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A HEALTH MONITORING SYSTEM FOR RAILWAY BRIDGE PIERS

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Abstract

A vibration based health monitoring method applicable for unmanned and continuous monitoring for railway bridge piers is developed. The vehicle load is utilized as the exciter and soundness of the bridge pier is evaluated through analysis of train-induced vibration measured by accelerometer, which is set on the top of the pier. As indicator for evaluation of soundness, the gradient of linear regression line between vertical and transverse acceleration response is proposed. In order to investigate the applicability of this indicator for evaluation, relationship between foundation condition and RMS response is studied based on three degree of freedom analytical model. Then, model experiment is conducted using sound and damaged bridge pier models. In addition, field monitoring of railway bridges is carried out for various speeds of vehicle, sediment condition and configuration of foundation. The result indicates that the proposed indicator is related to sediment loss at the foundation and the method has the potential for health monitoring of railway bridge piers.

INTRODUCTION

East Japan Railway Company (JR East) maintains 7,527km track in the eastern part of Japan (Fig.1). In this area, there are approximately 2,500 bridges over water, and about 1/3 of these bridges should be considered a risk of scour hazard. In order to avoid fatal train accidents due to scour hazard, not only constructing protective facilities around the bridge pier foundations, but also train suspension rule is enforced during higher risk of scour hazard.

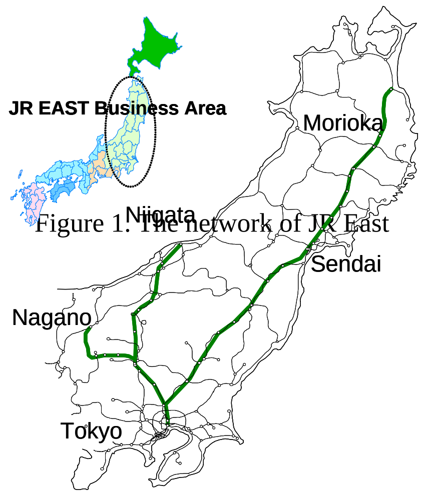


Figure 1: Clinometric type scour
monitoring devices are on these bridge piers

CLINOMETRIC TYPE SCOUR MONITORING DEVICE

The rule for train suspension currently in force is based on observation of inclination of a bridge pier caused by scour around a bridge pier. A clinometric type scour monitoring device is placed on the top of bridge piers, and monitors the inclination angle in real time (Fig.2). The threshold angle for the train suspension is derived from geometric relationship between the inclination angle of the bridge pier and the maintenance limits of track irregularity. When a inclination angle of a bridge pier exceeds the threshold angle, this device gives alarm to suspend train operation.

Figure 2.: Clinometric type scour
monitoring device

PROBLEMS IN THE CLINOMETRIC TYPE SCOUR MONITORING DEVICE

The clinometric type scour monitoring device cannot issue an alarm before a bridge pier is inclined. Even if inclination angle of a bridge pier is minute, reconstruction of the bridge pier tends to be a long time and high cost construction work accompanying suspension of train operation. In 1995, the bridge pier inclined and track distorted due to scour of the bridge foundation (Fig.3). In this case, train operation was suspended for 4 days until emergency reconstruction was finished, and it took more than 1 year to reconstruct the inclined bridge pier. In order to reduce the reconstruction cost, a new device to detect a symptom of scour damage before the occurrence of inclination is needed.

Figure 3: Site-situation of scour
hazard in 1995

BASIC IDEA OF HEALTH MONITORING METHOD

In order to observe the symptom of scour damage, evaluation using a natural frequency of the bridge pier is popular in Japan[2)], because the natural frequency generally decreases as scour develops. The technique for this evaluation is mainly carried out with percussion of heavy weight, such as steel ball weighting 30kg. Due to this heavy physical work, it is difficult to exercise this inspection frequently.

In order to reduce heavy physical work and realize frequent monitoring to detect symptom of scour damage of a bridge pier foundation, health monitoring system using train-induced vibration analysis is developed. In this system, the vibration is measured by an accelerometer set on the top of the bridge pier. The ratio of Root Mean Square (RMS) value of horizontal to vertical acceleration response is employed as the indicator for evaluation of soundness of a bridge pier foundation.

