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Investigation of the causes of the unusual gap between the bridge and abutment using long-term monitoring

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ABSTRACT: Unusual gaps at the ends of bridge girders can occur due to the displacement of abutments or insufficient initial gaps during construction. However, when such irregularities arise, it is difficult to estimate the cause through visual inspection alone. As analyses on the causes of these gaps and their expansion are needed, investigations into appropriate remedial measures have become important. For these analyses, we developed a device called the Expansion-Gap Measurement System (EGMS), which enables the causes of unusual gaps to be estimated based on continuous monitoring for temperature-related changes in gap distance. By capturing seasonal variations in gap distance, the system allows us to estimate the progression in abutment movement and the causes of damage. This paper presents the case study of a simple bridge made with H-shaped steel girders with unusual gaps where the EGMS was installed for approximately three years to investigate the causes of a gap. It was found that during the high-temperature summer months, the gap closed completely, whereas in winter, the gap remained. Furthermore, it was confirmed that the abutment saw no lateral movement during the winter, indicating the minimal progression of displacement. Based on these findings, the cause of the unusual gap was attributed to either an error in the abutment's initial placement during construction or to previous lateral displacement of the abutment.

KEY WORDS: Unusual expansion gap; Expansion-Gap Measurement System; Long-term monitoring; Girder bridge.

1 INTRODUCTION

At bridge girder ends, cases where the main girder is in contact with the abutment have been frequently observed [1]. This phenomenon is a type of damage known as 'an unusual gap', which occurs when there is insufficient clearance to accommodate the temperature-related expansion and contraction of the main girder. As a result, unexpected and harmful axial forces develop in the main girder. Additionally, it is suspected that some form of horizontal displacement is occurring in the substructure.

The horizontal displacement of the substructure can arise from various causes, and in some cases, it may continue over time. If such displacement persists, the restoration of the gap will be done by cutting off the end of the main girder to shorten, but it may lead to the recurrence of the unusual gap. Therefore, it is crucial to identify the cause of the substructure's horizontal displacement, to assess its persistence, and to formulate an appropriate repair strategy for the unusual gap.

However, identification of the cause of horizontal displacement in the substructure is not straightforward. When such displacement is suspected, typical approaches to determine the cause are to investigate the ground and foundation conditions. This process often requires geological investigations, such as boring surveys, but it can be costly. Generally, it is difficult to estimate the cause of horizontal displacement solely through visual inspections.

To address this issue, the authors have developed the Expansion-Gap Measurement System (EGMS) for girders [2]. This system continuously measures the gap distance and the temperature of the main girder, enabling the cause of horizontal displacement in the substructure to be estimated. The details of the EGMS are described in Chapter 2.

In this study, in order to verify the effectiveness of the EGMS, we installed the system on a simple steel girder bridge composed of H-shaped steel where an unusual gap had been observed. Over the course of approximately three years, we used the EGMS to determine the cause of the unusual gap.

2 OVERVIEW OF THE EXPANSION-GAP MEASUREMENT SYSTEM (EGMS) FOR GIRDERS

2.1 Configuration of the EGMS

The EGMS for girders primarily consists of linear displacement sensors and thermometer installed at the gap section. Figure 1 provides an overview of the EGMS. The linear displacement sensors are placed on the upper and lower sections of the main girder to continuously measure the gap distance at each location. These sensors can detect changes in the gap distance caused by the temperature-induced expansion and contraction of the main girder. Additionally, the thermometer attached to the main girder provides data for calculations on the theoretical expansion/contraction amount and the corresponding gap distance.

