Bridge Displacement Monitoring using Acceleration Measurement and Development of Efficient Bridge Management System

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Abstract

In this study, the concept of an efficient bridge management system focused on monitoring bridge displacements, was proposed for maintaining numerous bridges of municipal government in Japan. In order to monitor displacement easily, a displacement estimation method using measured acceleration data was proposed. The applicability of the proposed method, then, was verified through the field measurement using the prepared and weighed loading truck. The management system was proposed, and its application scenario using the developed system and measurement device, was also introduced for further actual operations in municipal government districts.

Keywords: acceleration measurement, displacement estimation, structural health monitoring, bridge management system

1 Introduction

Numerous civil infrastructures, which were constructed during the rapid economic growth of Japan, have been aged over time ahead of the world, and so much attention has been paid to the maintenance of infrastructures. There are over 700 thousand bridges in Japan and almost 70% of the total bridges is managed by the municipal government districts.

In addition, Japan's population has gradually shrunk to the date and the government finances are severely constrained because of falling tax revenues. Therefore, municipal governments are facing lack of financial and human resources, as well as technical knowledge on structures. Hence, it is essential to manage as many bridges as possible with the least cost and effort.

It is important to measure bridge displacement since it can be used to ensure the applicable limit of bridges. Moreover, displacement is directly related to the stiffness of bridges, and therefore bridge displacement can be used to understand the tendency of how existing bridges deteriorate by monitoring changes of bridge displacements induced by the known weight of the loading truck [1]. Also, displacement would be an index which is easy to understand for administrators without knowledge on structural engineering.

In this study, by considering the implementation cost and applicability of displacement measurement in field measurements, an acceleration based displacement monitoring system was proposed. By the proposed method, displacement can be estimated from one acceleration sensor. It enables measurement of the bridge displacements which can be easily compared to the measurement by contact displacement sensor. The field measurement of the loading tests using the prepared loading truck was conducted for the target bridge to measure displacements and accelerations. From the results of the field measurement, estimated displacements were compared to directly measured displacements using a contact displacement sensor. The accuracy of the proposed method was verified and the applicability of the proposed system for efficient management of bridges.

Finally, the bridge management system was developed in order to use this method efficiently. The system can store the information, such as measured data to the registered bridges, by using GPS location data. Moreover, the prototype device was developed to easily measure acceleration of bridges to encourage efficient applications.

2 Proposal of bridge displacement estimation method

2.1 Displacement measurement of bridge structures

As the aforementioned background, bridge dis-placement is of great importance for monitoring bridge behaviours and for assessing their structural performance. The relationship between the maximum bridge displacement and the loading onto the girder is as shown below:

$$\delta_P = \frac{PL^3}{48EI} \quad (1)$$

where, the length of the bridge girder span L , the modulus E and the moment of inertia I. If the ratio of δ_P to P is the measured loading of the prepared truck.

Therefore, the relationship between displacement and the flexural rigidity EI is inversely proportional as follows:

$$\delta_{normalized} = \frac{\delta_P}{\mathrm{P}} \propto^{-1} \frac{L^3}{48EI} \quad (2)$$

Thus, the monitoring of the structural deteriorations by monitoring the change of the maximum displacement with regards to the known weight of the prepared truck was made possible.

However, it is costly and not realistic to measure bridge displacements in field measurements since displacement measurement for bridges requires scaffoldings to implement contact-type displacement sensors. Even though there are reference free measurement systems such as a GPS-based system and a vision-based system, these systems are still costly and are difficult to install [2], [3].

Therefore, as a cost-effective and convenient method, displacement measurements using acceleration data have been encouraged and proposed in the recent researches from its easiness to implementation and cost-effectiveness.

