Performance Monitoring of Bridge Foundations under Multi-hazards

W. F. Lee[1], C. I. Yen[2], and C. K. Huang[3]
[1]*MICE Engineering Consulting Ltd. Co., Taipei, Taiwan*
[2]*GieFeng consultants, Taipei, Taiwan*
[3]*Sinotech Engineering Ltd. Co., Taipei, Taiwan*
E-mail: wflee0206@gmail.com

ABSTRACT: In an effort to proactively monitoring the safety of bridge foundations so as to probe the possible performance of bridge foundation during natural hazards such as floods, debris flows, rainstorms, and typhoons, an intelligent monitoring system was developed by the authors and had applied to several bridges. In this paper, theoretical background and development will be firstly described. Two case histories will then be presented to describe performance of bridge foundation during natural hazards. Such information will be also further discussed by integrating environment factors such as rainfall amount and flow velocity. Research progress presented in this paper is hoped to be helpful in understanding performance of bridge foundation during hazards so as to provide insights of pre-warning of bridge safety.

KEYWORDS: Multi-hazards, Flood, Scour, Bridge Foundation, Monitoring System, Performance Monitoring

1. INTRODUCTION

Recent climate change had induced large-scale natural hazards such as floods, debris flows, rainstorms, and typhoons, and caused destructive threats to transportation infrastructures. During 2007 to 2010 in Taiwan, there were numbers of highway bridges seriously damaged by such natural hazards resulted in causalities. The most dreadful event was Typhoon Morakot, which had caused failures of total 52 highway bridges (Figure 1). Morakot strolled through Taiwan during the period from August 7th to 9th of 2009. Enormous precipitation was brought into south-western Taiwan by Morakot. Accumulated rainfall exceeded 2500mm over a larger area in southern Taiwan; while the maximum rainfall intensity went beyond 70mm/hr and reached 100mm/hr for the most affected area down south over 24hours period. Forensic investigation on bridge failures concluded that combination of foundation scouring and over scaled flood (debris) force was the major reason causing destructive structure failure of bridges (Lee et al. 2010).

Figure 1 A highway bridge threatened by scour and debris during 2009 Typhoon Morakot (Lee et al, 2010)

At the time when those highway bridges failed, safety monitoring systems were limited to only monitor water level, flow velocity, or scour depth individually. None of the measurements could be used to straightforwardly judge structural integrity or safety of the bridge. No system was able to provide performance information of bridge foundation during such sever natural hazards. Moreover, most scour detectors adopted at that time were very vulnerable to harsh river conditions such as impacts from boulders and tree trunk debris. In an effort to proactively monitoring the safety of bridge foundations so as to probe the possible performance of bridge foundation during these hazards, an intelligent monitoring system was developed by the authors and had applied to several bridges (Lee et al., 2014, Yen et al, 2014). The developed system was designed to directly monitor vibration of bridge foundation, and to integrate measurement of flow velocity and water level in real time manner during hazard events. In this paper, theoretical background and details of such an intelligent monitoring system will be firstly described. Two case histories, Shi-Tzou bridge and XiBin bridge, will then be presented to describe performance of bridge foundation during natural hazards. Such information will be also further discussed by integrating environment factors such as water level and flow velocity. Research progress presented in this paper is hoped to be helpful in understanding performance of bridge foundation during hazards so as to provide insights of pre-warning of bridge safety.

2. PERFORMANCE MONITORING TECHNOLOGY FOR BRIDGE FOUNDATIONS

2.1 Previous Researches

Integrated technology for performance monitoring of bridge foundation were not much developed prior to this study. Most of the previous researches on bridge safety monitoring systems cannot withstand the test of typhoon flooding. They often were malfunctioned or even damaged during sever hazard events. Zarafshan et al. (2012) measured scour depth of riverbed by using Fiber Gragg Grating, FBG sensor attached to a steel rod of specific geometry. However, due to the vulnerability and limited capacity of FBG sensors, this system could be only appropriate for very shallow levels scour and mild stream flow conditions. Kong et al. (2013) also designed a monitoring system using fiber optic sensors, however, it was only tested in the laboratory. Lin et al. (2010, 2011) tried to apply several devices including floating Micro Electro Mechanical Systems, MEMS sensors, FBG sensors, and optical fiber sensors to monitor scour depth and structural performance. However, no actual performance data were ever recorded, only laboratory measurements were partially reported.

