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Scour Evaluation of Bridge Foundations Using Vibration Measurement

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ABSTRACT

The exposure of bridge foundations due to scouring has been recognized as the most critical cause for highway bridge failures in Taiwan, yet difficulties have been found to identify its risk level. In an effort to develop an efficient measure for the detection and estimation of the scour of bridge foundations, a series of field vibration measurements were conducted on selected highway bridges of which the foundations had been suffered different levels of scouring. In this paper, theoretical background of utilizing vibration measurement to estimate the exposure of bridge foundation is introduced. The setup of vibration measurement on bridges and schemes of data processing are described. Results of the mentioned field tests on bridges are presented, and the feasibility of using vibration measurement to evaluate the scour of bridge foundations is thus verified. The findings of this study are helpful in developing the inspection and monitoring technology for bridge scouring.

INTRODUCTION

Several major highway bridge failures occurred in Taiwan in recent years, leading to considerable casualties and property losses. Most of them were due to the exposure of the pier foundation due to scouring, which reduced the bearing capacity of foundation. These disasters can be prevented if the damage or the insufficient capacity of the foundation can be detected in advance, and the repair and retrofit works, or the restraint of use is timely executed. However, the exposure of pier foundation can not be directly observed visually if the water table is above the foundation level. Although it is possible to inspect the exposure in a contact manner by using instruments directly installed on the foundation, the flow-induced loading and the impact of the flow carryovers may destroy the instruments. Consequently, it is necessary to develop reliable non-destructive and indirectly scour evaluation techniques for bridge foundations.

The structural vibration response of a soil-structure system shows the characteristics of the system itself, and reflects the boundary conditions as well. Therefore, the vibration measurement has been extensively applied to the system identification and the damage detection of structures. Similarly, the measurement of structural vibration can be used to evaluate the foundation exposure due to scouring. It is easy to perform and ensures the durability of sensors since they are not installed on the foundation. Moreover, the vibration analysis methods are well-developed, and many criteria for damage evaluation were proposed and have been widely used.

In this study, the influence of foundation exposure on the vibration characteristics of the bridge superstructures was firstly investigated. The setup of field vibration measurements on bridges and the schemes of data processing were accordingly proposed. Field measurements on two highway bridges in Taiwan of which the foundations had been suffered scouring were then presented to actually examine how the foundation exposure affects the vibration behavior of bridge. Thus, the vibration measurement on the bridge can be applied to the scour evaluation of bridge foundations. It meets the requirements of regular inspection and long-term monitoring, and is therefore helpful to bridge management and disaster mitigation.

DAMAGE EVLUATION USING VIBRATION MEASUREMENT

Vibration characteristics for damage evaluation

The vibration characteristics of a structure system, *e.g.* the natural frequency, the modal shape, and the damping ratio, are related to the stiffness and the integrity of the system. When the structure is damaged, its natural frequency will be lowered because of the decrease of overall stiffness; the modal shape will be changed because of the stiffness redistribution due to the defects; and, the damping will be increased because of the development of the cracks. Hence, if the changes in the vibration characteristics of the structure can be identified experimentally, the structural damage can be thus detected (Doebling *et al.*, 1996). In the vibration measurement tests, the obtained vibration time history is often transformed into the frequency domain by spectrum analysis (*e.g.* fast Fourier transformation) to show its frequency content, and accordingly the structure can be characterized.

For the detection of the structural damage, instinctively the variation of the natural frequency is used. However, some random errors might be produced in the measurement due to the electrical noise, the environmental effects, and the variations in test conditions. Although the uncertainty level of the natural frequency is usually less than on other structural vibration characteristics (Farrar *et al.*, 2000), its variation is sometimes not sensitive enough to reveal the damage level, especially for the local component damage in a complex structure. Therefore, the precision of measurement must be high enough and the damage must be not too slight so that the damage can be detected merely by the variation of the structural natural frequency.

The natural frequency and the modal shape can be adopted simultaneously for a better estimation of structural damages (*e.g.* Kim *et al.*, 2003). Nakamura (1997) used both the natural frequency and the amplification amplitude of a system estimated from microtremors and proposed the vulnerability indices for the ground, the embankment, the viaduct, and the derailment/overturn of trains.