2.2 Difficulties in bridge displacement estimation from acceleration measurement

However, it is also difficult to estimate displacement from acceleration. Inevitable noise included in measured acceleration data causes a large estimation error during integration processes. To overcome this difficulty of integrating measured accelerations, Park et. al. [4] proposed an initial velocity estimation method. Additionally, Umekawa et. al. [5] have proposed an integration method using a wavelet transformation. A similar approach was also taken by Sekiya et. al. [6], proposing the method named "free vibration method" using multiple acceleration sensor.

These studies have demonstrated the possibility of estimating bridge displacements accuracy. However, these methods do not estimate displacements from measured accelerations automatically.

Taking into account the aforementioned integration problems and studies, this paper presents an integration method using only one accelerometer to estimate bridge displacement which enables automatic displacement estimation.

2.3 Proposed bridge displacement estimation method

The target displacement is a pseud static displacement induced when only one vehicle passes as shown in Figure 1. The bridge displacement regarding the known weight should be evaluated to monitor changes of the response as aforementioned equation (2). In addition, bridges managed by the municipal districts have small amount of traffic, and for these reasons, the proposed method focuses on estimating the bridge displacement induced when one loading vehicle passes through the bridge.

A displacement is induced when the vehicle passes onto a bridge girder and a pseudo-static displacement which is a half-length wave and mainly lower frequency based on the passing time, causing gravity direction. This displacement can be theoretically obtained by double integration of acceleration data.

However, measured acceleration data inherently include sensor noise. Such sensor noise causes a significant integration error in the process of integrations. Therefore, the estimation error should be removed for accurate estimation of the displacement.

The outline of the proposed method is as shown in Figure 2. Firstly, measured acceleration is theoretically integrated twice to obtain displacement (Figure 2a).

Hence, in this proposed method, the entrance and the exit of a passing vehicle is statistically detected in time domain from the displacement, as the induced displacement can be considered as a local change and is distinguished from the estimation error (Figure 2b).

The estimation error can be estimated by using the integrated result of polynomial spline estimation (Figure 2c). Finally, the theoretical displacement can be estimated by removing the estimated integration error in the time domain (Figure 2d). This applicability and accuracy of this method was verified by the field measurement using the loading trucks.

