an optical

fiber sensor using Brillouin and Raman instruments and a thermal infrared camera. The two-dimensional temperature distribution of the impermeable liner was created using the measurement data from the optical fiber sensor, and compared with the two-dimensional temperature distribution of the impermeable liner captured by the thermal infrared camera.

The objective of Experiment 2 was to understand the possibility of detecting water leakage using an optical fiber sensor. First, in order to simulate water leakage due to damage of the upper impermeable liner, a hose nipple was drilled through the upper impermeable liner in the center of the slope to enable water injection using a metering pump. The water injection points are shown in Figure-3. Next, temperatures were measured at room temperature using optical fiber sensors with Brillouin and Raman instruments and a thermal infrared camera. After that, pure water adjusted to 27.0°C in a thermostatic bath was continuously injected for 56 minutes using a micro volume metering pump. Immediately after the water was injected, temperatures were measured seven times at 8-minute intervals using optical fiber sensors with Brillouin and Raman instruments and a thermal infrared camera. The air temperature was 19.7°C, and the temperature of the injected water was approximately 7°C higher than the air temperature. The flow rate of the injected water was 17.1 mL/min.

2-4 Temperature Calibration

Since the optical fiber is placed in contact with the underside of the upper impermeable liner, the temperature of the optical fiber is considered to be approximately equal to the temperature of the upper impermeable liner directly above it. Therefore, we calibrated the temperature measured by the optical fiber sensor using the temperature of the upper impermeable liner directly above the optical fiber cable, which was measured by a thermal infrared camera.

2-5 Creation of Two-Dimensional Temperature Distribution

A two-dimensional temperature distribution was created from the temperature distribution data measured by the optical fiber sensor. The temperature distribution data from the optical fiber sensor consists of the distance from the starting point of the optical fiber and the temperature. The two-dimensional coordinates of each point were obtained from the wiring diagram of the optical fiber and the distance, and the two-dimensional temperature distribution was created using the data set of the two-dimensional coordinates and temperature. Contour plotting software (Visualizer Pro, Mallo Code) was used to create the two-dimensional temperature distribution.