As for the applications of vibration measurement to scour evaluation of bridges, Samizo *et al.* (2007) utilized the decline of the natural frequency of the bridge pier identified from microtremors and impact tests to evaluate the exposure of the foundation due to scouring. In their study, a data dividing and averaging analysis scheme was introduced to eliminate the dispersion of the predominant frequencies identified from long-term microtremor measurement.

Vibration measurement tests

Vibration measurement tests usually adopted for system identification include:

1. Ambient Vibration Measurement: The ambient vibration is randomly generated by man-made or natural disturbances in the environment and has a wide frequency content, and is therefore useful for the identification of structural dynamic properties. By measuring the input ambient vibration and the excited response of the structure simultaneously, the transfer function can be deduced for the identification of structural dynamic properties. For example, Ivanovic *et al.* (2000) extracted the natural frequency and the corresponding modal shape of a severely damaged RC building from the transfer function obtained from the ambient vibration data. For the case that the input motion is unavailable, it is still possible to characterize the structure merely by its excited response based on the assumption that the ambient vibration can be regarded as a white noise, that is, a random process with a constant power spectral density, *e.g.* Samizo *et al.* (2007).
2. Forced Vibration Test: The artificial vibration sources such as moving vehicles, the harmonic vibrator, and the hammer impact are utilized to cause the structure to vibrate. It helps to recognize the vibration characteristics of the structure for a specific vibration source or under a larger strain level. Ko and Chen (2009) derived the natural frequency and the corresponding modal shape of a full-scale school building specimen from the results of the forced vibration test using the harmonic vibrator. Samizo *et al.* (2007) conducted the impact test on the bridge for the natural frequency of the bridge pier. Chen *et al.* (2009) characterized the attenuation of ground vibration using the field measurement of the high-speed train induced vibrations and the falling weight test.

VIBRATION MEASUREMENT FOR SCOUR EVLUATION OF BRIDGE

Influence of scour on structural vibration of bridge

For a pier-soil system, when the ground level is lowered by scouring, the free length of the column is increased, leading to the decline of its lateral stiffness. If the scour is getting more severe and the foundation is exposed, the foundation stiffness is degraded so that the total stiffness of the system is further reduced. The stiffness reduction can be reflected by the variation of the structural vibration characteristics.

In order to investigate the influence of foundation exposure due to scouring on the vibration characteristics of the bridge superstructures, a FE model of a typical single-span simple supported bridge unit was established using SAP 2000 software, as shown in the top of Figure 1. It was composed of two piers with caisson foundation and a deck with girders. The structure configurations are based on the Wulin Bridge in Taiwan. The column, cap beam, and girder were modeled by beam element, the deck was modeled by shell element, and the caisson was regarded as a rigid body with the mass of infillings added. The support condition between the cap beam and the girder was regarded as a hinge since the small-strain vibration was considered here. The mass of the deck of the neighboring span is considered yet the confinement is ignored. The supporting soil is modeled by spring elements, and the foundation exposure is simulated by removing the soil springs.

Firstly, the modal analysis was performed, as shown in the bottom of Figure 1. The 1st mode is the local bending of the deck, with a corresponding fundamental frequency of 3.15 Hz; the 2nd mode is the coupled translation-rocking responses of the two piers in the horizontal longitudinal (HL) direction, with a fundamental frequency of 3.24 Hz; and, the 3rd mode is the coupled translation-rocking responses in the horizontal transverse (HT) direction accompanied by some local twist of the deck, with a fundamental frequency of 4.40 Hz. Since the local mode of the deck is hardly influenced by the foundation exposure, the focus will be on the HL and HT vibrations of the pier top hereafter.

