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A damage screening method of the concrete slab focusing on correlation of mode shapes

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ABSTRACT: In Japan, visual inspections have been conducted as every five years duty since 2014. To improve the quality of inspections, it is necessary to record the evaluation of the structure's condition and its performance until the next inspection. However, methods and technical level depend on the judgement of the road administrator. A city of Kitami, Hokkaido, Japan where our university is located, was merged with one city and three towns in 2006, and has the largest area ranking in Hokkaido area and 4th in Japan. The total number of bridges, viaducts and functional culverts over 2.0 m length became more than doubled to 524 bridges compared to before the merger. Therefore, it is necessary to establish a labor saving and cost-effective method to assess the performance of bridge structures. In recent years, it has become possible to easily measure structural responses by the improvement of sensor performance, and more research has been conducted on maintenance management methods. Among those, vibration characteristics have a significant effect on the stiffness and mass of a bridge member and will be the index that grasps easily various damage effects. In this study, a damage location screening method was investigated for concrete slab bridges where segregation was suspected, based on correlation between mode shapes by using the COMAC. As a result, it is shown that these techniques will identify the damaged location and be used as an effective method to screen damaged locations.

KEY WORDS: Damage screening method; Mode shape; Concrete slab bridge; Maintenance.

1 INTRODUCTION

In Japan, visual inspections have been conducted as every five years duty since 2014. Under the established inspection specification, to improve the quality of inspections, it is necessary to record the evaluation of the structure's condition and its performance until the next inspection. However, methods and technical level depend on the judgement of the road administrator [1]. A city of Kitami, Hokkaido, Japan where our university is located, was merged with one city and three towns in 2006, and has the largest area ranking in Hokkaido area and 4th in Japan. Farmland is spread out in the suburbs and road network is expanding widely. The total number of bridges, viaducts and functional culverts over 2.0 m length became more than doubled to 524 bridges compared to before the merger [2]. Therefore, it is necessary to establish a labor saving and cost-effective method to assess the performance of bridge structures.

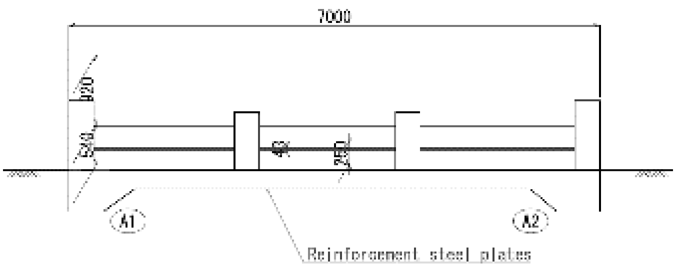
In recent years, it has become possible to easily measure structural responses by the improvement of sensor performance, and more research has been conducted on maintenance management methods [3], [4]. Among those, vibration characteristics have a significant effect on the stiffness and mass of a bridge member and will be the index that grasps easily various damage effects. Our research group has been studying a maintenance method using the COMAC focusing on a pedestrian bridge slab [5]. Consequently, it was shown that damage screening by co-relationship between mode shape is effective.

In this study, a damage location screening method was investigated for concrete slab bridges where segregation was suspected, based on correlation between mode shapes by using the COMAC.

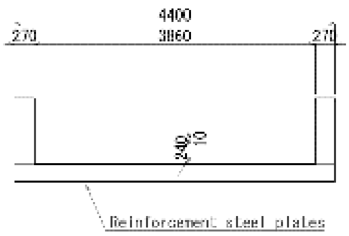
2 TARGET BRIDGE

2.1 Bridge specifications

The target bridge of this study is a reinforced concrete slab bridge. Since there is no detailed information such as construction records and drawing, shape measurements on site were taken as shown in Figure 1.



a) Side view



b) Cross section view

Figure 1. General arrangement drawing (unit: mm).