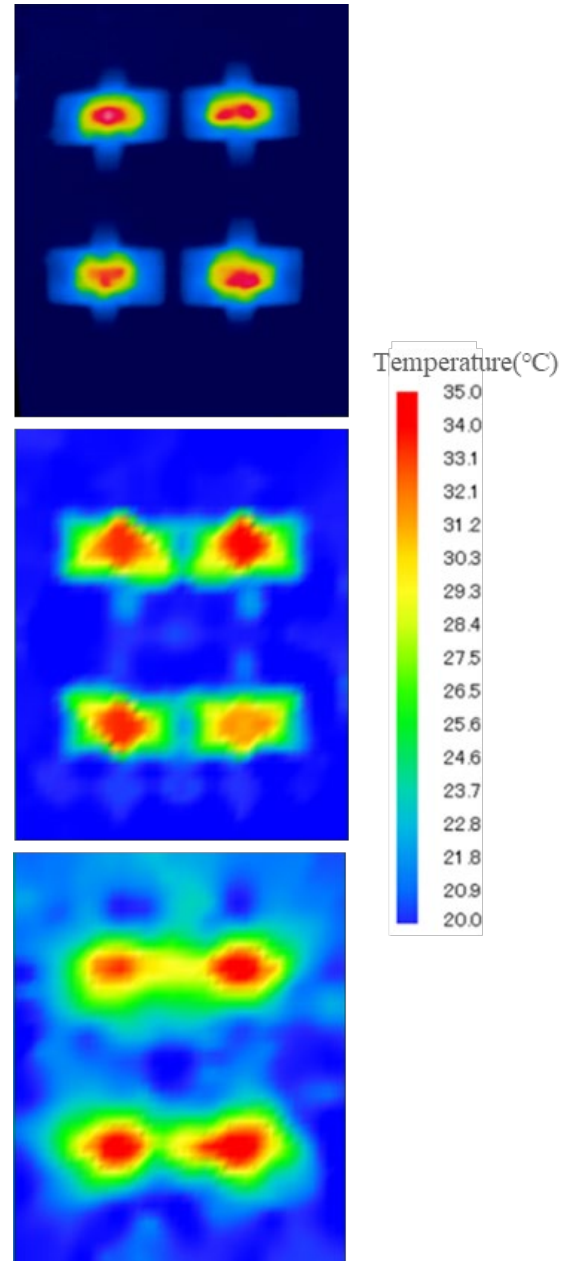


Figure-4 Two-Dimensional Temperature Distribution in Experiment 1 (Top: Thermal infrared camera, Middle: Brillouin measurement, Bottom: Raman measurement)

3. RESULTS AND DISCUSSION

3-1 Applicability to The Estimation of Two-Dimensional Temperature Distribution of Impermeable Liners

Figure-4 shows the temperature distribution of the impermeable liner taken by the thermal infrared camera in Experiment 1 and the two-dimensional temperature distribution generated from the data measured by the optical fiber sensor using Brillouin and Raman instruments.

The set temperature of the rubber heaters was 80°C,

whereas the maximum temperature of the upper impermeable liner was about 35°C. The rubber heaters were installed between the lower impermeable liner and the lower nonwoven geotextile, and the upper nonwoven geotextile existed between the rubber heaters and the upper impermeable liner. The high porosity of the nonwoven geotextile and the heat insulation effect of the air prevented the heat from the rubber heater from being transferred to the upper impermeable liner, which is thought to have caused the large temperature difference between the upper impermeable liner and the rubber heater.

There were four heat sources, and their presence was clearly identified by the thermal infrared camera. In the two-dimensional temperature distribution generated from the Brillouin data, the four heat sources were clearly identified, although not as clearly as with the thermal infrared camera. On the other hand, the two-dimensional temperature distribution generated from the Raman data showed four peaks in the temperature distribution, but the left and right heat sources appeared to be connected.

This is largely due to the difference in spatial resolution. The Brillouin measurement cannot capture temperature differences within a narrower range than the spatial resolution. The higher spatial resolution of 5 cm for the Brillouin measurement allows for a finer temperature distribution to be captured. However, in the Raman measurement, where the spatial resolution is as low as 100 cm, it would be difficult to distinguish the left and right rubber heaters separately in this experiment, where the distance between the left and right rubber heaters is 50 cm.

Although Brillouin measurement has better reproducibility in estimating temperature distribution, considering the actual size of the landfill and the size of the heat source, a spatial resolution of 100 cm is sufficient, and Raman measurement data is considered applicable in estimating the two-dimensional temperature distribution of the impermeable liner.

3-2 Applicability for Detecting Water Leakage from Impermeable Liner Damaged Areas

Figure-5 shows the change over time of the temperature measured by Brillouin measurements at two locations in Experiment 2: point A, which is the optical fiber sensor measurement point nearest the water injection point (hereinafter referred to as "water injection point"), and a point far from the water injection point and unaffected by the water injection (hereinafter referred to as "ambient temperature point"). Point a is located approximately 20 cm below the point of water injection in the direction of the slope gradient. The plots in the figure show data from seven measurements taken at eight-minute intervals, each plot being the value of an eight-minute measurement and plotted at the center of an eight-minute period.

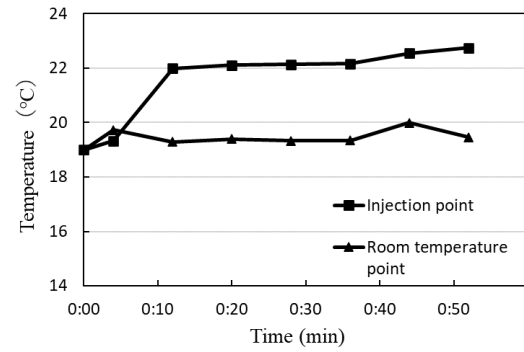


Figure-5 Temperature Change During Water Injection (Brillouin measurement)