The collected data is stored in a data logger for retrieval approximately once every two months. Since the data logger supports wireless data transfer, data can be collected from the bridge deck even if the data logger is installed underneath the main girder. The system is powered by either a solar battery or an 12V deep-cycle battery. A DC/DC converter is used to adjust the voltage to 5V, which is required for the linear displacement sensors and other components. The data logger,

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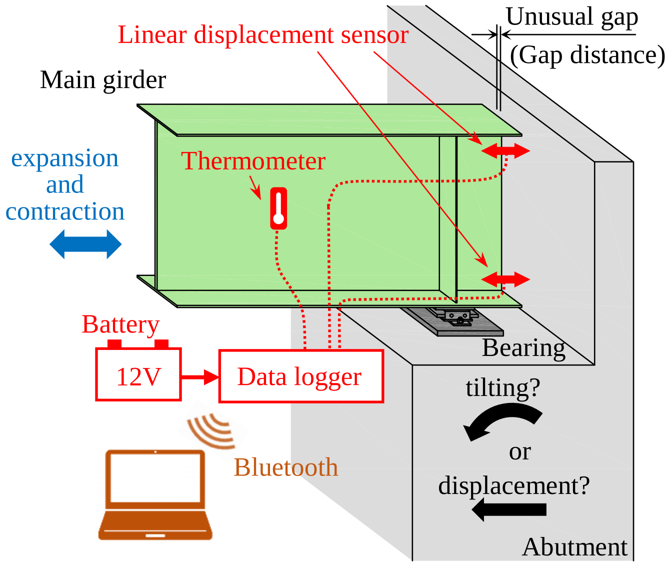

Figure 1. Overview of the EGMS.

battery, and DC/DC converter are housed in a compact, insulated box (approximately 15 × 25 × 20 cm) for protection.

Additionally, to verify the system's performance in cold environments, an operational test was conducted at −35°C [3]. The system was confirmed to function properly even at extremely low temperatures.

The system is designed to determine the cause of unusual gaps simply and efficiently, without relying on large-scale equipment. As described above, it is composed of readily available devices.

2.2 Causes of Deformations Determined by the EGMS

In the EGMS, the gap distance at both the upper and lower sections of the main girder at each support, together with the temperature of the main girder, are continuously measured. Since the system records the temperature of the main girder, the theoretical gap distance at each support can be calculated (Figure 2(a)). At the same time, the EGMS measures the actual gap distance at the upper and lower sections of the main girder, allowing for a comparison between the theoretical and actual gap distance.

For example, in the case of a simple girder, if the gap distance becomes 0 mm during summer, when the main girder temperature is high, and recovers in winter, when the temperature is low (Figure 2(b)), then it can be assumed that the abutments remain stationary and that the gap reduction is stable due to an initially insufficient clearance between the abutments. In such a case, cutting off the end of the main girder would prevent further reductions in gap distance.

On the other hand, if one of the abutments (fixed bearing) undergoes horizontal displacement and continuously pushes the superstructure, the gap distance at the movable bearing remains 0 mm regardless of temperature changes (Figure 2(c)).

Additionally, if tilting occurs, a difference in the gap distance between the upper and lower sections of the main girder can be expected. In this scenario, since the horizontal displacement of the abutment is ongoing, cutting off the end of the main girder would lead to another reduction in the gap distance. Therefore, measures to stop the horizontal displacement of the abutment