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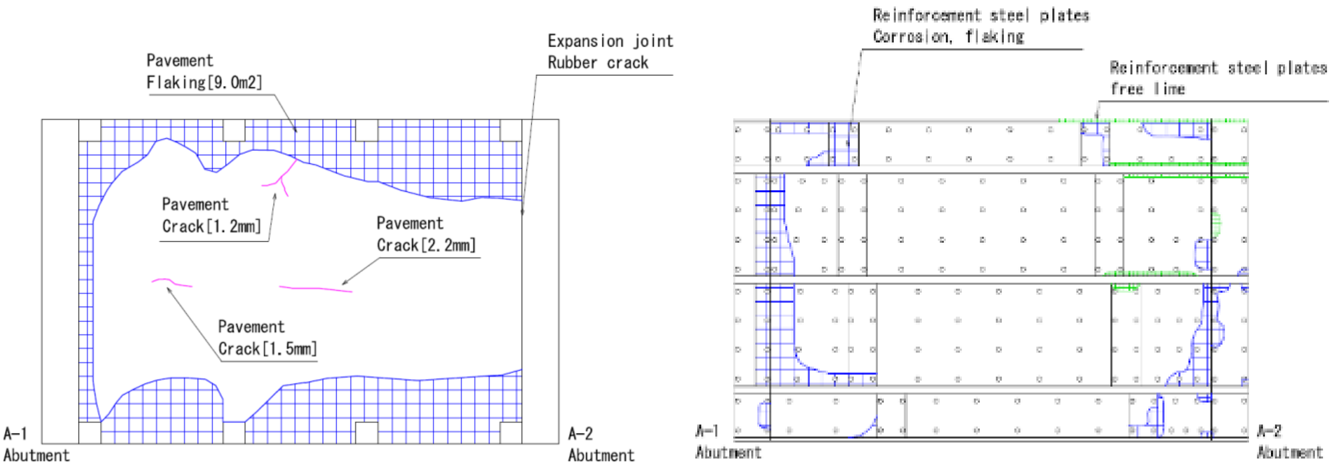
Figure 2. Inspection photos.



a) Pavement surface

b) Slab bottom surface

Figure 3. Inspection results.

2.2 *Inspection results*

Visual inspection was conducted to grasp degree of damage of each component by our research group in 2023. As a result of this inspection, widespread flaking has been found at the pavement on both sides, and corrosion and free lime can be seen on the reinforcement steel plates underside of the slab. Especially, icicle-like free lime has been found upstream side on the A2 abutment. Since this bridge does not have a waterproof layer on the concrete slab, it was suspected that segregation of the slab surface occurred more than in other areas. However, the pavement and steel plates make it difficult to see damage directly. A non-destructive survey by using electromagnetic waves was conducted on the pavement, but it did not obtain a clear waveform from the surface of the slab. Inspection status and results are shown in Figure 2 and Figure 3.

3 VIBRATION MEASUREMENT

3.1 *Measurement conditions*

Vibration characteristics were identified from acceleration data obtained by passing vehicle. The location of the accelerometer and passing situation of the vehicle are shown in Figure 4. Since this bridge has a short span and a roughly square planar shape, nine accelerometers were installed at equal spacing on the pavement surface to identify the bowl-shaped vibration mode shapes. In addition, accelerometers of number 1~3 and 7~9 were located under the tire lane, so they were moved 300mm outward.

Accelerometer is 3-axis MEMS type manufactured by Japan Aviation Electronics Industry, shown in Figure 5, with a sampling rate of 2000Hz. The vehicle passed over the bridge at 20km/h and measurements were taken 3 times in each direction.

