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Vibration monitoring of railway bridge pier and probability of scour occurrence

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Abstract. This study aims to propose a way to estimate probability of scour occurrence of a railway bridge pier by means of ambient vibration monitoring. A remote real-time scour monitoring scheme utilizing ambient vibrations of piers is considered as an alternative method for conventional impact test. A stochastic approach to deal with uncertainty of estimated frequencies caused by relatively poor signal to noise of the ambient vibration is discussed. The probability distribution of the identified frequencies in a normal condition is modeled with a stable distribution, and the probability of scour occurrence is estimated using a logistic curve. The validity of proposed method is verified using monitoring vibration data during swollen river water period in the past.

Introduction

Scour that undermines bridge foundations during flooding caused by increasing chances of heavy rainfall due to climate change is one of the major threats of bridges crossing rivers. Japanese railway companies conduct impact tests in which a weight is dropped and hit the target pier to excite the pier, and its natural frequency is identified for the purpose of assessing occurrence of scour. Although it gives bridge owners quantitative information for its structural stability, it is time and labor consuming method. Furthermore, it is inapplicable during the swollen river water (SRW) period because of difficulties to approach the pier for the safety reason.

This study thus investigates a real-time vibration monitoring for scour detection during SRW period as an alternative method for the conventional impact test. Tri-axial accelerometers with power supply equipment were installed on top of a railway bridge pier, and the monitored vibration data is transmitted to a cloud computing system via Wi-Fi [1]. This study also proposes a way of estimating the probability of scour occurrence from ambient vibration monitoring. Since train operation would be suspended when the water level is high, it is more convenient to utilize ambient vibrations for scour assessment during SRW period than to utilize train-induced vibrations. It is noteworthy that the amplitude of ambient vibrations of the bridge pier is usually weak and easily affected by noise, which indicates the necessity of considering uncertainties in ambient vibration-based scour assessment. Therefore, stochastic system identification and statistical approach are necessary to consider the scour assessment by means of ambient vibration.

To estimate mean and standard deviation of the natural frequency of the target pier, a Fast Bayesian FFT [2] is adopted in the real-time monitoring. The identified mean frequencies in a normal condition are accumulated, and the probability density function (PDF) of the stable distribution is estimated by means of maximum likelihood estimation (MLE) because the stable distribution was well fitted to the identified mean frequencies. In order to estimate the probability of scour occurrence, the logistic curve is modelled based on the PDF and the Japanese guideline [3].

Fig. 1 Monitoring railway bridge pier.

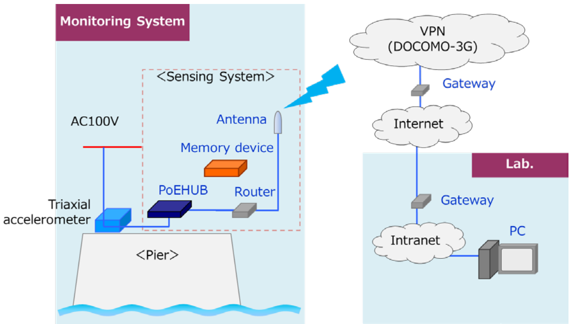

Fig. 2 Remote monitoring system.

Target Bridge Pier and Monitoring System

The target bridge is a steel plate girder railway bridge with a single railway track, and the span length of the bridge is 22.5m. The monitoring pier is one of its piers with the height of 9m and width of 3m as shown in Fig.1. The sampling frequency of the sensors is 200Hz. For a real-time scour assessment, the remote monitoring system shown in Fig. 2 was deployed at the bridge. A long-term vibration monitoring was started in September 2017. Fig.3 shows the sensor deploying map for the impact test and ling-term monitoring.

Reference Natural Frequency of the Target Pier

Modal properties of the target pier such as frequency, damping ratio and mode vector were first identified from the vibration data during the impact test. During the impact test, 13 sensors were installed on the pier and connected girders to distinguish the pier-oriented mode with the girder modes. Stochastic subspace identification (SSI) [4] was utilized to identify modal parameters for the impact test, and the stabilization diagram (SD) [5] was used to decide steady vibration modes.