2.2 Intelligent Monitoring System for Bridge Foundation

2.2.1 Theoretical background and methodology

The vibration monitoring methodology proposed in this study was first developed and patterned by Lee (Lee, 2011, Lee, 2012a). Fundamental mechanism of the proposed method is depicted in the schematic drawing shown in Figure 2. Figure 3 demonstrates changes of boundary condition, foundation resistance, and flow induced forces on bridge foundation under flood and scour conditions. As depicted in the Figures, when a bridge foundation is scoured and exposed, the vibration frequency decreases. In the meanwhile, vibration amplitude increases with increase of stream induced flow pressure or forces. On the contrary, when debris deposition occurs as stream slowing down, the frequency increases, and the amplitude falls due to decrease of acting on forces. Both amplitude and frequency could be used as the direct indices to bearing capacity and structural stability of bridge foundation. The proposed system is capable of monitoring multi-hazards such as flood, scour and possible debris. Moreover, the proposed system was developed based on vibration theory and had utilized dynamic sensors those are capable of measuring seismic responses of structures. Its applications to seismic monitoring is also straightforward.

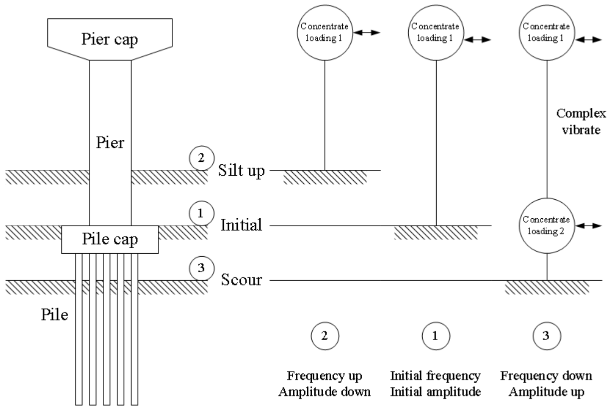


Figure 2 Mechanism of vibration monitoring methodology (after Lee, 2011)

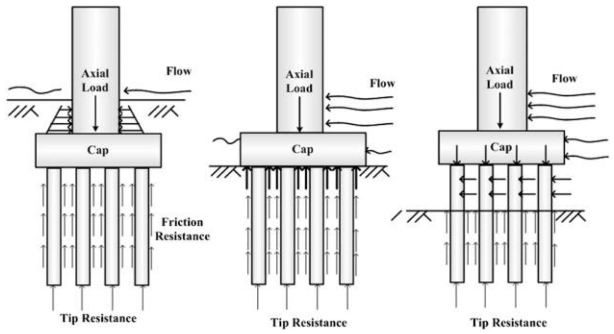


Figure 3 Schematic drawing of a bridge foundation under scour and flood (after Lee et al., 2014)

An important issue of the proposed methodology is to develop the time history of performance of bridge foundation during the hazard events. In this study, response amplitudes and frequencies of acceleration, velocity, or movement of bridge foundations are proposed as the performance indices. Time histories of amplitudes of such performance indices could be directly measured using sensors. However, it was challenging to develop time histories of response frequencies. In the developed methodology, the recorded time history data was first divided equally into specific time segments. Each segment of time history data was then converted into a frequency spectrum by applying the Fast Fourier Transform computation algorithm. Characteristic frequencies that were predicted or analyzed by means of structural modelling or vibration tests were then identified and extracted from each frequency spectrum. The selected characteristic frequencies were then assigned with time tags defined by midpoint of the defined time segments to obtain time histories of response frequencies (Lee et al., 2014, Yen et al., 2014).