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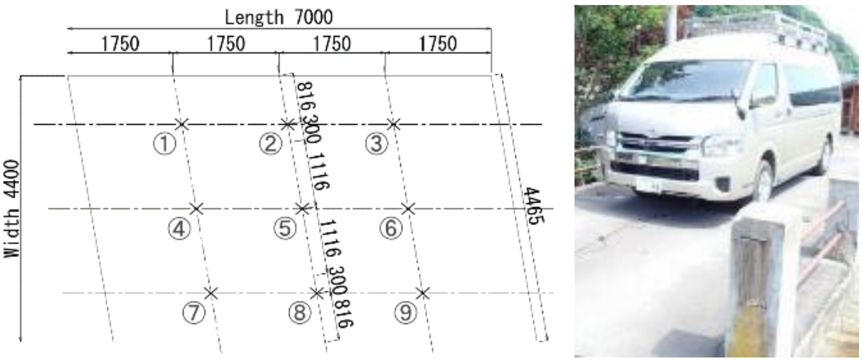
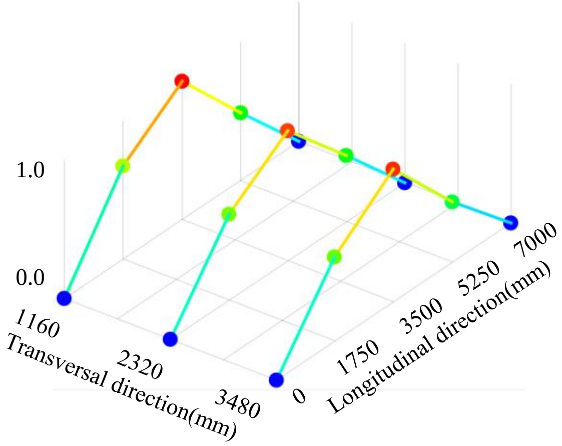
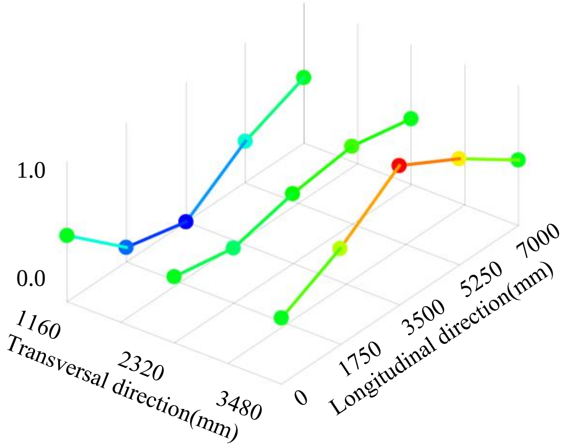


Figure 4. Measurement position and the test vehicle.

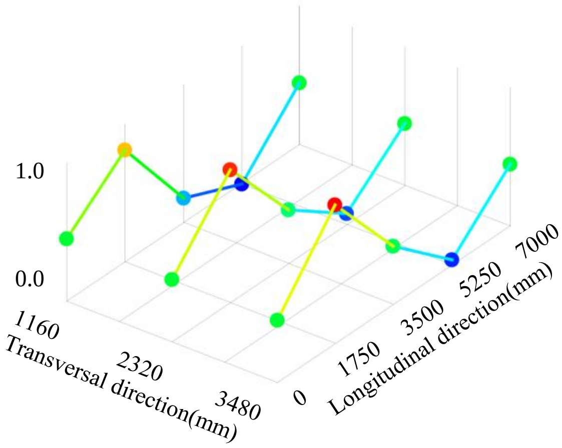
Figure 5. Accelerometer (JA-70SA).



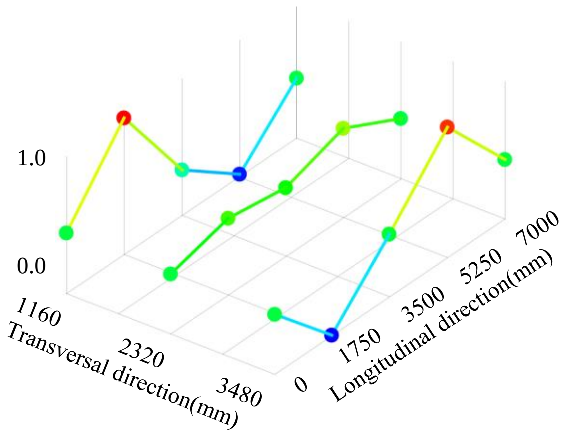
a) 1st mode: 17.3Hz



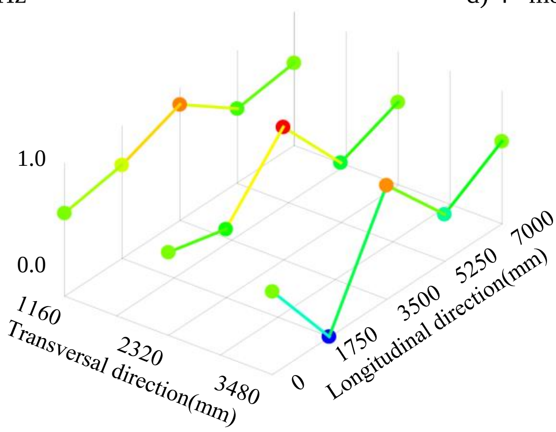
b) 2nd mode: 29.5Hz



c) 3rd mode: 47.5Hz



d) 4th mode: 68.8Hz



e) 5th mode: 101.3Hz

Figure 6. Mode shapes.