Fig. 4 shows the SD, where the horizontal axis indicates the frequency and the vertical axis shows the model order. The black dots indicate the modal frequencies associated with each model order, and the red circles on it indicate the steadily estimated modes which are satisfied with the predefined deviation tolerance of the modal properties. The frequency deviation tolerance was 0.25 Hz, that for the damping ratio was 0.1%, and the lower bound of modal assurance criteria (MAC) was 0.95. Those tolerances were decided by a trial and error since there are no specific rule for deciding the tolerance. The vertical blue dashed line in Fig. 4 refers to the dominant mode that satisfies the tolerance. Dominant frequency was 9.2 Hz from the impact test as shown in Fig. 4. It is relevant to the transversal rocking mode of the monitoring pier as shown in Fig. 5. The frequency for the rocking mode is called target frequency in this study.

For the scour assessment during in-service, it needs vibration data from both normal river water (NRW) period and SRW period. This study focuses on microtremor (ambient vibration) of the bridge pier as the source of the reference frequency samples. Fig. 6 shows examples of those microtremors at the NRW period and during SRW period. Microtremor measurement whose amplitude was less than 0.1 gal was observed during the NRW period (see Fig. 6a)) which is assumed as a healthy state, while during SRW period it was around 1 gal (see Fig. 6b)) caused by rising water and increasing speed of river's flow.

For the discussion in the latter chapter, PDF of identified frequencies at NRW period is investigated. A histogram of identified frequencies is shown in Fig. 7 with the PDF curve of the stable distribution depicted in the blue solid line. It is noted that the previous research [6] figured out that tails in the stable distribution match better than those in the normal distribution. The parameters of PDF of the stable distribution during NRW period were estimated by means of MLE and the values of the equation (1) were obtained.

$$X \sim S_N(\alpha_N = 1.58, \beta_N = 0.71, \gamma_N = 0.21, \delta_N = 9.21) \tag{1}$$

where $\alpha_N, \beta_N, \gamma_N, \delta_N$ represent characteristic exponent, skewness parameter, scale parameter and location parameter, respectively. It should be noted that the mean value f_N of the stable distribution is given by the equation (2).

$$f_N = \delta_N - \beta_N \gamma_N \tan\left(\frac{\pi \alpha_N}{2}\right) = 9.32 \tag{2}$$

The cumulative probability density function (CDF) of the stable distribution is also shown in Fig. 8 (blue line) with observed CDF (empirical CDF) curve. It is obvious that the CDF curve of the stable distribution matches well with that of observed CDF (orange line) especially at tail of the CDF.

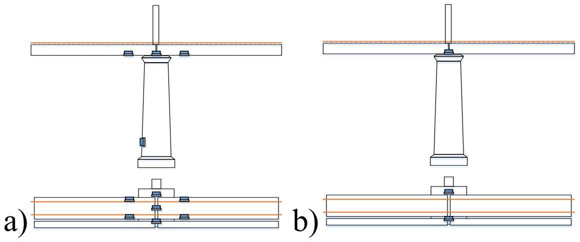

Fig. 3 Sensor deploying location:
a) for the impact test, and
b) for the long-term vibration monitoring.

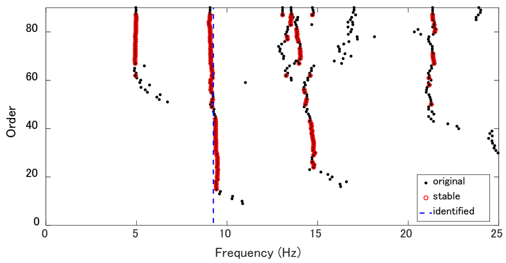

Fig. 4 Stabilization Diagram.

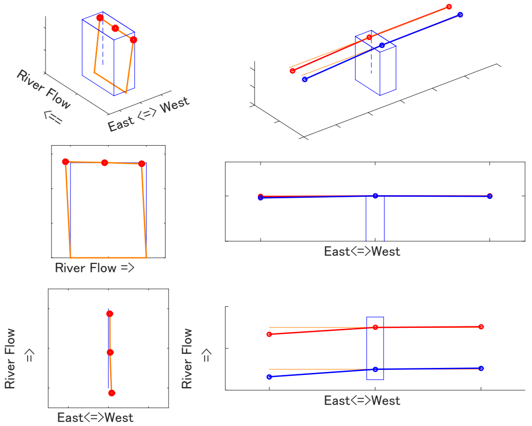

Fig. 5 Identified mode shapes (9.2Hz).