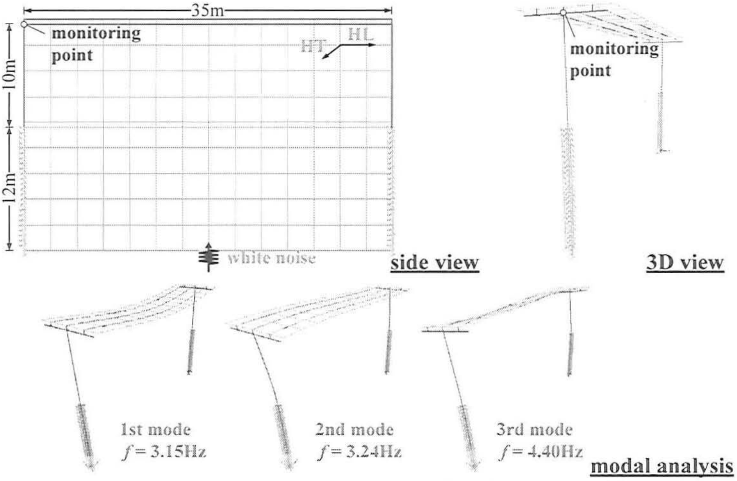


Figure 1. FE model and modal analysis of a simple-supported bridge unit.

Then, the dynamic time history analyses were conducted by using white noise as the input motion at the foundation. Three foundation exposure conditions were adopted, including no exposure, 2.5m exposure, and 5m exposure. The Fourier spectra of the excited HL and HT responses at the top of pier in each case are shown in Figure 2. The predominant frequencies for the HL and HT vibrations in the no-exposure case are confirming to the fundamental frequencies of the 1st and 2nd modes just mentioned, and are lowered as the exposure gets more severe. It is noticed that the decline of the predominant frequency for the HT vibration is more obvious, and the increase of the peak amplitude with respect to the exposure level is also observed.

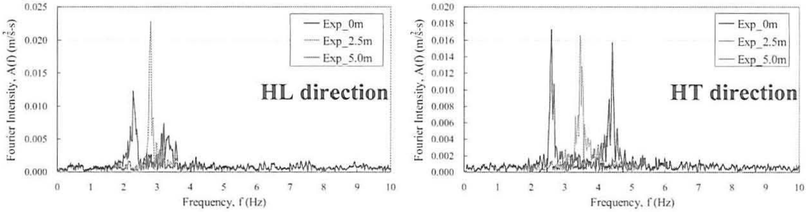


Figure 2. Fourier spectra of excited responses of the bridge unit model.

Setup and data processing of vibration measurement on the bridge

1. Vibration sources

(a) <u>Vehicle induced vibrations</u>: Dynamic loads from the moving vehicles is directly applied on the deck and is the main vibration source of the bridge. Nevertheless, when the weight of the vehicle is too small or the speed is too low, it might merely induce the local vibration of the deck instead of the vibration the entire pier-soil system. In this case, the vibration response can characterize only the superstructure of the bridge or the vehicle mechanical properties rather than the pier-soil system, and in this case the foundation exposure can not be reflected.

(b) <u>Ambient vibrations</u>: If the ambient vibration is input from the ground into the bridge foundation and propagates up to the superstructure, it can be used to characterize the pier-soil system. However, the amplitude is usually small and is easy to be concealed by the vehicle induced vibration unless no vehicle passing.

2. Test configurations

In the vibration measurement, the velocity sensors were used. Sensors were deployed on the cap beam of the tested pier or on the deck right above the tested pier, as shown in Figure 3, where the vibration responses showed the characteristics of the pier-soil system. The vibrations in the HL direction and in the HT direction were continuously recorded for 10~20 minute at off-peak traffic flow condition with a sampling rate of 200 Hz.

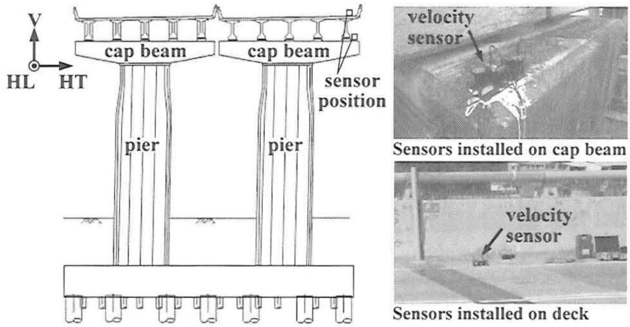


Figure 3. Sensor positions in vibration measurement on the bridge.