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3.2 Conditions for data processing

The data processing was carried out by the following steps. First, the power spectrum of each set of acceleration data was obtained by Fast Fourier Transform (FFT). Next, natural frequencies were identified by the peak picking method. Finally, mode shapes were estimated from the filtered wave amplitude in each sensor node.

3.3 Measurement results

As shown in Figure 6, the five vibration modes were identified from the experiment. In addition, the points at both ends where no accelerometers are plotted as zero value to make the mode shape easier to understand.
As a result, the first mode was the lower vertical symmetric bending mode. The second mode was the lower torsional mode. The third mode was the unsymmetric bending mode. The fourth mode was the higher torsional mode. And the fifth mode was the higher vertical symmetric bending mode.

4 ESTIMATION OF DAMAGE AREA BY MODE SHAPE CORRELATION

4.1 Estimation method

As a result of the inspection shown in Figure 3, icicle-like free lime has occurred upstream side on the A2 abutment, then it is thought the segregation has progressed more than in other areas. At the relationship between sensor position and icicles position shown in Figure 7, it shows that the icicle-like free lime is near the sensor number 3. In this study, the COMAC (Coordinate Modal Assurance Criterion) [6] technique is adopted to try to identify the damaged location. This technique is the calculation of correlation values at each coordinate over all the correlated mode pairs via the use of equation (1).

$$\mathrm{COMAC}(j) = \frac{\sum_{i=1}^{N} \left| \{\phi_O\}_i^j \{\phi_D\}_i^j \right|^2}{\sum_{i=1}^{N} \left[\{\phi_O\}_i^j \right]^2 \sum_{i=1}^{N} \left[\{\phi_D\}_i^j \right]^2} \quad (1)$$

Where, j is sensor number, N is the number of the modes, $\{c_{o.}\}_a$ and $\{r_{d.}\}_i$ are the mode vectors in different situations respectively. In this study, the sensors were set at 9 locations, and the modes are 5 as total identified modes.
Now, there was no initial data for this bridge, it wasn't able to

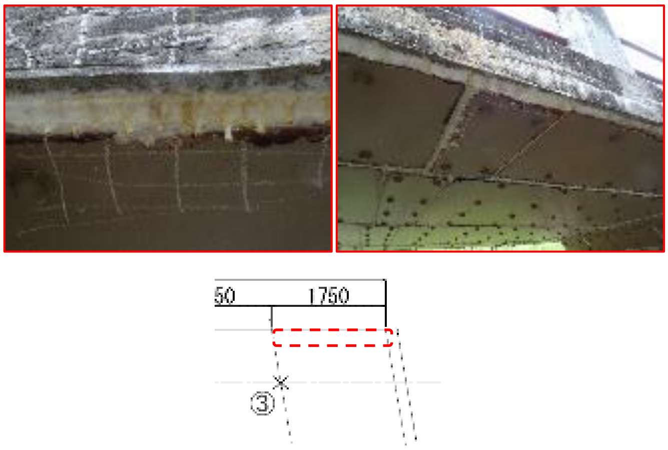
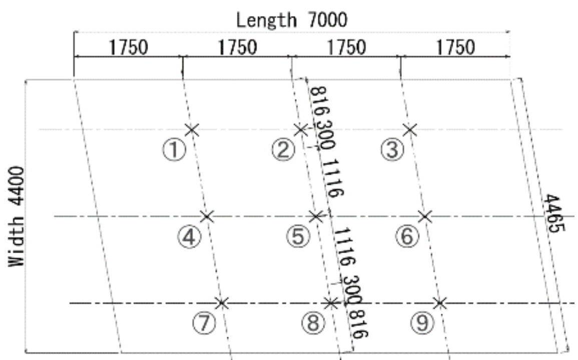
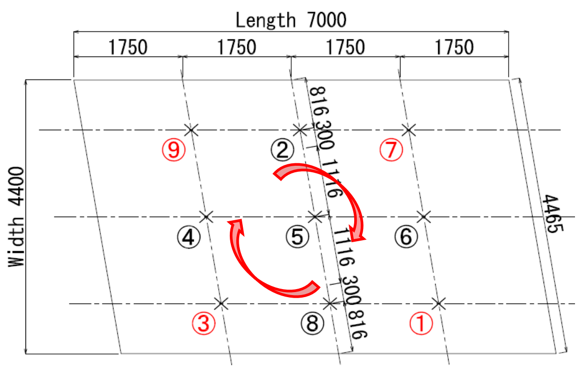