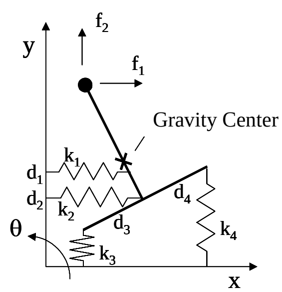


Figure 4: Three degree of
freedom model of bridge pier

In order to evaluate the sensitivity of RMS value of acceleration response, a three degree freedom analytical bridge pier model, which is shown in Fig.4, is applied. Development of scour is represented by unbalance of soil stiffness between right and left side of a bridge pier. In this analysis, k_3+k_4 are supposed to be constant to eliminate the effect of a shift of natural frequencies. The degree of unbalance b is defined by,

$$k_3 = k_3^0(1-b), k_4 = k_4^0(1+b). \qquad (1)$$

Substituting specific data of an actual railway bridge pier into this model, the relationship between the RMS value of horizontal and vertical acceleration response and the degree of unbalance is investigated (Fig.5). In this simulation, white noise which variance is $1kN^2$ is applied as external force by train live load. When the degree of unbalance is increased, the RMS value of vertical acceleration response becomes smaller and the RMS value of horizontal acceleration response becomes greater. Consequently, the ratio of RMS value of horizontal to vertical acceleration response is increased according to increase of the degree of unbalance. From this result, the ratio of RMS value of horizontal to vertical acceleration response is applicable to the evaluation.

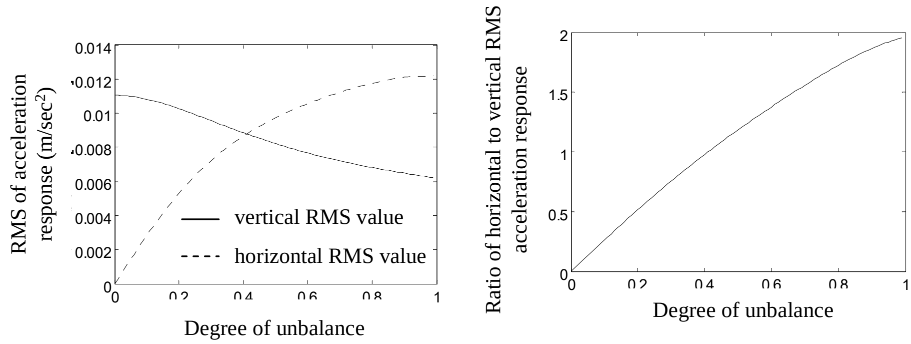


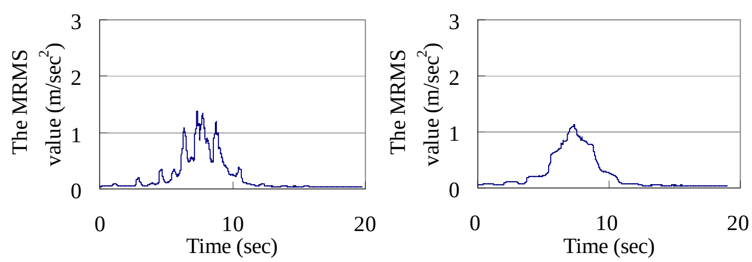
Figure 5. The relationship between the RMS value of horizontal and vertical acceleration response and the degree of unbalance

THE EXPERIMENTAL HEALTH MONITORING SYSTEM

The experimental health monitoring system is composed of 2 piezoelectric accelerometers, a signal conditioner, AD-board and a personal computer. These accelerometers are set on the top of the bridge pier. One of them measures transverse acceleration response of bridge pier and another measures the vertical acceleration response. Lowpass filter with cut-off frequency of 200Hz is applied to the observed vibration.

The magnitude of acceleration response is strongly affected by a transient component of acceleration response, such as impact caused by passing train over jointed trucks, although it does not have strong relation to soundness of a bridge pier. In this monitoring system, "moving root mean square (MRMS)" is applied to eliminate this effect. Note that the average of obtained time-series is corrected for zero before calculation of RMS; therefore this RMS value is equal to the standard deviation.

The "MRMS" has similar characteristics of a lowpass filter. By longer interval for averaging, lower frequency component is highlighted. The effects of averaging interval on the value of MRMS are shown in Fig.6. From this figure, when averaging interval is set as longer than 1 second, transient effect is eliminated and lower frequency component, such as vibration induced by train live load, is emphasized. Thus, the averaging interval is set as 1 second.