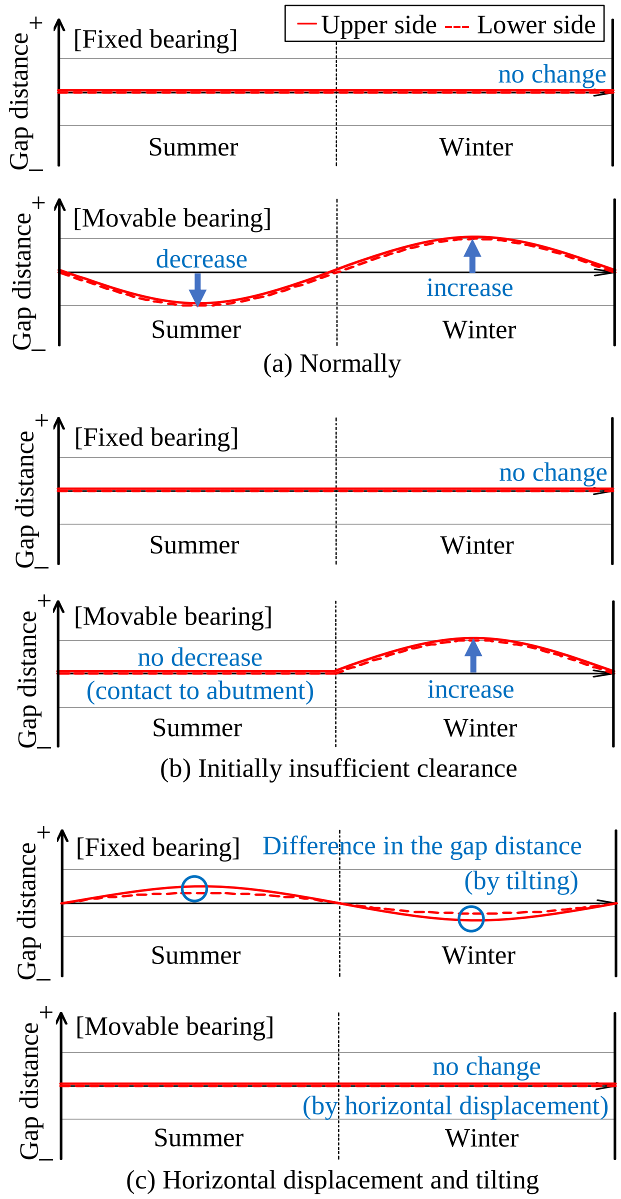

Figure 2. Example of theoretical and actual gap distance of a simple girder.

are necessary.

Although based on a classical approach, the Expansion-Gap Measurement System for girders enables the determination of the cause of unusual gaps by analyzing the horizontal displacement of the substructure. Furthermore, it facilitates the development of an appropriate repair strategy.

3 OVERVIEW OF EGMS INSTALLATION

3.1 Bridge Covered by the Study

Figure 3 provides an overview of the bridge investigated in this study. The target bridge is a simply supported non-composite H-shaped steel girder bridge in Hokkaido, Japan, with a total length of 14.6 meters. Each of the four main girders has the dimensions of H800×300×14×26 mm. The deck is a 19 cm-thick reinforced concrete slab with a 70 mm-thick asphalt pavement. The abutments are of the reversed T type and are

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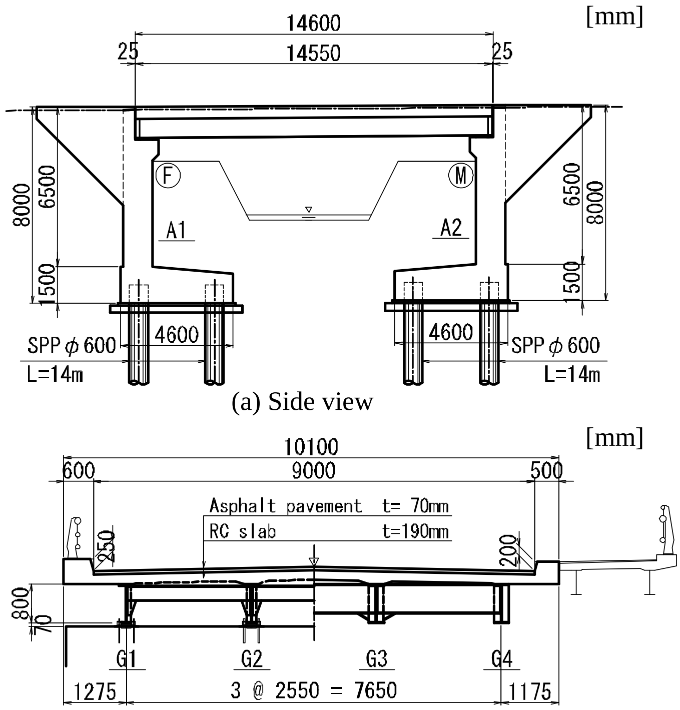

(a) Side view

(b) Cross section

Figure 3. Overview of the target bridge.