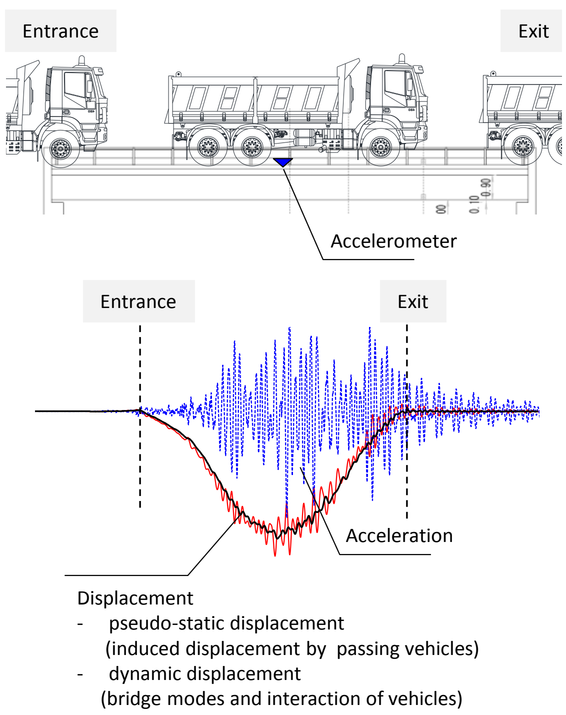


Figure 1. Outline of bridge displacement estimation from measured acceleration

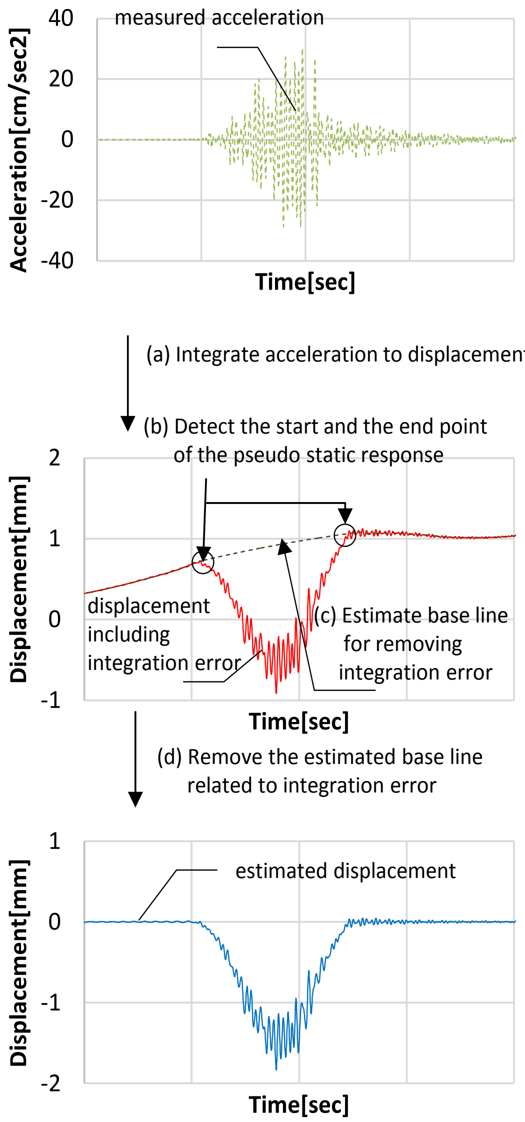


Figure 2. Outline of the proposed method

3 Field measurement and loading test

3.1 Target Bridge and field measurement

The target bridge is a steel girder bridge as shown in Figure 3. The span length is 24 [m] and the effective width is 4.9 [m]. The target bridge was selected as local bridges have commonly short or medium length span (~30m), and are located in low-traffic area.

The MEMS acceleration sensor was attached to the installation point, lower flange of the girder with a magnetic base plate. The carbon rod connected with a universal joint, was attached at the same location. The top of this rod has the plate to be measured by a contact displacement sensor that is attached and extended to the ground.

The contact displacement sensor was also installed as a reference data to verify estimation results using acceleration data by comparing these data. These sensors were connected to the same data logger with a sampling frequency of 100 [Hz].

Loading test was conducted using a 2 axles Truck and a passenger car, which were prepared for inducing enough large displacement. The total weights of these vehicles are 6.2 [ton] and 1.5 [ton]. The passing speed of the loading truck was set to over 20 [km/h] considering the span of the bridge to accelerate.