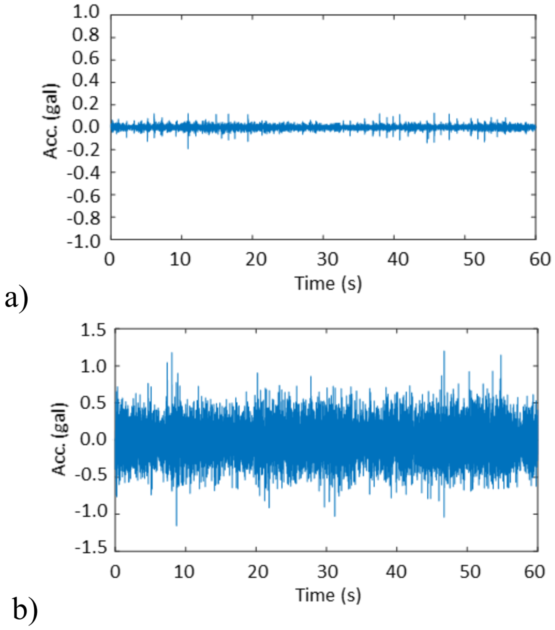

Fig. 6 Measured microtremors:
a) normal river water period, and
b) swollen river water period.

Table 1. Scour Index [3].

Scour Index	Category	Assessment
$\kappa \leq 0.70$	A1	Scour: repair or reinforcement are needed
$0.70 < \kappa \leq 0.85$	A2	Need to check the progress of scour
$0.85 < \kappa \leq 1.00$	B	Low probability of scour
$1.00 < \kappa$	S	Healthy

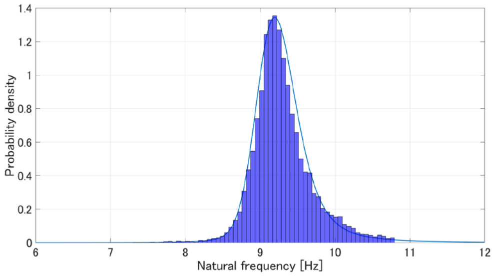

Fig. 7 Histogram of observed frequency of the pier in normal condition (bars) and PDF of the stable distribution (blue line).

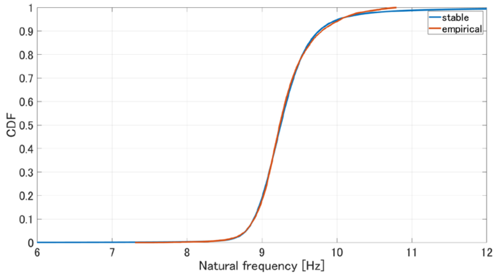

Fig. 8 CDF of the observed frequency in normal condition (orange line), and CDF of the stable distribution (blue line).

Scour Assessment using Scour Index

The scour index that shown in Table 1 is used to detect scour during SRW period. The scour index κ is calculated by the equation (3) [3].

$$\kappa = \frac{f_s}{f_h} \tag{3}$$

where, f_s is observed frequency during SRW period, and f_h is the target frequency during NRW period under healthy condition. From Table 1, it can be seen that repair or reinforcement are needed when the observed frequency is less than 70% of the target frequency under healthy condition. Therefore, 70% of the target frequency of healthy condition, f_{a1}, is used as the threshold for scour occurrence in this study to make discussions simple. Using the value of equation (2), f_{a1} is equal to 6.57Hz.

Probability of Scour Occurrence

During SRW period, the probability of scour occurrence given the identified frequency f_s, $\mathrm{P}(\theta_S)$, can be treated as a binary classification. Therefore, the probability of non-scour occurrence given the identified frequency f_s, $\mathrm{P}(\theta_N)$, can be calculated by the following equation (4).

