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Remote vibration monitoring for scour detection of a railway bridge

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ABSTRACT: This study is intended to discuss real-time scour detection focusing on changes in frequencies of a railway bridge pier. Both train-induced vibrations and microtremor of a railway bridge pier were monitored. A wireless sensing device was adopted for the long-term monitoring which can be remotely controlled. A Bayesian approach to identified posterior distribution of frequencies was adopted to improve identification accuracy. A relationship between dominant frequencies and meteorological conditions (i.e. precipitation and wind speed) was also observed. The natural frequency of the bridge pier during a flood was identified in real-time, and it can be concluded that there exists rare possibility of scour due to the flood from train-induced vibrations and microtremor.

1 INTRODUCTION

The scour of railway bridges is one of the main causes of railway bridge failures during floods. How to provide a proper decision on the train operation control during heavy rain has been a keen technical issue for railway companies (Prendergast et al., 2013). The impact test on the bridge pier to identify changes in frequencies is a promising and conventional way of the scour detection. However the impact test is a laborious and time-consuming method, and is inapplicable for the real time monitoring to make a proper decision on the train operation control during heavy rains. An alternative way of the impact test is utilizing ambient vibrations or microtremor although quality of the identified frequency information might be poorer than the impact test.

A real-time monitoring method focusing on bridge vibrations under operational conditions thus has been considered as an alternative method to the visual investigation for scour assessment during a flood. Since changes in structural integrity lead to changes in modal parameters such as natural frequencies, identification of modal parameters is the first step for the scour detection by means of vibration monitoring (Chang and Kim, 2016). Once sensors were installed and electric power was supplied in the monitoring bridge, the real time vibration monitoring guarantees highly frequent real-time scour inspection compared to the impact test. The real-time vibration monitoring helps railway authorities to make a quick decision on resuming of train operation.

This study is intended to discuss real-time scour detection focusing on changes in frequencies of a railway bridge pier that are identified from train-induced vibrations and microtremor. The accelerations of bridge girders connected to the target bridge pier are also examined to clarify influences of girder vibrations to the vibrations of the pier. For the real-time and long-term scour monitoring of a railway bridge, a wireless sensing device comprising a tri-axial accelerometer that can be remotely controlled was deployed on the top of the bridge pier.

Both stochastic subspace identification (SSI) (Overschee and Moor 1996) and Bayesian operational modal analysis (BAYOMA) (Au *et al.* 2013) are adopted to identify natural frequency of the bridge pier. The SSI is the adopted as a time-domain method while the BAYOMA is adopted as a frequency-domain method. It is noteworthy that the Bayesian approach provides coefficient of variances of the identified modal parameters and S/N ratio of modal responses, which is useful to assess reliability of observed data during flood. The influence of environmental factors such as water level, wind speed and passing train to identified pier frequencies is also investigated.

2 SYSTEM IDENTIFICATION METHODS

2.1 Stochastic Subspace Identification in Operational Condition

In this study modal parameters of bridges in operational condition are identified utilizing the stochastic subspace identification (SSI) method that is a time domain method. The algorithm for the SSI is briefly described (Heylen *et al.* 1997, Overschee and Moor 1996).

The dynamic system of a structure is modeled by the state-space model as follows.

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{w}(k) \tag{1}$$

$$\mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{v}(k) \tag{2}$$

where $\mathbf{x}(k)$ and $\mathbf{y}(k)$ denote the state of structure and measurement at each time step k respectively. $\mathbf{w}(k)$ and $\mathbf{v}(k)$ denote the process noise and measurement noise vectors respectively, and are assumed to be stationary white noise. System matrices **A** and **C** which contain the modal information are estimated by means of the least squares method for the minimal prediction error of state $\mathbf{x}(k)$ given by the forward Kalman filter. The poles of the dynamical system provide modal properties of the dynamical system.