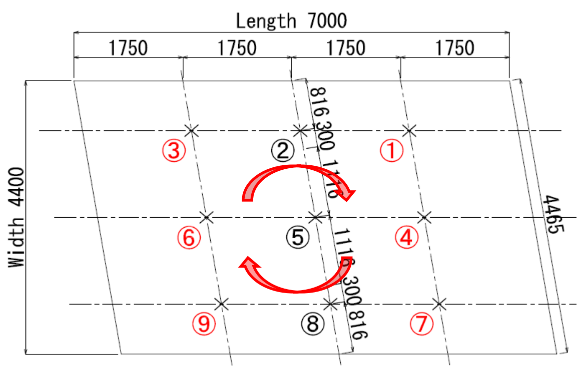
Figure 7. The icicle-like free lime and the position.



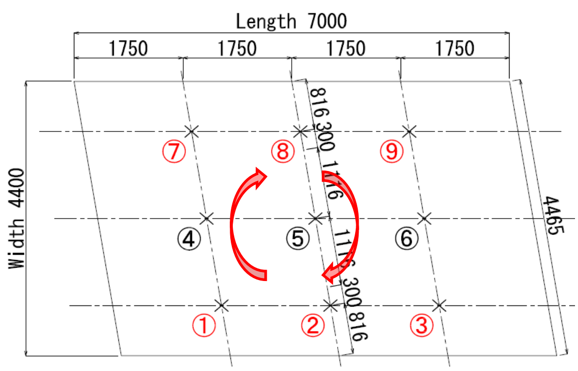
a) Pattern-1: Basic arrangement



b) Pattern-2: cross swapping



c) Pattern-3: swapping left and right



d) Pattern-4: swapping upper and lower

Figure 8. Swapping mode vectors.

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calculate the COMAC. Therefore, the following assumption was assumed. Since the planar shape of this bridge is biaxially symmetrical, it was assumed that the mode vectors at the measurement points on the diagonal line can switch each other as shown in Figure 8b). The same assumption was also assumed for the axes at the center of the span and the center of the width as shown in Figure 8c) and Figure 8d). Hence, the COMAC was calculated by the four patterns combination as shown in Figure 8. However, since the sensor number 5 is located in the center, it cannot swap. And even numbered sensors are limited to only two patterns. Here, considering bridge shapes of small span concrete slab bridges that were managed by Kitami City. Since many of these bridges are almost symmetrical shape include skew angles, this swapping approach method is widely applicable. Many of bridge located on suburban routes with little traffic and cracks do not tend to occur on the underside of the slab. In addition, the cross section of the pavement has a 2% drainage gradient, and the ends of the girders are prone to damage due to pooled water. Therefore, simply identifying damaged areas at the four corners of the slab provides extremely useful information for maintenance.

4.2 Result of estimation

The calculated results of the COMAC are shown in Figure 9. The vertical axis of this graph indicates the COMAC value, and the horizontal axis indicates the sensor number of the basic arrangement as shown in Figure 8a). As the COMAC approaches 1.0, it indicates that the correlation between these two different situations is high.

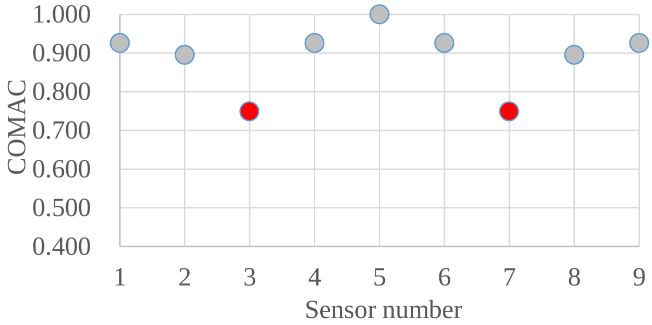
In the COMAC comparison between patterns 1 and 2, it shows the values at sensors 3 and 7 are relatively low. Also, in the COMAC comparison between patterns 1 and 4, it shows the values at the sensor number 3 and 9 are more clearly lower. On the other hand, the COMAC result between patterns 1 and patterns 3 is less clear than the others, it barely lowered sensors 1 and 3. From these results, the COMAC value at sensor number 3 is generally low. Here, a graph of the three results multiplied together is shown in Figure 8d) in order to clarify the difference in the COMAC values for each sensor. The correlation at the sensor number 3 was the single lowest.