(a) Averaging interval: 0.25s (b) Averaging interval: 1.0s

Figure 6. MRMS values calculated in change of averaging interval

EXPERIMENT WITH SMALL SCALE MODEL

The experiment was carried out with 1/87-scaled train model (Fig.7). The bridge model consists of plastic bridge girders, wooden bridge piers and foundation ground made from silicon rubber. The accelerometers are set on the top of each bridge pier model. Using these accelerometers, vibration of transverse and vertical acceleration response of each bridge pier is measured. Except that one of the bridge foundation (P1) has imitated the scoured foundation by removing half of the silicon rubber covering on the foundation, the other specification of both models are the same.

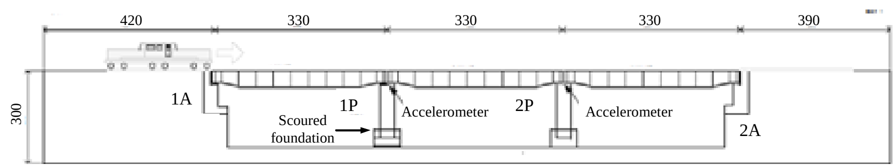


Figure 7. Model used in the experiment

The maximum MRMS value of acceleration response induced by a running vehicle model is observed in change of vehicle model speed, which is set at 0.29, 0.45 and 0.60 km/h. The relation between vehicle speed and the MRMS value of vertical and transverse acceleration response are shown in Fig8. From this figure, it is confirmed that both vertical and transverse MRMS value become greater by higher vehicle speed.

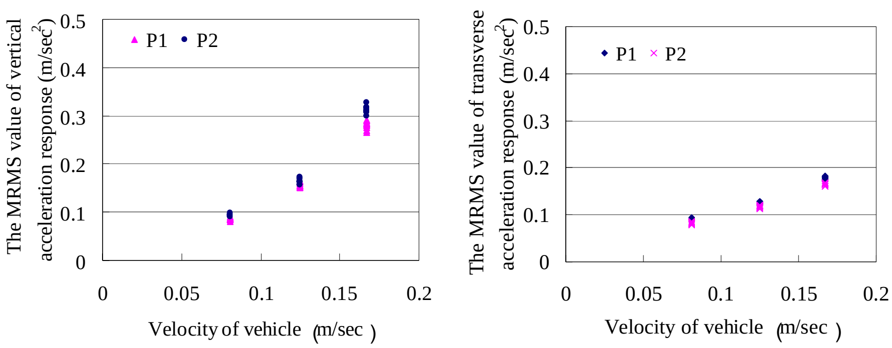


Figure 8. Relationship between vehicle speed and the maximum MRMS value of vertical and transverse acceleration response

Measurement of vehicle speed by unmanned health monitoring system is practically impossible. In order to eliminate the effect of vehicle speed against the MRMS value, the correlation between the maximum transverse and vertical MRMS value is paid attention. The correlation between these MRMS values which are observed in change of vehicle model speed is shown in Fig.9. From this figure, it is found that there is the strong linear correlation between these maximum MRMS values and the y-intercept of regression line is not zero. The ratio of the transverse to vertical RMS value, which is discussed in chapter 4, vary in change of vehicle speed, because y-intercept of regression line is not zero. On the other hand, the gradient of linear regression line is constant in change of vehicle model speed and it is equal to the ratio of the RMS value when the y-intercept of regression line is zero. From this reason, the gradient of linear regression line is applied as the indicator for evaluation of soundness of bridge piers.

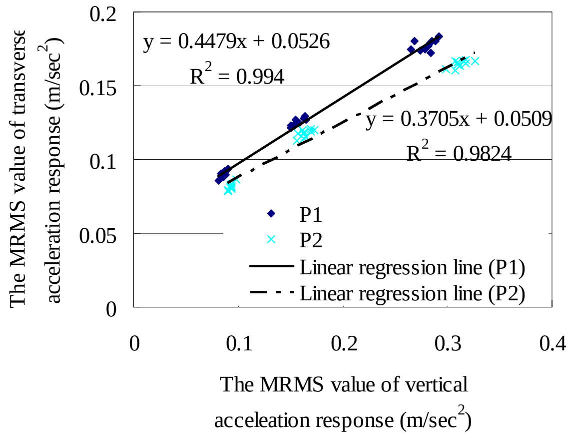


Figure 9. Correlation between the maximum MRMS values of transverse and vertical accelerations

Next, the effect of scoured foundation against the MRMS value is analyzed. The comparison between the maximum MRMS values measured at scoured and sound foundation is shown in figure 9. P1 is the pier that imitated the scoured foundation and P2 is sound foundation. The vertical MRMS value measured on P1 is 4 to 8% smaller than the MRMS value measured on P2. On the other hand, the transverse MRMS value measured on P1 is 7 to 10% greater than the MRMS value measured on P2. Consequently, the gradient of linear regression line of P1 becomes greater than P2. These results are coincided with the result obtained by theoretical analysis referred in Chapter 4. Therefore, feasibility of the gradient of linear regression line as the indicator for the health monitoring is confirmed.