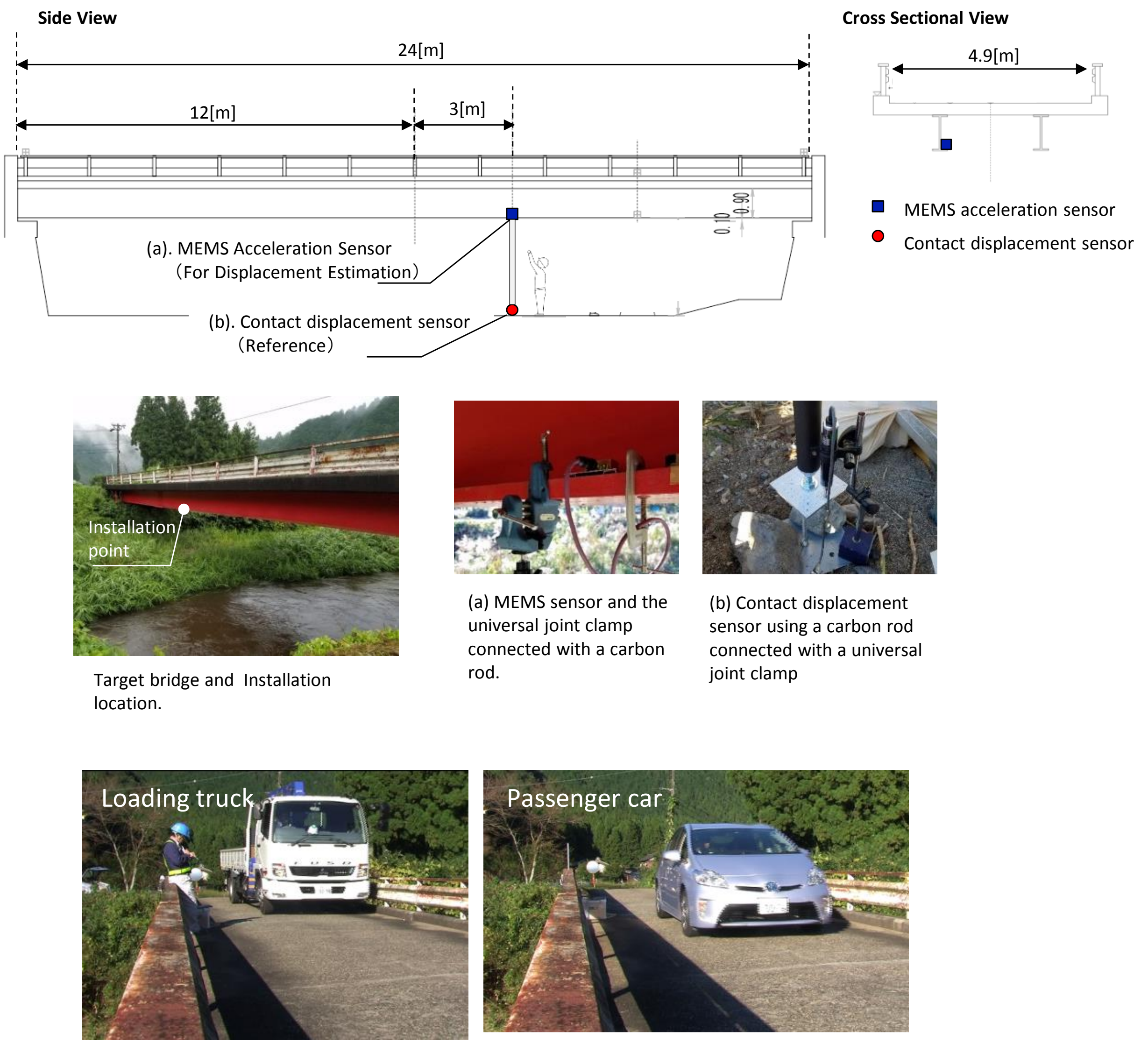


Figure 3. Target bridge and the detail of measurement equipment (steel girder bridge)

3.2 Verification of estimated displacement by using the proposed method

The displacement induced by the loading truck was measured by a contact displacement sensor, and estimated from measured acceleration data by the proposed method. The verification results were as shown in Figure 4. These results show high correlation between the bridge displacements derived from the measured and theoretical acceleration data by using the proposed method.

In the case of the loading truck, the maximum displacement was 1.64 [mm]. The frequency of this induced pseudo-static dis-placement was roughly 0.05 [Hz] (passed time = 9 [sec]). In this frequency band, it is difficult to obtain the accurate integration results since the larger integration error occurs when the frequency of noise is lower than 1 [Hz]. In other cases of a passenger car, the maximum displacement was around 0.3 [mm]. This result showed the high accuracy even for small displacement. It is difficult for other displacement sensors to measure accurately this order of small displacement, and therefore these results demonstrated the high applicability for estimating even small displacements.

The estimation errors were calculated by three times of standard deviation (3σ) of the difference between measured and estimated displacements in each case. It showed that the displacements could be estimated from a measured acceleration data with high accuracy as described in Table 1. Although there are still a few errors between the two data, the difference was caused by differences between sensor specifications of the applicable frequency bandwidth. Thus, this accuracy can be considered sufficient for measuring bridge displacements instead of using a contact displacement sensor.