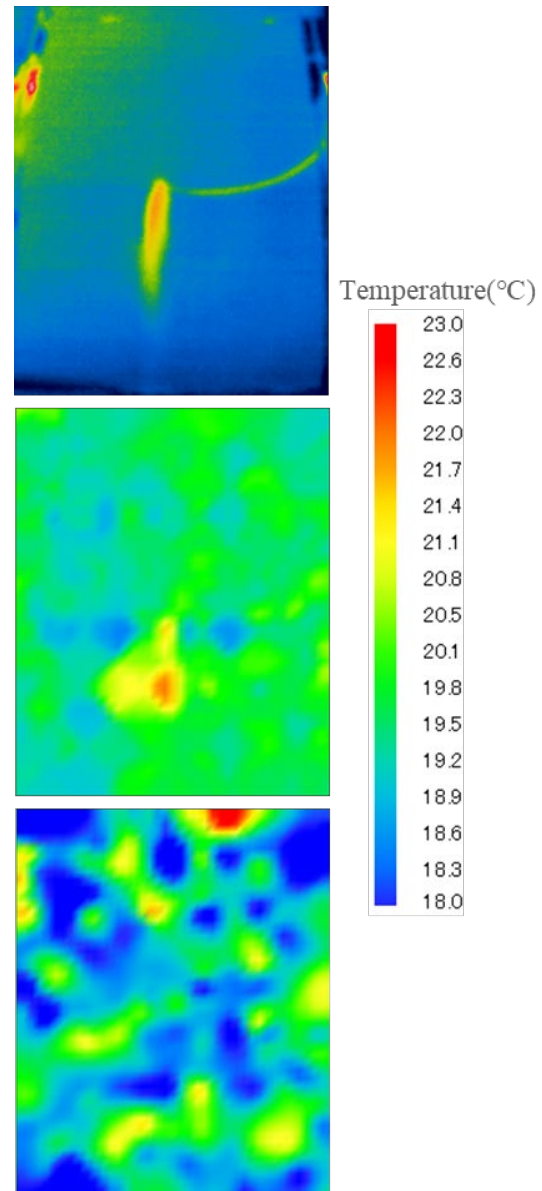


Figure-6 Two-Dimensional Temperature Distribution in Experiment 2 (Top: Thermal infrared camera, Middle: Brillouin measurement, Bottom: Raman measurement)

The temperature at the water injection position was continuously 2 to 3°C higher than that at the room temperature position from 8 minutes after the start of water injection. The reason for the delay in the measured temperature increase from the point of water injection is considered to be that point a, which is called the water injection position, is about 20 cm away from the water injection point, and it took about 8 minutes for the water injection to reach the point. The temperature of the injected water was about 7°C higher than the room temperature, but the temperature difference between the injection point and the room temperature point was smaller than that, suggesting that the injected water was cooled in the process of reaching the injection point from the injection point to the injection point.

When such a leak causes a sudden temperature change that can be detected by an optical fiber sensor, it is considered to be an abnormal temperature fluctuation that could be detected by an optical fiber sensor.

Figure-6 shows the temperature distribution of the impermeable liner taken by the thermal infrared camera 48 minutes after the start of water injection in Experiment 2, as well as the two-dimensional temperature distribution generated from the data measured by the optical fiber sensor using Brillouin and Raman instruments.

The thermal infrared image shows that the water injection was flowing down the slope in the direction of the slope gradient. The maximum temperature in the thermal infrared image was 21.5°C, while the temperature of the injected water was 27.0°C.

The two-dimensional temperature distribution generated from the Brillouin measurement data showed hot areas similar in shape to the hot areas seen in the thermal infrared image associated with water injection. The hot area in the Brillouin measurement was located slightly below the hot area in the thermal infrared image. This is because the optical fiber was not located directly below the water injection point, and the optical fiber whose temperature changed with water injection was located below the water injection point. Thus, the Brillouin measurement indicated that leakage can be detected if a large area with a temperature about 2°C higher than the normal temperature is generated in association with the leakage.