2.2.2 Composition of system

Based on the mechanics concept, the proposed bridge monitoring system was designed to directly measure vibration characteristics of bridge foundations to observe the structural reactions that occur during flood or scour events. Vibration characteristics of bridge foundation are monitored using MEMS accelerometers and dynamic inclinometers. For measuring vibration of foundations of bridges, the system was designed to be installed at pier tops of bridges where vibrations of substructure could be amplified most and instrumentation could be secured away from floods and debris.

Important system design issues are to integrate different sensors, to conduct calculation onsite, and to relate measurements to environmental factors. The system was composed by three major components: the monitoring box, environmental monitoring instrumentation, and the communication component. The monitoring box includes a tri-axial accelerometer, biaxial inclinometer, a GPS, and a micro-computer module. Environmental instrumentation includes a thermometer, water level gauge and flow rate meter. With these instruments the system can immediately monitor the bridge's acceleration, inclination, temperature change, water level, and change in flow velocity. The micro-computer allows that large quantity of data could be calculated and analysed on site. It would be very helpful in saving transmitting time and power consumption. Efficiency of the designed system is improved dramatically when data could be analysed onsite. The system's communication component includes a wifi wireless transmitter, fiber optic transmitter and 3G wireless transmission (Yen et al. 2014).

The proposed system is designed for long term performance monitoring, i.e. health monitoring. Therefore, data recorded during normal time could be saved as the performance baseline. During hazard events, the monitoring results could be compared to such baseline or bench mark data to judge safety level of bridge so as to threshold of activate warning.

3. CASE STUDY I- SHI-TZOU BRIDGE DURING 2009 TYPHOON MORAKOT

3.1 Basic Information of Bridge

Shi-Tzou Bridge is one of the important highway bridges crossing the longest and largest river in Taiwan, Jou Suei River. Figure 4 illustrates the location of Shi-Tzou Bridge and Jou Suei River catchment. Shi-Tzou Bridge is a 2.7km long PC girder bridge with regular span length of 35m. The bridge had suffered serious scour problem in the past (Figure 5). Soil strata of the riverbed is mainly sand, silty sand, and clay seam interlayers. Such typical alluvium deposits in west coast Taiwan could be as deep as 60 to 80m before reach the bedrock. The SPT-N value of such riverbed deposits ranges 6-14 for top 10 to 15m, yet it increases with depth. During the monitoring period, foundation retrofit works for improving scour and seismic resistance were undertaken.

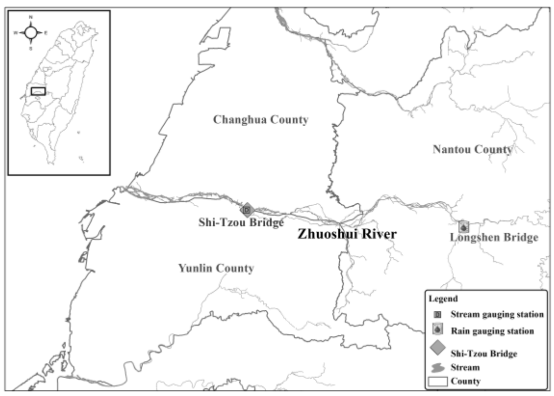


Figure 4 Location of Shi-Tzou Bridge (after Lee et al., 2014)