Hence, from the conducted loading tests, the applicability and the accuracy of this proposed method was verified by comparing to measure displacements as referential data. This developed method was implemented in the proposed bridge management system to apply this method easily.

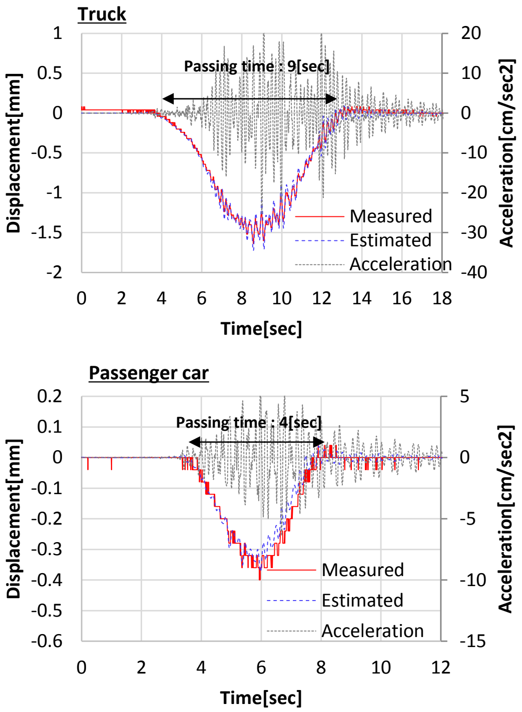


Figure 4. The results of bridge displacement estimation.

Table 1. The evaluation of estimated results and its accuracy

Case	Type	Total Weight [ton]	Measured [mm]	Estimated [mm]	3σ [mm]
1	Truck	6.2	1.60	1.64	0.20
2			1.68	1.62	0.24
3			1.64	1.74	0.25
4			1.76	1.75	0.30
5			1.52	1.52	0.29
6			1.80	1.90	0.22
7	Car	1.5	0.33	0.36	0.07
8			0.29	0.32	0.08
9			0.32	0.36	0.07

3.3 Effect on bridge displacement of passing position

The accuracy and applicability of the proposed method was verified as aforementioned. However, the maximum displacement had some variations even though the same truck passed through the bridge. This variation was caused by the passing position of the loading truck, and this effect was confirmed in the other target bridge.

The other field measurement was conducted and the target bridge was a two-span problem bridge with tow-lane road and a sidewalk as shown in Figure 5. Each span length is 28.9 [m] and two MEMS sensors were install to each side of the wheel guard at the mid span. The loading truck was a 3 axle dump truck and 20[ton].

The loading truck passed through lane 1 and lane 2 several times, and the bridge displacement at the sensors attached, were estimated using the proposed method. The results show that the maximum bridge displacement on both sides was affected by the passing position of the loading truck as shown in Figure 6.

The maximum bridge displacement when the loading truck passed on lane 2 was bigger than when the loading truck passed on lane 1. These results demonstrated that the rotation of the girder to transverse direction strongly happened because of the loading position.

Therefore, it could be confirmed that the bridge displacement at both side, should be measured and the passing position of the loading truck is also needed to monitor the effect on rotation of the girder.