OBSERVATIONS ON ACTUAL BRIDGE PIERS

The acceleration response of actual bridge piers excited by train live load is observed on the top of several bridge piers. The characteristics of these bridge piers are shown in Table 1.
The relation between the vertical and transverse MRMS values observed on 1P and 2P of bridge B are shown in figure 10. In both cases, the strong linear correlation is

Table 1. The characteristics of the bridge piers where monitoring is carried out

	Height	Material	Foundation	Penetration depth	Natural frequency
Bridge A	Single-track bridge, Steel plate girder, Span 19.2-22.8m				
4P	11.5m	Concrete	Spread footing	4.2m	4.9Hz
5P	11.5m	Concrete	Spread footing	6.2m	5.1Hz
Bridge B	Single-track bridge, Steel plate girder, Span 12.9m				
1P	6.1m	Concrete	Spread footing	1.5m	2.4Hz
2P	6.0m	Concrete	Spread footing	Foot protection	2.2Hz

observed in common with the correlation obtained by experiment with a reduced model. Although the value of the gradient has not yet been quantitatively evaluated, it can be seen that this indicator can be used for qualitative assessment of a structural condition.

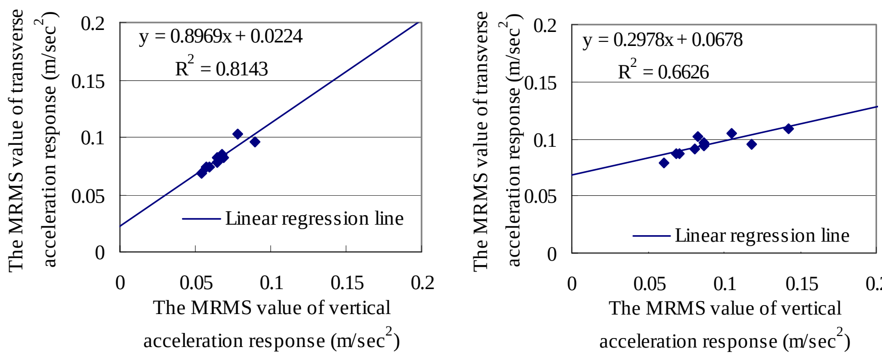


Figure 10. Relationship between the MRMS of vertical and transverse acceleration ssresponse

ALARM SYSTEM USING THIS METHOD

The health monitoring method is expected to be used for an alarm system to indicate immediate detailed inspection of the bridge pier. When scour develops around the bridge pier, the gradient of a linear regression line is changed, and the MRMS value is away from the original linear regression line. The threshold value to issue the alarm is determined based on distance from the linear regression line. The distribution of error around the linear regression line is obtained from the accumulated MRMS data. Therefore, threshold value of the MRMS is determined as the upper and lower bound of the confidence intervals corresponding to each MRMS value of vertical acceleration response. Figure 11 shows the linear regression line and the upper and lower bound of the two sided 95% confidence interval.

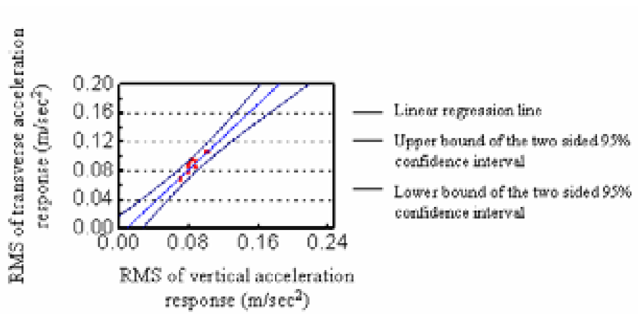


Figure 11. the linear regression line and upper and lower bound of the two sided 95% confidence interval.

CONCLUSIONS

The development of the health monitoring device is discussed in this article. In this article, it is confirmed that the gradient of linear regression line is related to sediment loss at the foundation and the proposed method is capable for health monitoring of railway bridge piers. At present, it is considered that this health monitoring device is installed to a practical clinometric scour monitoring device.

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