$$\mathrm{P}(\theta_N) = 1 - \mathrm{P}(\theta_S) \tag{4}$$

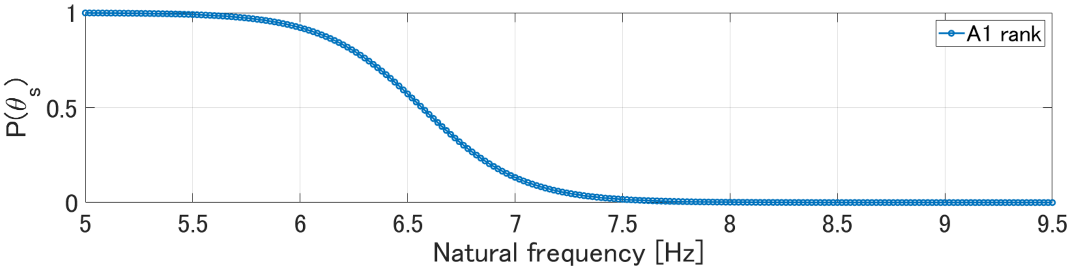

Fig. 9. The logistic curve to estimate the probability of scour occurrence.

The $\mathrm{P}(\theta_S)$ could be close to zero if f_s were over f_h, while $\mathrm{P}(\theta_S)$ would be close to 1 if f_s is close to less than f_{a1}. Therefore, the logistic regression formulated by the equation (5) is adopted to model the probability of scour occurrence.

$$q = \frac{1}{1+e^{-z}} \tag{5}$$

where z is the linear predictor of the identified frequency X at the NRW condition as random variables. Here, z can be expressed as equation (6) based on the logistic distribution.

$$\mathrm{z} = \beta_0 + \beta_1 X \tag{6}$$

where β_0 and β_1 are unknown parameters which can be estimated by means of MLE in this study.

The parameters of PDF of stable distribution during swollen water period, S_S is shown in the equation (7).

$$X \sim S_S(\alpha_S, \beta_S, \gamma_S, \delta_S) \tag{7}$$

Assuming that δ_S corresponding to the identified frequency would decrease while other parameters would not be changed, the CDF of S_S, $\Psi(S_S, x)$ can be written as equation (8)

$$\Psi(S_S, x) = \Psi(\alpha_N, \beta_N, \gamma_N, \delta_S, x) \tag{8}$$

Based on equation (2), $\mathrm{P}(\theta_S|f_s)$ can be expressed as,

$$\mathrm{P}(\theta_S|f_s) = \Psi(S_S, f_{a1}) = \Psi\left(\alpha_N, \beta_N, \gamma_N, f_S + \beta_N \gamma_N \tan\left(\frac{\pi\alpha_N}{2}\right), f_{a1}\right) \tag{9}$$

Finally, the unknown parameters of the logistic curve can be estimated by means of the MLE and the result is shown in the equation (10) and plotted in the Fig. 9.

$$\mathrm{P}(\theta_S|f_s) = \frac{1}{1+e^{-(27.61-4.19 f_S)}} \tag{10}$$

Natural Frequencies and Probabilities of Scour Occurrence during SRW Period

On July 3 in 2019, heavy rainfall was observed at the target bridge region. The water level per five minutes from 12:00 September 30 to 12:00 October 1 is shown in Fig. 10a). It should be noted that "water level" represents the distance between water surface and lower flange of the bridge girder: i.e. as the water surface goes up, the "water level" gets smaller. Monitored ambient vibrations were investigated to identify dominant frequency of the target pier during the SRW period by means of the fast Bayesian FFT [2]. Plots of the identified frequency per every minute are shown in Fig. 10b). In the fast Bayesian FFT, the dominant frequency between 7.2Hz and 10.8Hz was identified since the target frequency relevant to the rocking mode was around 9.3Hz.