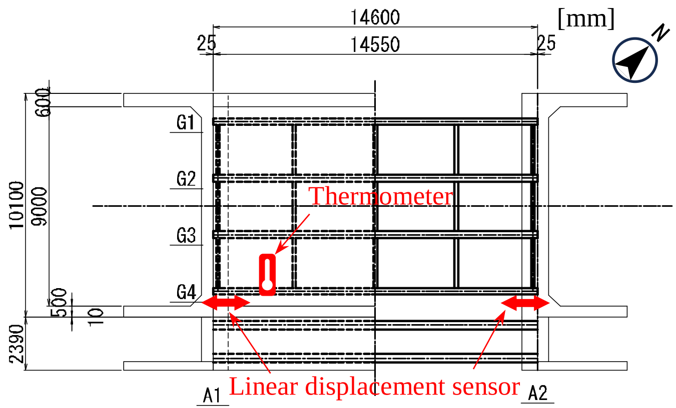

Figure 4. EGMS installation locations.

(a) A1 (b) A2

Figure 5. Installation status of the linear displacement sensors.

constructed of concrete. The foundation consists of six steel pipe piles each with a diameter of 600 mm and a length of 14 meters. The lowest winter temperature in the region where the bridge is located is approximately −30°C [4].

Regarding the ground conditions, the soil to a depth of 4 m below the road surface consists of a gravel layer with an N-value of approximately 10. Below this, from the depth of 4 to 18 m, clay layers with N-values ranging from 2 to 11 are distributed. Beneath the clay layers, a sandy layer with an N-value of 30 or higher (bearing layer) is present. According to the design drawings, the pile foundation reaches the bearing layer.

The bridge was completed in 1971, but a periodic inspection in 2012 found the gap at both abutments to be 0 mm. However, there were no indications of lateral movement, and the cause of the unusual gap remained unknown, posing challenges to the selection of appropriate remedial measures.

3.2 *Installation Status of the EGMS*

Figure 4 illustrates the installation locations of the EGMS for girders. The linear displacement sensors were installed at both the upper and lower sections of the girder ends on the north-side main girder (the G4 girder), with one sensor placed at each location. These sensors exhibited a measurement range of 50 mm, with an accuracy of ±0.3% at full scale. Figure 5 shows the installation of the linear displacement sensors. Additionally, a thermometer was installed on the web of the G4 girder to measure the temperature of the main girder. Various devices, including the data logger, were installed on the bearing seat surfaces of each abutment.

The measurement interval for the gap distance and the temperature was set to 30 minutes. Continuous measurements were conducted from September 30, 2021, to October 21, 2024.

4 MEASUREMENT RESULTS AND DISCUSSION

4.1 *Gap Distance Measurement at the Fixed Bearing*

Figure 6 shows the measured gap distance at the A1 abutment, which serves as the fixed bearing. The gap distance is displayed with the initial measurement value set to 0 mm. Figure 6 also includes the temperature of the main girder for reference.

At the fixed bearing, the variation in gap distance was minimal, remaining within the range of ±0.7 mm. Since the bearing at the fixed support has a 2 mm clearance, it is presumed that movement within this range occurred at the bearing. This confirms that the fixed bearing is functioning properly.

On the other hand, a difference in gap distance between the upper and lower sections of the main girder was observed over time. This discrepancy suggests that the abutment may have tilted. Therefore, a more detailed investigation of this issue is conducted in Section 4.5.

4.2 *Gap Distance Measured at the Movable Bearing*

Figure 7 shows the measured gap distance at the A2 abutment, which serves as the movable bearing. As for the A1 side, the gap size is displayed with the initial measurement value set as 0 mm. The temperature of the main girder is shown as a blue line, while the theoretical gap distance, calculated based on the girder temperature, is indicated in gray.

At the movable bearing, significant variations in the gap distance are observed in response to temperature changes. During the winter, when temperatures were low, the main girder contracted, and the measured gap distance closely

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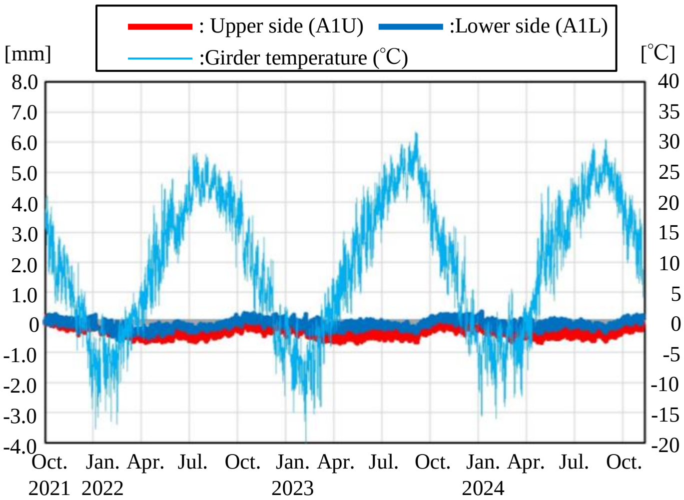

Figure 6. Variation in clearance (A1 abutment).