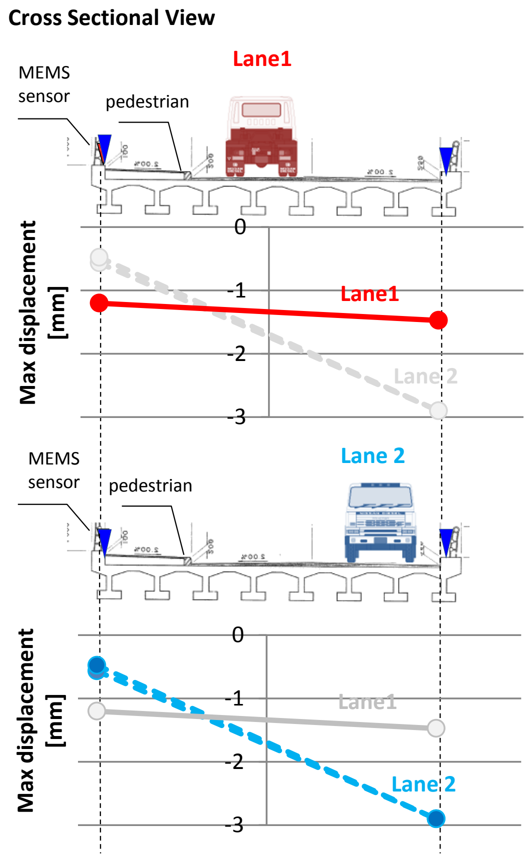
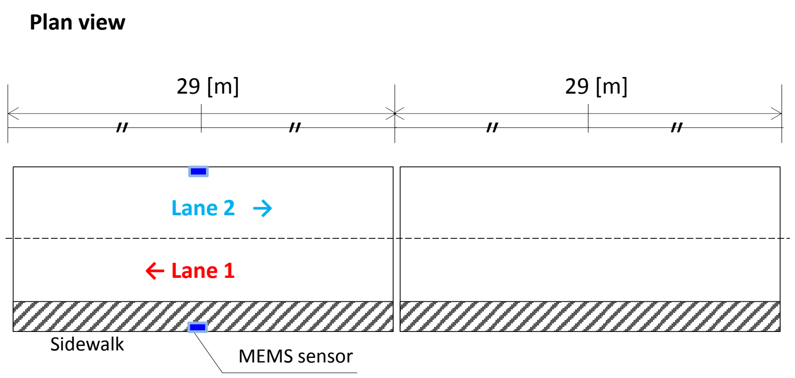
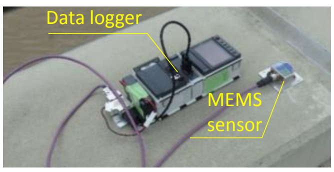


Figure 6. Effect on bridge displacements of passing positions of the loading truck





a) Measurement equipment

b) Loading test and prepared truck

Figure 5. Target bridge and the detail of measurement equipment (2-span prebeam bridge)

4 Application of the proposed bridge management system

4.1 Preparation for bridge displacement measurement

The proposed bridge management system requires only one acceleration sensor, and it was possible to provide the information on bridge natural frequencies of bridges and displacements induced by passing vehicles.

As acceleration can be installed on the girder using the base plate anchored to wheel guard of bridges as shown in Figure 7a, and this plate enables measurement of the acceleration from on the bridge.

4.2 Operation scheme of the proposed system

The actual application scheme of this proposed system is as shown in Figure 6. The brief outline of the actual operations of this proposed system is as follows:

1) The base plate is attached to the center of wheel guards of bridges to enable acceleration measurement from over bridges. Then, an acceleration sensor is attached to the base plate, before the field measurements using the prepared truck are conducted.

2) The prepared loading vehicle passes through bridges, and acceleration data are measured at each bridge. The total weight of the loading truck should be measured beforehand. Then, the measured data is uploaded and stored to Could server through IoT communication with GPS location information. The simultaneously uploaded measured data are analyzed by Cloud computing engine including the proposed analysis algorithm.

This system can be considered capable of supporting the problems such as cost, human resource, and technical shortage in municipal government districts. In addition, the proposed bridge management system was developed as the WEB application [7] as shown in Figure 5b.

4.3 Development of the prototype device

In order to increase the applicability of this system for the municipal government districts, it was important to develop the measurement system to use easily. The prototype device was developed as shown in Figure 6. This device includes MEMS accelerometer, a GPS module and an IoT module.

The sensor can be connected to the internet. The measured data can be uploaded, and results can be stored to the WEB application system. These procedures can be operated simply by pressing a switch or button. This system and device enables measurement of the bridge displacement and vibration with low cost and effort, making it possible to measure tens of bridges in a day.