From the system matrices, we obtain the oblique projection matrix $\boldsymbol{O}_i$ is estimated as following equation.

$$\boldsymbol{O}_i = \mathbf{Y}_\mathrm{f}\mathbf{Y}_\mathrm{p}^\mathrm{T}\left(\mathbf{Y}_\mathrm{p}\mathbf{Y}_\mathrm{p}^\mathrm{T}\right)^\dagger\mathbf{Y}_\mathrm{p} \tag{3}$$

where $(\,\cdot\,)^\dagger$ denotes Moore-Penrose pseudo inverse matrix. $\mathbf{Y}_\mathrm{f}$ and $\mathbf{Y}_\mathrm{p}$ are block Hankel matrices of the future and past outputs respectively and defined as follows.

$$\mathbf{Y}_\mathrm{p} = \begin{bmatrix} \mathbf{y}(0) & \mathbf{y}(1) & \dots & \mathbf{y}(j-1) \\ \dots & \dots & \dots & \dots \\ \mathbf{y}(i-2) & \mathbf{y}(i-1) & \dots & \mathbf{y}(i+j-3) \\ \mathbf{y}(i-1) & \mathbf{y}(i) & \dots & \mathbf{y}(i+j-2) \end{bmatrix} \tag{4}$$

$$\mathbf{Y}_\mathrm{f} = \begin{bmatrix} \mathbf{y}(i) & \mathbf{y}(i+1) & \dots & \mathbf{y}(i+j-1) \\ \dots & \dots & \dots & \dots \\ \mathbf{y}(2i-2) & \mathbf{y}(2i-1) & \dots & \mathbf{y}(2i+j-3) \\ \mathbf{y}(2i-1) & \mathbf{y}(2i) & \dots & \mathbf{y}(2i+j-2) \end{bmatrix} \tag{5}$$

The singular value decomposition (SVD) is then applied to factorize $\boldsymbol{O}_i$ as

$$\boldsymbol{O}_i = \mathbf{USV}^{\mathrm{T}} = (\mathbf{U}_1\mathbf{U}_2)\begin{pmatrix}\mathbf{S}_1 & \mathbf{0} \\ \mathbf{0} & \mathbf{S}_2\end{pmatrix}(\mathbf{V}_1\mathbf{V}_2)^{\mathrm{T}} \simeq \mathbf{U}_1\mathbf{S}_1\mathbf{V}_1^{\mathrm{T}} \tag{6}$$

where $\mathbf{U}$ and $\mathbf{V}$ are unitary matrices with the appropriate size and $\mathbf{S}$ is a diagonal matrix with non-negative elements. The diagonal elements of $\mathbf{S}$ are known as singular values of $\boldsymbol{O}_i$. Singular values in $\mathbf{S}$ are listed in descending order. Therefore the components in $\mathbf{U_1S_1V_1^T}$ contain most of the information defining the elements in $\boldsymbol{O}_i$ and components in $\mathbf{U_2S_2V_2^T}$ are regarded as trivial components. Theoretically, the optimal state sequence$\mathbf{X}_i = [\mathbf{x}(i) \quad \mathbf{x}(i+1) \quad \dots \quad \mathbf{x}(i+j-1)]$ predicted by the Kalman filter in least square sense is obtained as follows.

$$\mathbf{X}_{\mathrm{i}} = \mathbf{S}_1^{1/2}\mathbf{V}_1^{\mathrm{T}} \tag{7}$$

The significant components of orthogonal vectors in the state sequence can be extracted by applying SVD to $\boldsymbol{O}_i$, and the system matrices are obtainable from $\mathbf{X}_i$. The number of poles corresponds to the number of singular values determined in Eq. (6). In other words, we can extract the significant modal components of the bridge from the measured acceleration data by the SVD.

2.2 Bayesian Approach during Flood Condition

The identified frequencies and mode shapes of the bridge pier utilizing train-induced vibrations before flood can be collected, and the probability distribution of the collected frequencies are exploited as reference information. Therefore, it is possible to detect changes in stability of the bridge pier due to scour by comparing distributions of the identified frequencies before and after flood. However, a preliminary investigation on the target bridge, which is discussed in section 4, demonstrated that the identified frequencies by the SSI from a low amplitude ambient vibration (microtremor) during the suspend operation under the flood had too large variations to be used in scour monitoring. To cope with this technical problem, the Bayesian operational modal analysis (BAYOMA) (Au *et al.* 2013) as a Bayesian approach is adopted to identify natural frequencies of the bridge pier from microtremor during a flood.