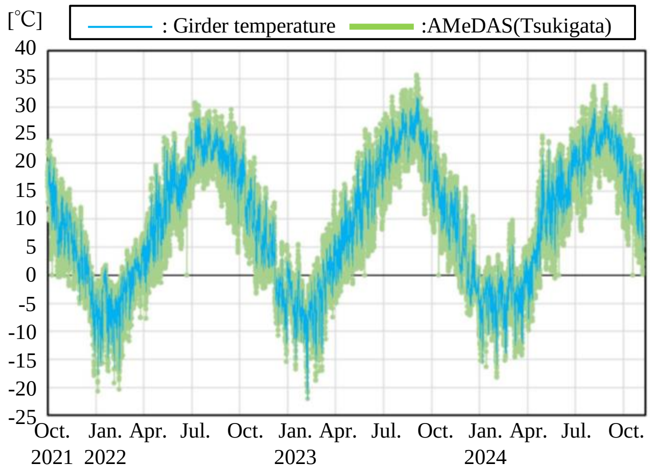

Figure 8. Comparison of temperatures measured at the main girder with those measured by nearby thermometer.

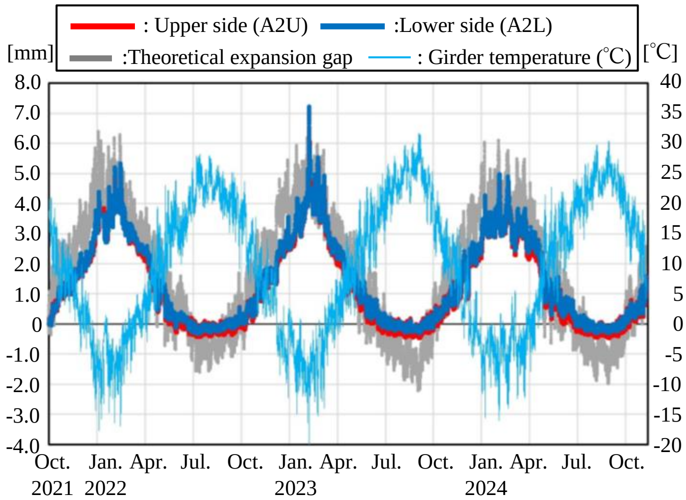

Figure 7. Variation in clearance (A2 abutment).

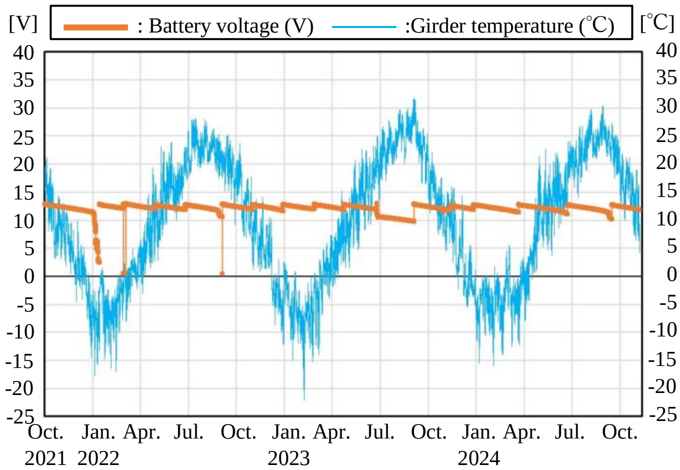

Figure 9. Battery voltage variation (A1 abutment).

matched the theoretical gap distance. In the summer, when the temperatures were high, the gap distance decreased. However, the gap reduction was less than the theoretical value. Onsite inspection confirmed that the main girder was in contact with the abutment parapet. A more detailed investigation into the gap distance behavior during warmer periods is discussed in Section 4.6.