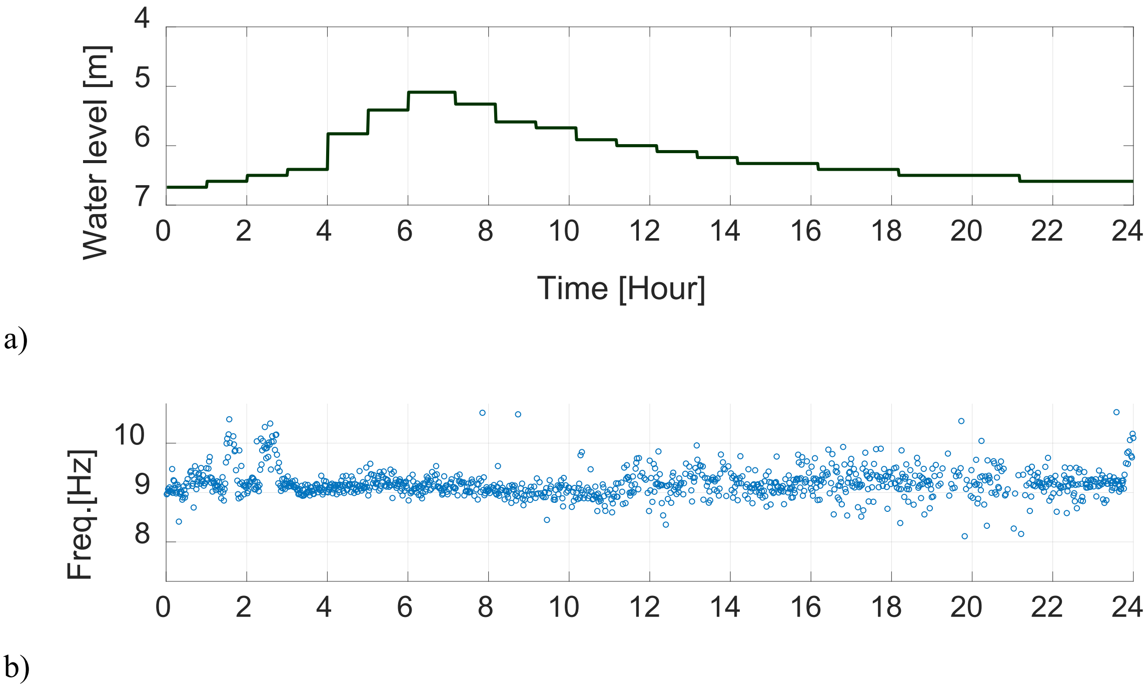

Fig. 10 Observed identified frequencies and water level from 0:00 July 3 to 24:00 July 3: a) water level per an hour, and b) identified frequencies

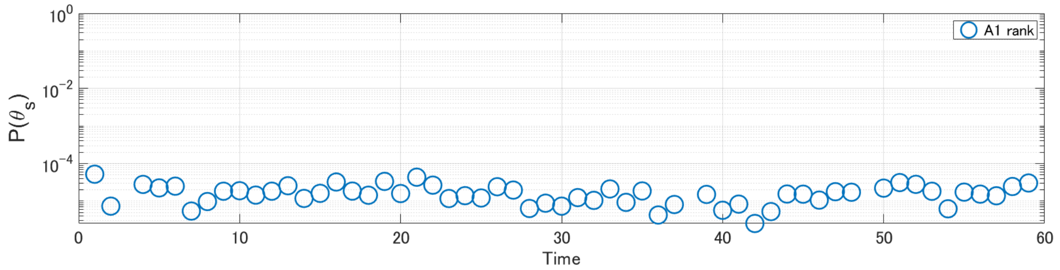

Fig. 11 Time series of the proposed probability of scour occurrence.

Variation in identified frequencies was quite small during the SRW period, while it was scattered during the NRW period. On reason for scattering might be weak signals with low signal to noise of the microtremor during the NRW period as shown in Fig. 6a).

The probability of scour occurrence is estimated using the ambient vibration data monitored from 6:00 to 7:00 on July 3th when the water level is the highest. The identified frequency at every minute is substituted to the equation (10) and time-series of the proposed probability of scour occurrence during the SRW period is summarized in Fig. 11 in which the vertical axis indicates the probability of scour occurrence and the horizontal axis does the monitoring time. It can be seen that the probabilities are less than 10^{-4} that means the possibility of scour occurrence is quite low.

Conclusion

This study investigates a way of estimating the probability of scour occurrence by means of ambient vibration monitoring of the bridge pier during SRW period. The natural frequency of the bridge pier was identified with a stochastic system identification method. A way of estimating probability of scour occurrence is proposed using the estimated target frequency of the target pier. Since the probability of scour occurrence can be treated as a binary classification, this study introduces a logistic regression to model the probability of scour occurring. Based on the Japanese guideline, threshold of the identified frequency that scour occur is set, and parameters of the logistic curve is estimated by means of the MLE. The proposed method is applied to the microtremor data during SRW period, and demonstrated that the probability of scour occurrence is quite low.

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