The Bayesian approach offers a powerful perspective for system identification that explicitly addresses uncertainty. It treats the modal identification as an inference problem where probability is used as a measure for the relative possibility of outcomes under a given model of the system and measured data. Another strong perspective of the BAYOMA is that it provides probability distribution of modal forces and power spectrum density (PSD) of prediction error. The coefficient of covariance (COV) and S/N ratio are adopted as indicator of uncertainty of identified values. Identified frequencies with low variance are selected utilizing the most probable value (MPV) which maximizes the posterior distribution in the Bayesian approach and the COV of the posterior distribution since the smaller the COV is, the smaller the uncertainty of the identified result is. The S/N ratio is the ratio of PSD of modal acceleration responses and PSD of prediction error, and a high S/N ratio can be interpreted as a high quality data comprising precise modal information of the bridge pier.

3 FIELD EXPERIMENT

The target bridge is commenced in 1890, and is located about 7 km far from the sea. It is a two-lane steel-girder railway bridge, and mass of the girder is around 30 t. Two lanes are connected at its superstructure, but two RC piers support each lane independently. The target bridge pier with a ship shape is located at the upstream, and train passes from the west to the east (see Figure.1).

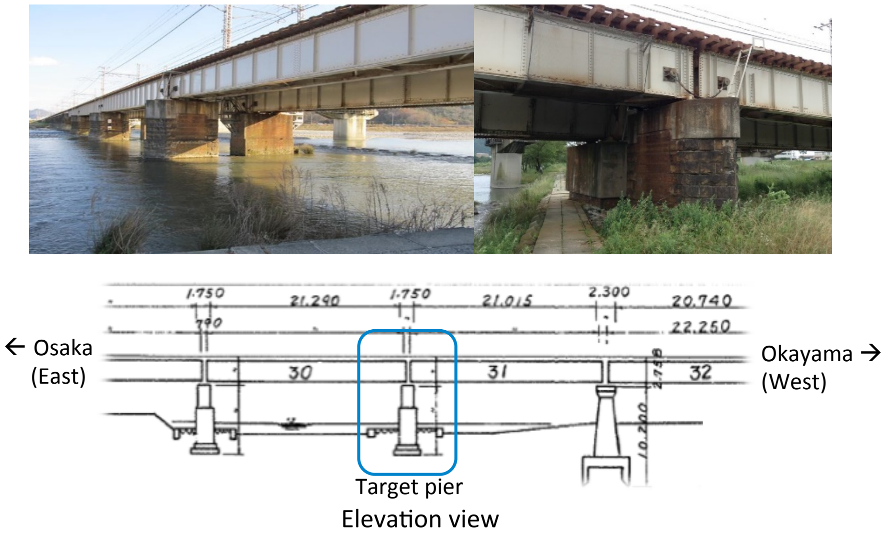

Figure 1. Photo and elevation view of the observation bridge and pier.

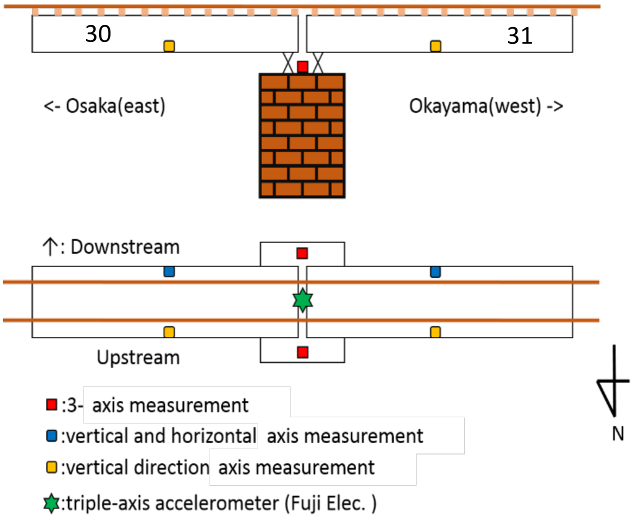

Figure 2. Sensor deployment map.