3. Data processing scheme

When a long-term field vibration measurement is performed, the vibration characteristics at different moments show some dispersion since the environment and the vibration source are not constant. In order to eliminate the dispersion, Samizo *et al.* (2007) used a concept that sections with a fixed duration are extracted from the overall record, and each section is partially overlapped with the next. The Fourier spectrum is calculated in each section, and the structural natural frequency is identified accordingly. Finally, all these natural frequencies are averaged to obtain a representative one. Based on this idea, an averaged Fourier spectrum is deduced in this study, as shown in Figure 4. Thus, the structural characteristics can be better described, while the time-dependent variance can still be reduced.

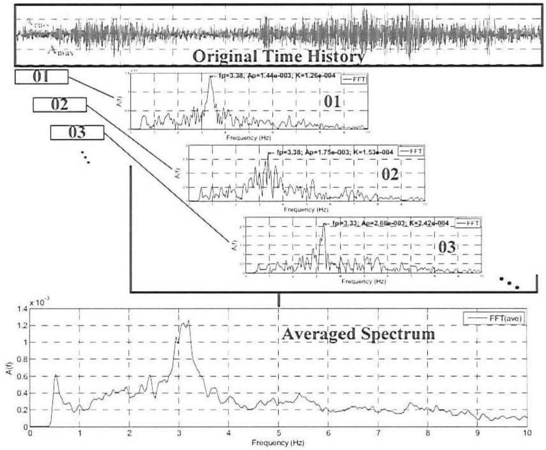


Figure 4. Processing scheme of averaged spectrum analysis.

FIELD VIBRATION MEASUREMENTS OF BRIDGES

Case study I- Wensui Bridge

The Wensui Bridge of Provincial Highway No. 3 in Taiwan had suffered the exposure of the caisson foundations of the piers located on the riverbed due to scouring, and the reconstruction using the pile group to replace the caisson was started in late 2008 and has been finished in late 2009. During the reconstruction, the riverbed level beside the pier P3 was lowered for the work space below the deck, causing the caisson to be exposed around 6~7m, as shown in Figure 5. In order to investigate the difference of the vibration characteristics of the bridge superstructures at different levels of foundation exposure, the field vibration measurements were made simultaneously at the pier P3, of which the foundation was severely exposed, and at the neighboring pier P2, of which the foundation was slightly exposed and had been reinforced by gabions. In this case, the sensors were deployed on the deck right above P2 and P3 respectively since there was no access to the cap beam.

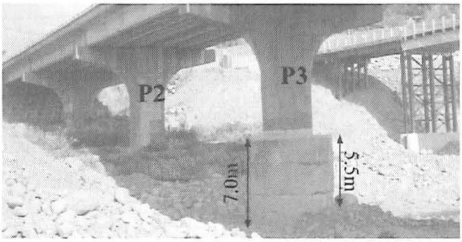


Figure 5. Foundation exposure of Wensui Bridge at the field measurement.

The previous mentioned average spectrum analysis scheme is adopted here to reduce the time-dependent variability of the field measurement. Figure 6 shows the averaged Fourier spectrum of the vibrations at P2 and P3. For the HL direction, the spectral curves of P2 and P3 are similar, with a main peak at the frequency of about 3.5 Hz. It might be the constraint in the HL direction provided by the deck and girders to make the characteristics of the HL vibration of the two piers close to each other. Hence, the vibration in HL direction can not reflect the foundation exposure very well in this case. As for the HT direction, the averaged Fourier spectrum of P2 has two peaks, located at 1.7 Hz and 2.1 Hz, respectively; while only a major peak at 1.7 Hz shows for P3, with a larger amplitude than the peak at 1.7 Hz for P2.

For a better interpretation of the peaks in these averaged Fourier spectra of HT vibrations, the FE model of the unit P2-P3 of the Wensui Bridge was generated for the modal analysis. The model is similar to that one in the previous section, yet the degree of freedom in the HL direction is restrained for simplification. The modal shapes obtained are given in Figure 7. The 1st mode shows the in-phase coupled translation-rocking responses in the HT direction of P2 and P3 with a fundamental frequency of 1.72 Hz, in which the modal displacement of P3 is larger than that of P2. The 2nd mode represents the out-of-phase coupled translation-rocking responses in the HT direction of P2 and P3 with a fundamental frequency of 2.09 Hz, in which the modal displacement of P2 is larger. Consequently, the peak at 2.1 Hz in the averaged Fourier spectrum of the HT vibration of P2 characterizes the structural behavior of P2, while the peaks at 1.7 Hz in both the spectra of the HT vibration of P2 and P3 characterize P3. Since the severe foundation exposure of P3 reduced its lateral stiffness, the lower predominant frequency and the larger amplitude of the vibration of P3 exhibited, which even influenced the vibration response of P2.