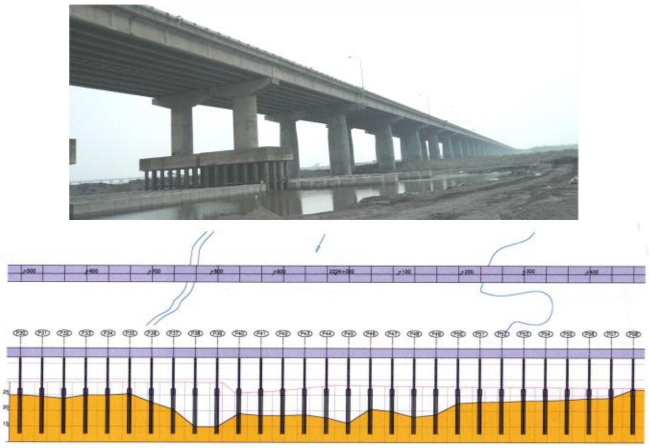


Figure 5 Shi-Tzou Bridge before 2009 Typhoone Morakot

3.2 Instrumentation Scheme

The developed system was installed onto two piers, Pier 36 and Pier 42. Pier 36 sits next to the northern bank of Jou Suei River and had suffered serious scour prior to Typhoon Morakot that hit Taiwan in 2009. Foundation of Pier 36 was group pre-cast pre-stress concrete piles with 80cm in diameter and 28m in length. Pier 42 locates in the main river channel of Jou Suei River. It had just retrofitted by “under pinning” method one year before Morakot. Additional cast-in-situ piles with 1.5m in diameter and 50m in length were installed to strengthen the foundation. The foundation cap was lowered to 10m under the existing riverbed. The pier structure was enlarged and reinforced by wrapping steel plates (Figure 6).

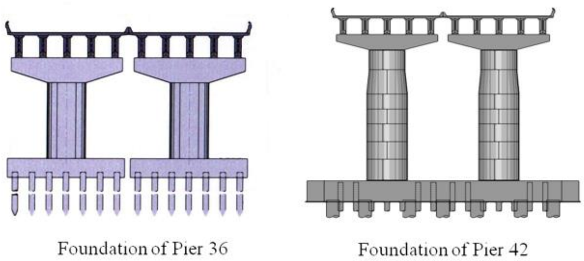


Figure 6 Different types of Piers

Both piers were installed with a monitoring box, an external temperature sensor, and power supply and a communication unit. The water level sensor was installed under the deck between Pier 42 and Pier 43, and was integrated to the monitoring box at Pier 42. Shi-Tzou Bridge experienced critical flood and scour during Typhoon Morakot. Serious flood and debris hit foundation of Pier 36 as shown in Figure 1. Figure 7 shows the turbulent flow surrounding Pier 42 indicating that possible contraction scour was underway. During Typhoon Morakot, traffic of Shi-Tzou bridge was closed on August 8th to 9th, 2019, for safety reason. In addition, the power supply was shut off from around noon of August 9th to noon of 11th resulting in system interruption and data loss. Despite of loss of data near the end of the event, valuable performance data for bridge under floods and scours was still obtained when power supply was sustained.

3.3 Performance of Bridge

Figures 8 and 9 show performance data of Pier 36 in response amplitudes and Pier 42 in response frequencies respectively. As shown in the figures, conditions before flood or scour, occurrence of scour, riverbed backfilling, flood condition, and even end of hazard events could be clearly identified from the interpreted time histories of characteristic frequencies and response intensities. As shown in the figures, vibration amplitude of Pier 36, which had already suffered from scour, increased as water level rose. Record amplitudes have reasonable good agreement to water level indicating water pressure acting on the scoured bridge foundation. Moreover, as flow volume rate increased to certain threshold values, 2,500m^3/sec and characteristic frequencies started to descend indicating initiation of scour on Pier 42, even no visual observation is available.