Vibration modes of the bridge pier include rocking and sway modes of the pier and some modes from adjacent girders. Therefore this study first estimates vibration modes of the bridge pier and adjacent girders by a network of cable accelerometers, and decides the target pier mode to be monitored for scour detection. It is noteworthy that the impact hammer test was conducted in 2011, and the rocking mode of the pier was identified as 15.93 Hz. Scour has not been occurred since then. For practical applications, it is necessary to install sensors as few as possible to reduce monitoring cost. Therefore, one wireless sensor node, with an integrated tri-axial MEMS accelerometer (CPUKSNSS-00, Fuji Electric), was installed on the top of the bridge pier for the long-term and real-time scour monitoring. The wireless sensor enables us to control the sensor node remotely during floods. Sampling frequency was 200 Hz. The sensor deployment map is shown in Figure 2. A laser water level meter was also installed in the bridge.

On September 20 in 2016, typhoon no.16 was approached, and the water level was measured from 7:30 a.m. on September 20 to 16:00 a.m. on September 21. Figure 3a) shows the time history of the water level in which the water level denotes the distance between bottom flange of girder and the water surface, i.e. the higher the water level goes up, the smaller the measured value is. The water level starts to increase around 10:30 a.m. on September 20, and the peak water level of 1.8 m reached at 17:10 on September 20. The railway company has its own train operation criteria following water level, which are "Warning" at the water level of 2.5 m, "Reduce Speed" at the water level of 2.0 m and "Suspend Operation" at the water level of 1.5 m. The peak water level for the bridge was 1.8 m that is between "Reduce Speed" and "Suspend Operation" levels. For information, time-history of wind speed (m/s) from 0:00 a.m. to 12:00 p.m. on September 20 is shown in Figure 3b) even though the observation point of wind was place about 2 km distance from the target bridge.

4 SCOUR MONITORING

4.1 Fundamental vibration modes

This study first identified vibration characteristics from the train-induced vibrations measured for three days before flood utilizing the cabled sensors by means of the SSI. To extract stable structural modes form the stabilization diagram obtained in the SSI, this study determined a pre-selected frequency deviation tolerance as 0.25 Hz, 0.1 % as a pre-selected damping deviation tolerance, and 0.95 as a pre-selected lower bound of modal assurance criteria (MAC). It should be noted that the cable sensors were less sensitive to measure microtremor, and utilized only for measuring train-induced vibrations.

Figure 4 shows vibration modes relevant to the transverse mode of girders (4.8 Hz) and rocking motion of the pier (15.4 Hz) from the train-induced vibration. The identify dominant frequency of bridge pier utilizing the train induced vibration showed a smaller value than that of the impact test result, 15.9 Hz. However considering additional mass by the passing train as well as bridge-train interaction it can be concluded that the frequency 15.4 Hz is relevant to the pier's rocking mode.

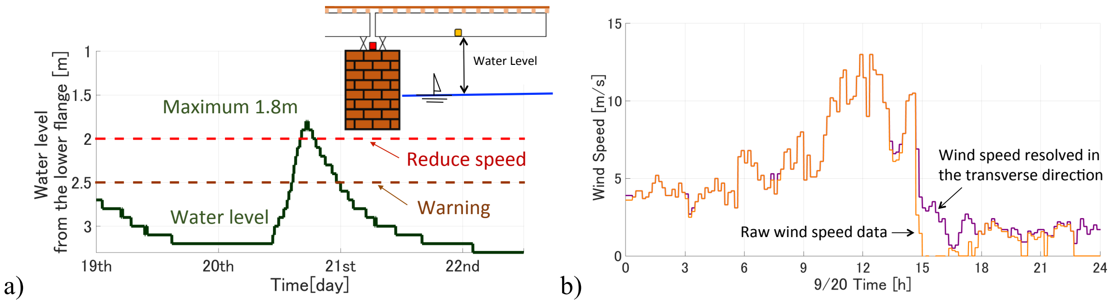

Figure 3. Water level and wind speed during typhoon no.16.

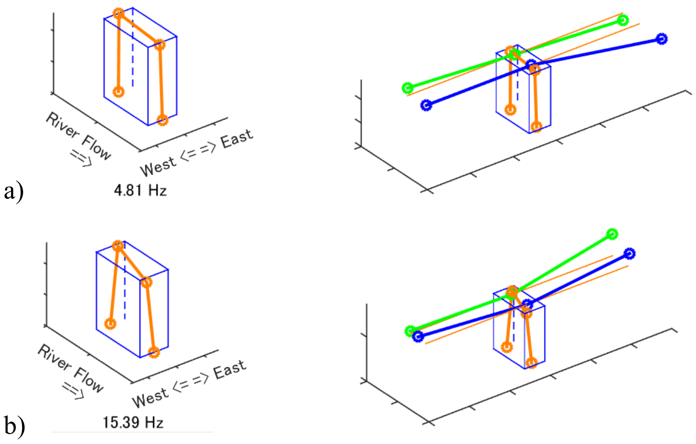

Figure 4. Identified mode shapes and dominant frequencies from the train-induced vibrations: a) near 5Hz for the transverse mode of girders, and b) near 15.9 Hz for rocking motion from the impact test.