4.3 Temperature Measurements

To verify the accuracy of the temperatures measured by the thermometer installed on the main girder, a comparison was made with the temperatures recorded by thermometer at a nearby station of the Japan Meteorological Agency's Automated Meteorological Data Acquisition System (AMeDAS) [4]. Figure 8 presents this comparison. The bridge and the AMeDAS thermometer are approximately 15 km apart.

As shown in Figure 8, the temperature measured by the thermometer on the main girder closely approximates the temperature recorded at the AMeDAS station. However, the temperature variations observed on the main girder are smaller than those recorded by AMeDAS. This is likely due to the fact that the main girder is made of steel, which takes time to respond to changes in ambient temperature. Since the measured values were generally consistent with the nearby temperature data, the measurement results are considered valid.

4.4 Transition of Battery Voltage

The battery used for the displacement sensors may experience voltage drops at low temperatures. Since the displacement sensors output data based on voltage, a drop in input voltage makes accurate displacement measurements difficult. Therefore, the battery voltage was also monitored. Figure 9 shows the changes in the voltage of the battery installed in the system at the A1 abutment.

The battery voltage decreases due to system operation, so periodic replacements were planned. However, at the end of 2021, the battery voltage dropped sharply, causing the system to shut down. This was attributed to power consumption by the system and to the cold temperatures. Therefore, from 2022 onward, the battery was replaced approximately every two months to prevent system shutdowns.

Except for the period at the end of 2021, the battery voltage remained above 10 volts. Since the 5 volts that is required to operate the displacement sensors and other components was maintained, the gap measurements obtained by the system were

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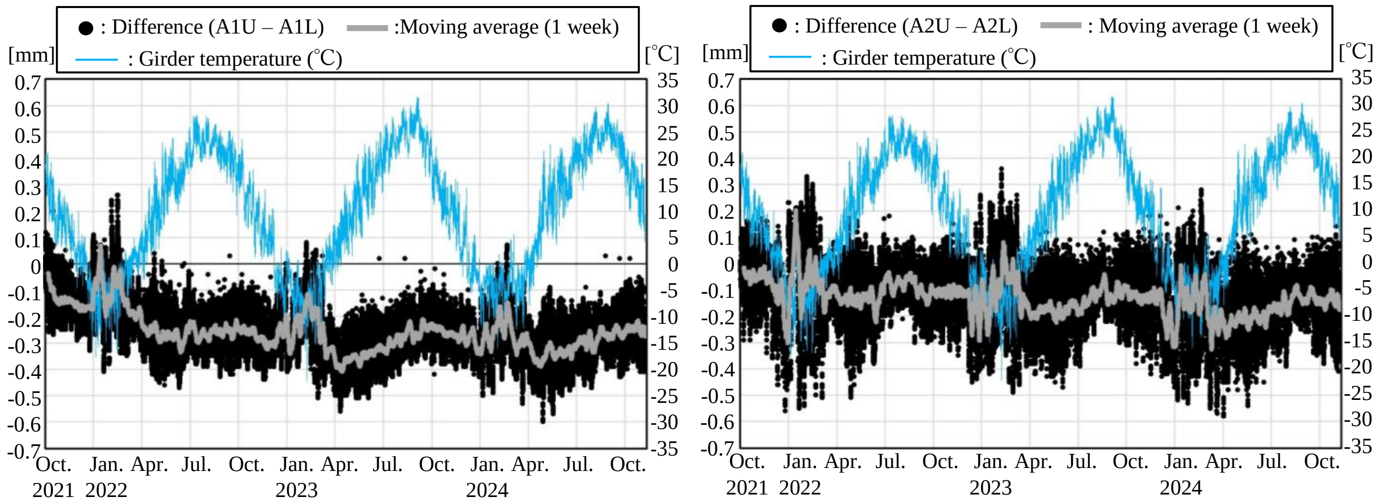

(a) A1 abutment (fixed bearing) (b) A2 abutment (movable bearing)

Figure 10. Variation in the difference of clearance between the upper and lower parts of the main girder.

confirmed to be accurate. Additionally, by replacing the battery regularly, it was confirmed that this system can be applied even in cold environments where temperatures drop below −20°C.