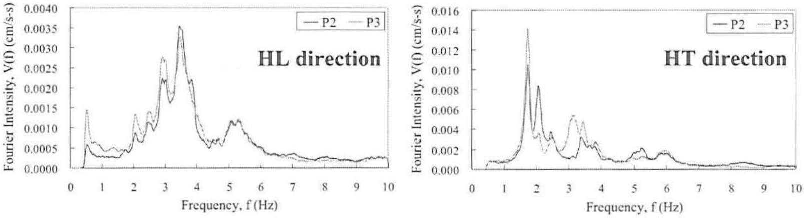


Figure 6. Averaged Fourier spectra of vibration at P2 and P3 of Wensui Bridge.

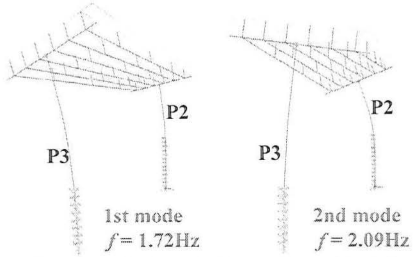


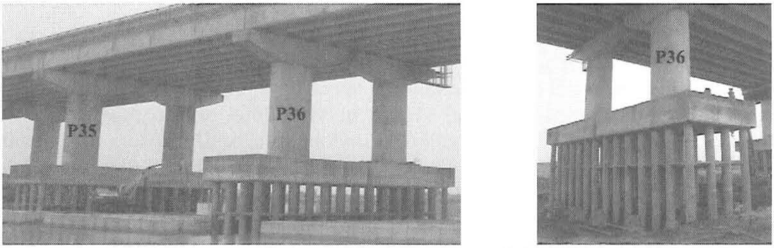
Figure 7. Results of modal analysis of Wensui Bridge unit model.

Case study II- Hsichou Bridge

The Hsichou Bridge of Provincial Highway No. 1 in Taiwan also had suffered the scour of its group-pile foundation and the piles had been severely exposed. The retrofit work of foundations by lowering the foundation level, adding piles and enlarging the pile cap was started in May 2009 and is expected to be finished in September 2010. The pier P36 was adopted for study. Before the retrofit (April 2009) the piles of P36 were about 4.5m exposed, while during the retrofit work (July 2009) the riverbed level beside the P36 was lowered for the work space, causing the piles to be exposed around 7.5m, as shown in Figure 8. Field vibration measurements were made at P36 under the two mentioned foundation exposure conditions respectively. In this case, the sensors were installed on the cap beam.

Figure 9 depicts the averaged Fourier spectra of the vibrations at P36 at 4.5m exposure and at 7.5m exposure. For the HL vibration, the predominant vibration frequency is about 3.6 Hz at 4.5m exposure and is 3.4 Hz at 7.5m exposure. The later is slight lower yet the difference is small. It might be also due to the constraint in the HL direction from the superstructure. As for the HT vibration, the averaged Fourier spectrum of the 4.5m exposure case has two peaks, located at 2.0 Hz and 3.7 Hz, respectively, and the averaged Fourier spectrum of the 7.5m exposure case also has two peaks located at 1.5 Hz and 3.5 Hz. Assuming that the peaks around 1.5~2 Hz and around 3~4 Hz are corresponding to two different vibration modes, then the former one reflects the foundation exposure better. The corresponding predominant frequency at 7.5m exposure is 20% lower than at 4.5m exposure. It should be noted that though the amplitude of the averaged Fourier spectrum is larger for the 7.5m exposure case in both direction, it is not appropriate to attribute this to the foundation exposure since the test conditions (especially the vibration source) were not the same.