The two-dimensional temperature distribution generated from the Raman data did not clearly identify the temperature increase associated with water injection. In the case of Raman measurements, the spatial resolution is 100 cm, and the temperature is the average of a 100 cm interval centered at the measurement point. In other words, if the anomalous temperature associated with the leakage does not occur in the same section as the spatial resolution, there will be no change in the average temperature. When considering water leakage on a slope, it is assumed that the leakage flows down the slope direction and does not spread widely in the direction

perpendicular to the slope direction. Therefore, Raman measurements with coarse spatial resolution are considered unsuitable for leak detection on slopes.

Next, focusing on the Brillouin measurement data from Experiment 2, we examined the effective routing of optical fibers for leak detection on a slope. In order to compare the case where the optical fibers are laid parallel (longitudinal) and perpendicular (transverse) to the slope direction, we created two-dimensional temperature distributions using only the longitudinal data and the transverse data from the Brillouin measurement data in Experiment 2.

The results are shown in Figure-7. In the longitudinal wiring, the optical fiber was not located directly under the point of water injection, and the water injection did not spread widely in the horizontal direction, so the temperature change of the optical fiber due to water injection was limited and the water injection could not be clearly captured. On the other hand, in the lateral wiring, the optical fiber was located in the penetration area of the water injection, and the temperature change caused by the water injection could be clearly captured. The results showed that the lateral wiring of optical fibers is effective in detecting water leakage on a slope.

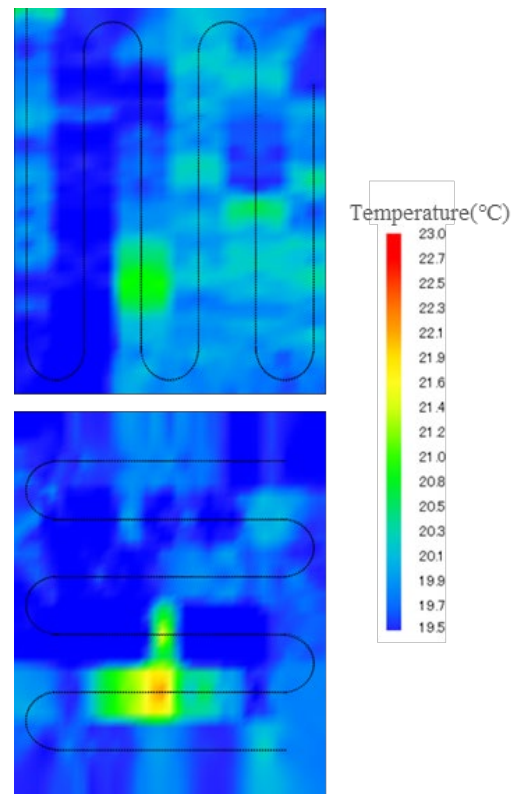


Figure-7 Difference in Two-Dimensional Temperature Distribution between Wiring Parallel and Perpendicular to The Direction of Slope Gradient (Brillouin measurement)

4. CONCLUSIONS

In this study, single-mode optical fibers were wired to a model of a reclaimed land slope with an impermeable liner to investigate the applicability of an optical fiber sensor in estimating the temperature distribution of the impermeable liner and detecting water leakage. The following is a summary of the findings obtained. The findings are as follows.

- 1) Brillouin measurement is more reproducible than Raman measurement in terms of temperature distribution. However, considering the actual size of the landfill and the size of the heat source, a spatial resolution of 100 cm is sufficient, and the Raman instrument is considered sufficient for estimating the temperature distribution of the impermeable liner.
- 2) If a temperature change that can be captured by an optical fiber sensor occurs with a leak, leak detection is considered possible.
- 3) For leak detection on slopes, it is effective to route optical fiber cables orthogonally to the slope direction.

As future issues, it is necessary to study the durability of optical fiber cables against impact, loading, and cyclic loading, and the long-term chemical durability of optical fiber cables for landfill disposal. It is also necessary to consider the installation method of optical fiber cables to the impervious sheet, appropriate wiring intervals, and leakage conditions under which leakage can be detected.

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