4.5 Evaluation of the Abutment Inclination using the Difference Between the Upper and Lower Displacement Sensors

To investigate the cause of the difference in gap distance between the upper and lower segments of the main girder at the fixed bearing over time, Figure 10 illustrates the transition of that difference for each abutment.

As shown in Figure 10a, at the A1 abutment (the fixed bearing), the difference became negative and that negative difference continued to increase over time. It is noted that the difference fluctuated significantly during the cold winter season, likely due to girder deflection caused by snow accumulation and the impact of snow removal. In contrast, the change in the difference at the A2 abutment (the movable bearing) remained minimal.

Referring to Figure 6, while the lower gap distance of the main girder remained around 0 mm, the upper gap distance showed a decreasing trend. This indicates that the increase in negative difference is caused by a decrease in the upper gap distance. Since the lower gap distance remained unchanged while the upper gap distance decreased, it is assumed that the A1 abutment is tilting toward the main girder. Therefore, it is presumed that the cause of the unusual gap lies in the A1 abutment.

However, since the decrease in the upper gap measurement was approximately 0.5 mm over three years, it is considered to have no immediate impact on the safety of the bridge.

4.6 Determination of Damage Causes Using the Correlation Between Temperature and Gap Distance

To examine in detail the condition of girder gaps during periods of rising temperatures, Figure 11 shows graphs for each linear displacement gauge, with temperature on the horizontal axis and gap displacement on the vertical axis. To show the transition of gap distance, data points are color-coded by year, and the theoretical gap distance is represented in gray.

At the A1 abutment (the fixed bearing) (Figures 11a and 11b), the gap distance fluctuates within the range of ±0.4 mm regardless of temperature. Additionally, while the gap distance of the lower segment of the girder changes linearly with temperature, no distinct trend is observed in the upper segment. This is likely because the lower segment primarily undergoes thermal expansion and contraction due to the steel material of the girder, whereas the upper segment is constrained by the concrete deck, which has a different specific heat capacity. However, since the overall variation in displacement is small, it is confirmed that the A1 abutment is functioning as a fixed bearing.

At the A2 abutment (the movable bearing), it is observed that the gap distance increases as the temperature decreases. However, when the temperature exceeds 15°C, the decrease in displacement plateaus. The difference between the theoretical and measured gap distances increases, and at 30°C, this discrepancy reaches approximately 2 mm.

Since gap distance is maintained during periods of temperature decrease at the A2 abutment, it is unlikely that the abutment is consistently leaning against the girder. In contrast, as noted in Section 4.5, a slight tilt was observed at the A1 abutment. This suggests that one possible cause of the unusual gap is the gradual tilting of the A1 abutment after the bridge was completed. However, since no significant inclination is visible on the front of the abutment, another potential cause could be past abutment movement or an insufficient distance between abutments during construction.

In any case, since no ongoing horizontal displacement of the abutments was detected and the average annual tilt of the upper part of the A1 abutment is approximately 0.1 mm, cutting off the girder ends is expected to be effective in preventing axial force from being input into the main girder.

5 CONCLUSION

We have presented a case study in which the authors utilized their Expansion-Gap Measurement System (EGMS) for girders to identify the cause of unusual girder gaps in a simple steel