Similar to the previous case study, the FE model of the unit P35-P36 of the Hsichou Bridge was established to perform the modal analysis for a better interpretation. The model is similar to the previous models except the pile was modeled by beam element. The modal shapes of the model with an exposure of 4.5m are given in Figure 10. The 1st mode is the in-phase coupled translation-rocking responses in the HT direction of P35 and P36 with a fundamental frequency of 1.97 Hz, close to the first predominant frequency from the field vibration measurement in the 4.5m exposure case. The 2nd mode is the out-of-phase coupled translation-rocking responses in the HT direction of P35 and P36 with a fundamental frequency of 2.29 Hz. The 3rd and 4th modes are the local bending and twist of the deck, with the fundamental frequencies of 3.49 Hz and 3.83 Hz. For the case of 7.5m exposure, the modal shapes of the first four modes are similar. The fundamental frequencies for the 1st and 2nd modes are 1.54 Hz and 1.74 Hz, which dropped significantly, while those of the 3rd and 4th modes are 3.42 Hz and 3.60 Hz, only slightly lowered. Thus, it can be concluded that the predominant frequencies of the HT vibration around 1.5~2 Hz from the field measurements were corresponding to the in-phase coupled translation-rocking mode in the HT direction of the two piers, and were lowered significantly when the foundation was more severely exposed. While those around 3~4Hz were related to the local mode of the superstructure and therefore were close in the two foundation exposure condition.



April 2009 (piles exposed around 4.5m) July 2009 (piles exposed around 7.5m)

Figure 8. Foundation exposure of Hsichou Bridge at the field measurement.

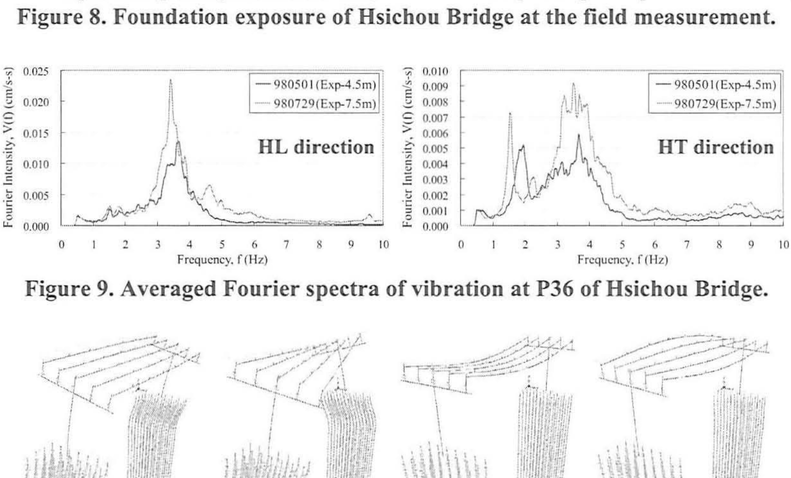


Figure 9. Averaged Fourier spectra of vibration at P36 of Hsichou Bridge.

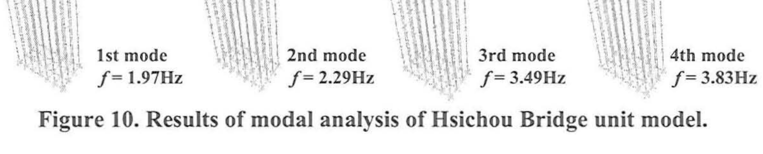


Figure 10. Results of modal analysis of Hsichou Bridge unit model.

CONCLUSION AND FUTURE APPLICATIONS

According to the results of the numerical analyses and field vibration measurements presented, several conclusions can be drawn as follows:

1. By the dynamic analysis of the bridge unit FE model, it is shown that the foundation exposure will decrease the overall stiffness of the bridge-soil system and lower the predominant frequency of the vibration of the superstructure, especially in the HT direction.
2. According to the results of field vibration measurements, the influence of the foundation exposure on the vibration behavior of the superstructure of the bridge is actually verified.
3. The vibration measurement on the superstructure of the bridge gives a reasonable assessment of the foundation exposure due to scouring. In addition, since the real bridge is a complex soil-structure system, it is recommended that a numerical model should be established for a better interpretation of the vibration response.

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