4.2 Identified frequencies from microtremor

The microtremor during the flood on September 20 was examined, and the identified frequencies from 14 Hz to 17 Hz were plotted in Figure 5 with PSD of the modal force, S/N ratio, wind speed and water level. The data length used in identification by means of the BAYOMA was 1 minute. Horizontal axis shows a time scale in hour. The plots in Figure 5a) showed the mean identified frequencies and standard deviation of identification. The coefficient of variation (COV) was estimated from the mean and standard deviation values to filter out outliers. In this study COV of 0.05 and S/N ratio of 2.5 were adopted as thresholds to remove outliers in the identified frequency. About 90 % of identified results were passed these filters. Those filtered results are plotted in Figure 6. During 0:00 to 9:00 a.m., when the wind speed and water level are low, identified frequencies and modal forces have scattered, and even the S/N ratio was low. On the other hand, during the period of strong wind from 9:00 a.m. to 15:00 p.m., modal forces and the S/N ratio are large, and identified frequencies showed less variation. In the period of the flood from 15:00 to 24:00, identified frequencies were converged to 15.7 Hz.

Distributions of the frequency identified from microtremor during normal, strong wind, and flood conditions are summarized in Figure 7 in which mean values of the frequency under normal, strong wind and flood conditions were 15.9 Hz, 15.2 Hz and 15.7 Hz. There exists small difference between normal and flood condition. However interesting observation was influence of the wind speed although the mechanism is not examined yet: in comparing strong wind and flood conditions the mean frequency in the period of strong wind was 3.12% smaller than in flood period. Figure 8 shows the relationship between wind speed and amplitude of Fourier spectrum, which demonstrated the amplitude of Fourier spectrum drastically increased at wind speed of 6 m/s.

It should be noted that there is no change in frequency during the flood, and it can be concluded that rare possibility of scour during high water level.

Finally Figure 9 shows distribution of identified frequencies before and after flood utilizing train-induced vibrations. It can be seen negligible changes in mean value and variance. Therefore it also indicates rare possibility of scour due to the flood.

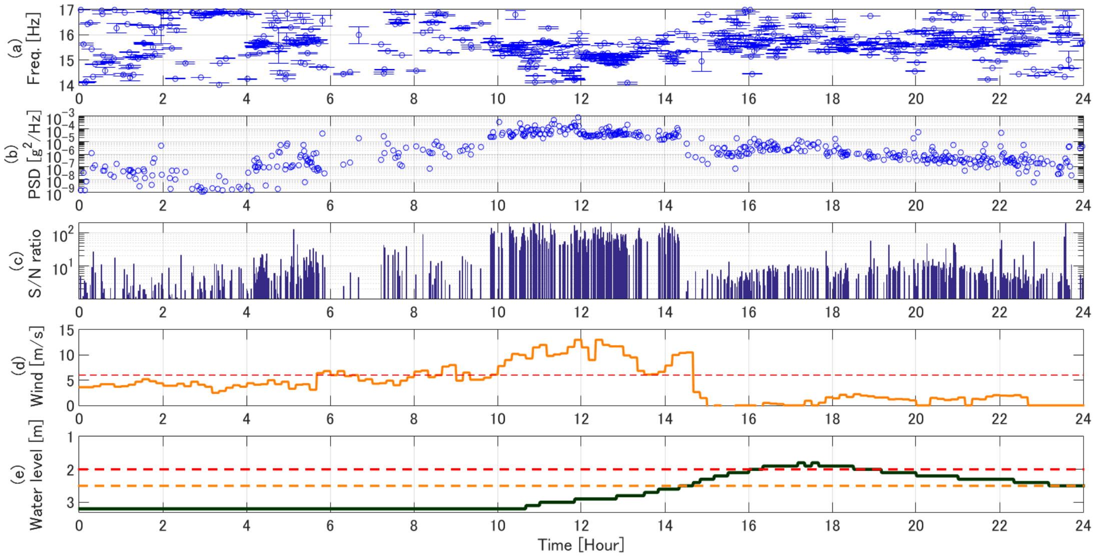

Figure 5. Bayesian approach: a) Identified frequencies; b) PSD of modal forces; c) S/N ratio; d) wind speed; and e) water level.