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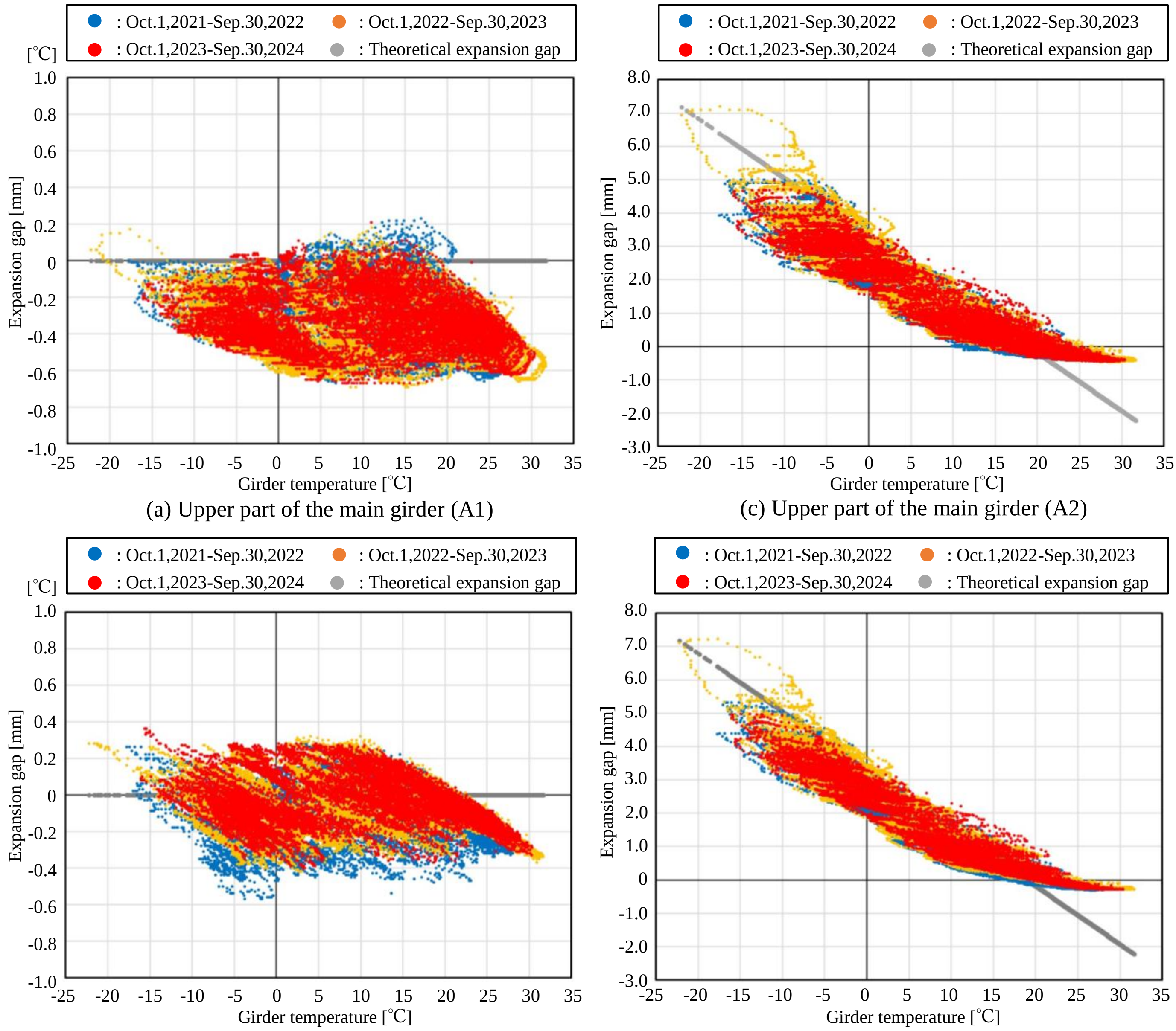

(a) Upper part of the main girder (A1)
(c) Upper part of the main girder (A2)
(b) Lower part of the main girder (A1)
(d) Lower part of the main girder (A2)

Figure 11. Relationship between temperature variation and clearance.

girder bridge composed of H-shaped steel. The following findings were obtained.

(1) The EGMS enables the long-term monitoring of girder gap variations.

(2) In the investigated bridge, the A1 abutment was found to be tilting toward the main girder, suggesting that the cause of the unusual gap lies in the A1 abutment.

(3) As the temperature rises, the gap displacement at the A2 abutment decreases, and when the girder temperature reaches 30°C, the difference between the theoretical and measured gap distance is approximately 2 mm. Since the tilt of the A1 abutment on this bridge is gradual, cutting off the girder ends is considered effective to prevent axial force from acting on the main girder.

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