As a result of the above, it was considered that the COMAC value of sensor number 3 which was located near the icicle-like free lime was the lowest, the rigidity of the concrete slab may have been reduced by the pooled water at the invisible inside, it affected the mode shape of the sensor number 3. It was also shown that even without initial structural values or historical measurement data, it is possible to screen for the damaged locations by swapping vibration mode vectors, even the locations are limited.

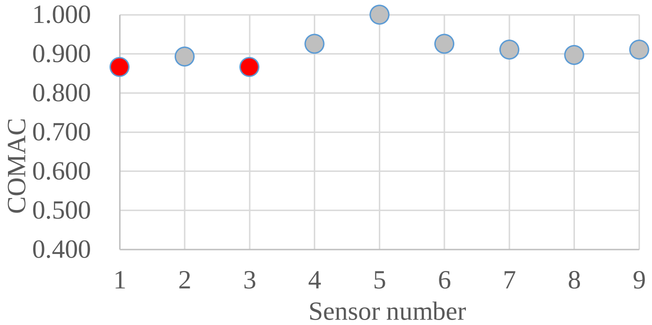
5 CONCLUSIONS

In this study, a damage location screening method was investigated for concrete slab bridges where segregation was suspected, based on correlation between mode shapes by using the COMAC. The results of this study are as follows:

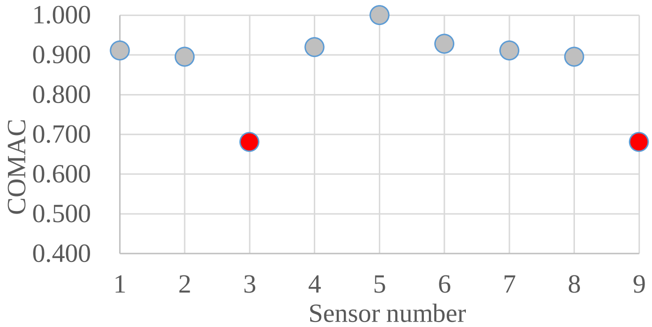
- According to the inspection results for the reinforced concrete slab bridge, it was suspected that segregation of the slab surface at the upstream side on the A2 abutment.
- Vibration characteristics were identified from acceleration measurement by vehicle passing, six vibration modes and natural frequencies were obtained.



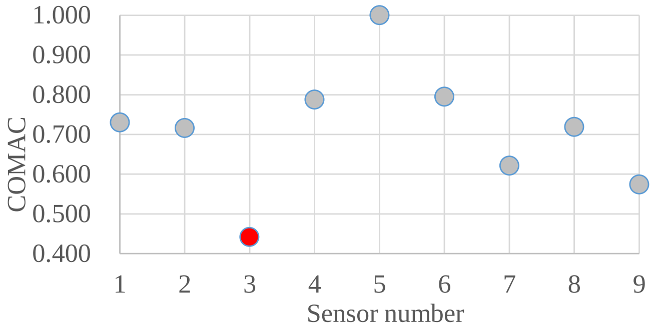
a) correlation Pattern-1 and Pattern-2



b) correlation Pattern-1 and Pattern-3



c) correlation Pattern-1 and Pattern-4



d) multiplication between a) - c)

Figure 9. COMAC results.

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- From the results of COMAC, the sensor number 3 which was located near the icicle-like free lime was the lowest. The rigidity of the concrete slab may have been reduced by the pooled water at the invisible inside, it affected the mode shape of the sensor number 3.
- Since many of these small span concrete slab bridges that were managed by Kitami City are almost symmetrical shape include skew angles, this swapping approach method is widely applicable.

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