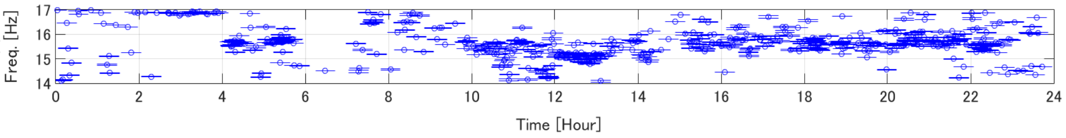

Figure 6. Bayesian approach (filtered identified frequencies).

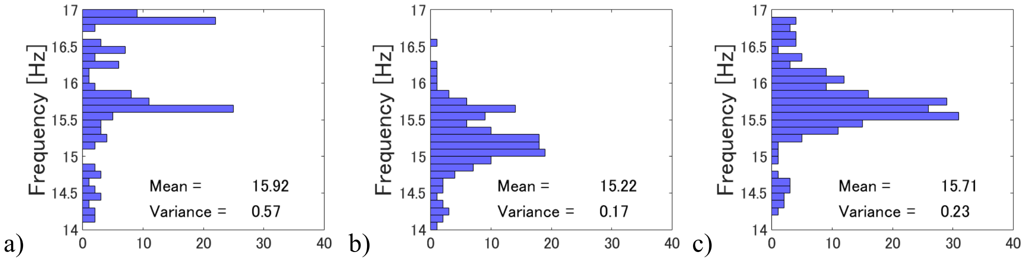

Figure 7. Identified frequency distribution: a) normal condition; b) strong wind condition; c) flood condition.

5 CONCLUSIONS

This study investigates a real-time scour assessment by means of vibration monitoring. The Bayesian approach and stochastic subspace identification are adopted for system identification. The water level and wind speed were also considered in the monitoring. Observations from this study are summarized as follows:

The natural frequency of the bridge pier during a flood was identified in real-time, and there exists only a small difference between normal and flood condition. However comparing strong wind and flood conditions the mean frequency in the period of strong wind was smaller than that in flood period.

There was no change in frequency during the flood, and it can be concluded that rare possibility of scour during high water level. Similar conclusion of rare possibility of scour was derived from identified distribution before and after flood utilizing train induced vibrations.

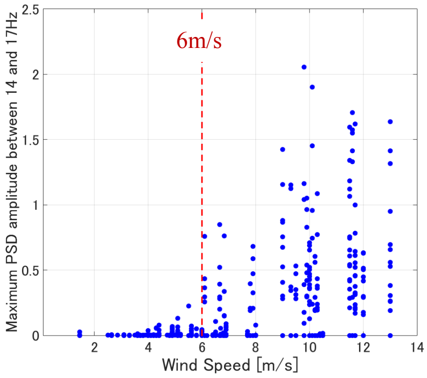

Figure 8. Relationship between wind speed and maximum amplitude of Fourier spectrum.

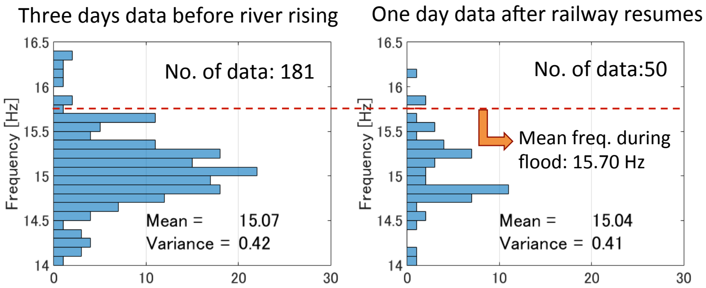

Figure 9. Distribution of natural frequency for one day after flood.

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