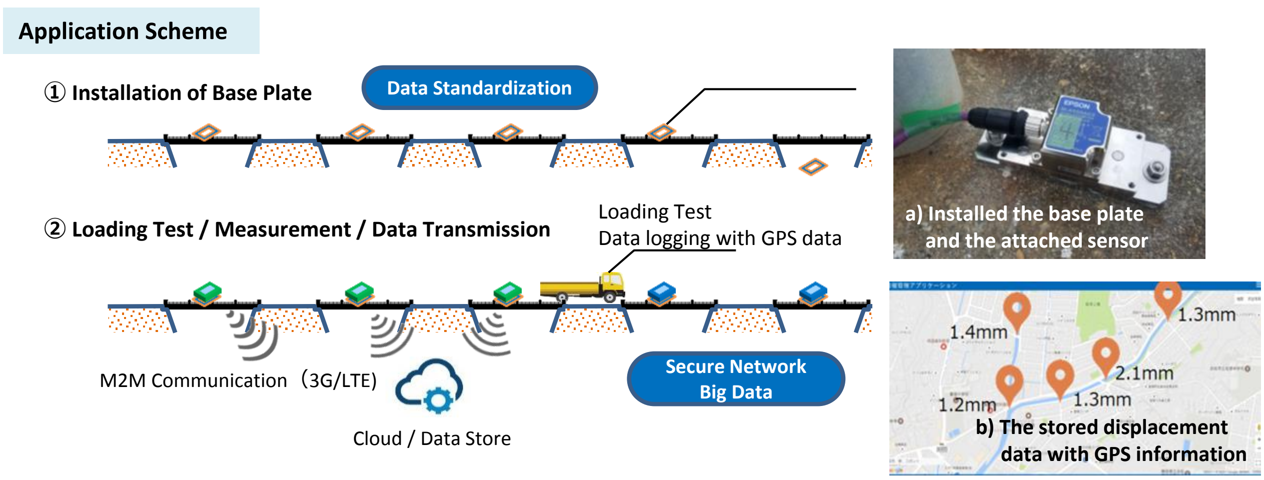


Figure 7. The application scheme of the proposed bridge management system

5 Conclusion

The purpose of this study was to propose a bridge displacement estimation method by using one acceleration data to develop a convenient displacement measurement method.

A bridge estimation method was proposed, and applied for measured accelerations of the target bridge. The results have then been verified by comparing estimated displacements to measured displacements using a contact displacement sensor. In addition, to apply this proposed method as a bridge management system, the actual operation procedure was proposed and this procedure made it possible to measure more bridges in a day. In addition, the bridge monitoring system which includes data storage and analysis engine was developed. The results can be summarized as follows:

1) A bridge displacement estimation method was proposed, and its applicability was verified through field measurements using prepared loading trucks.

2) The accuracy of the proposed method was verified by comparing estimated displacements to measured displacements.

3) The concept of the efficient bridge management system was introduced. Then, the actual operating procedures have also been introduced. In addition, the bridge management system and the measurement device were developed to encourage efficient applications.

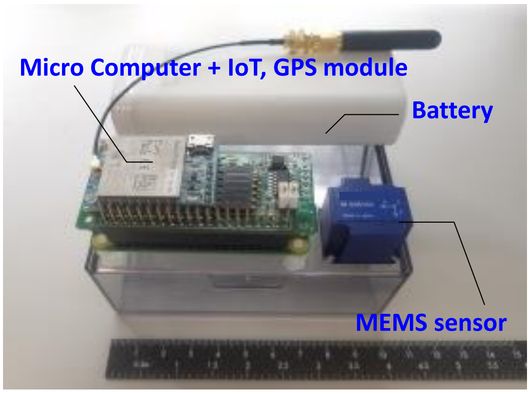


Figure 8. The prototype device for efficient measurement of acceleration data

With regards to infrastructure, the same situation as Japan would happen in the world sooner or later. Hence, this proposed system can be considered effective to maintain large number of bridges not only in Japan but also in the world.

6 References

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