Figure 7 Scour occurring to Pier 42 during Typhoon Morakot

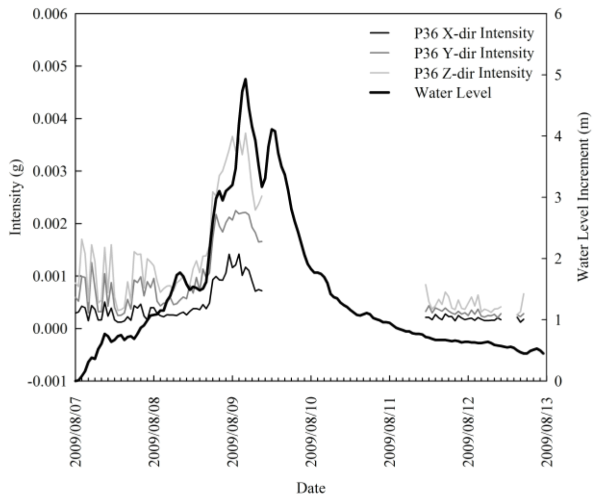


Figure 8 Monitoring result of response amplitude intensity versus wter level for Pier 36

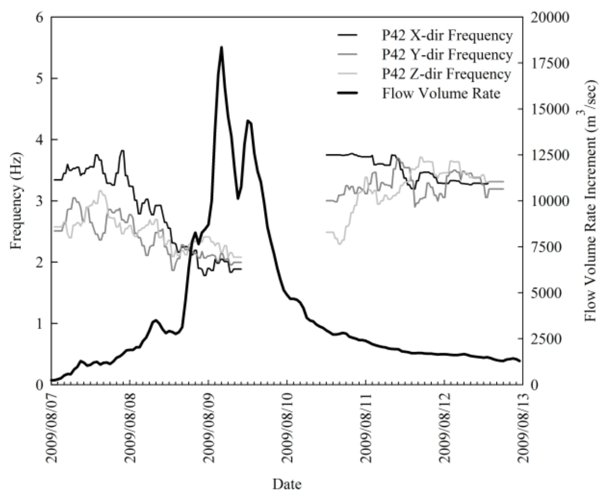


Figure 9 Monitoring result of response frequency versus flow rate for Pier 43

To further analyze the response frequencies and amplitude intensities as performance indices of bridge foundation during multi-hazards including floods, scours, and debris. Figure 10 plots measured frequencies versus amplitude intensities of Pier 42 during typhoon Morakot in flow (Y) direction. As shown in the figure, the monitored bridge foundation gradually lowered its characteristic frequencies from high levels to lower ones indicating that scour had developed. Pier 42 then experienced scour and flooding during the event with increasing intensities and decreasing frequencies. At end of the event, the pier resumed to low intensities level and high characteristic frequencies level as before the event indicating riverbed was backfilled and stabilized. Figure 11 shows result of similar performance index analysis of Pier 36 in flow (Y) direction. As shown in the figure, Pier 36 started with low frequency levels and small amplitudes indicating that the pier had already suffered scour prior to the event. It then felt to even lower frequency levels with higher amplitude intensities during typhoon. At end of the event, Pier 36 recovered to high frequency levels and low intensities because of riverbed backfilling. Analysis shown in Figures 10 and 11 gives an example of straightforward judgment to define stability of the bridge foundation using the proposed performance indices. Traffic controls could be efficiently executed based on such performance index analysis.

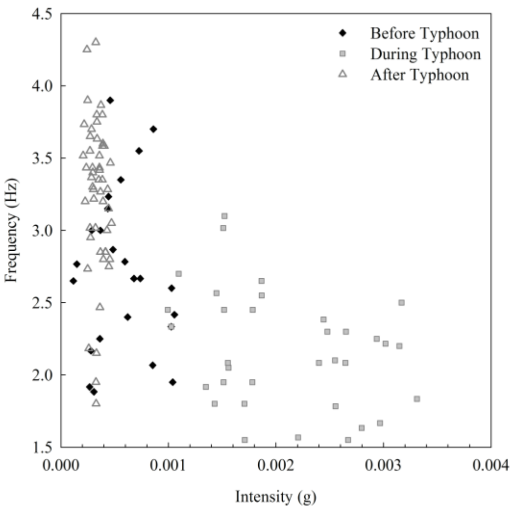


Figure 10 Measured frequencies versus amplitude intensities of Pier 42

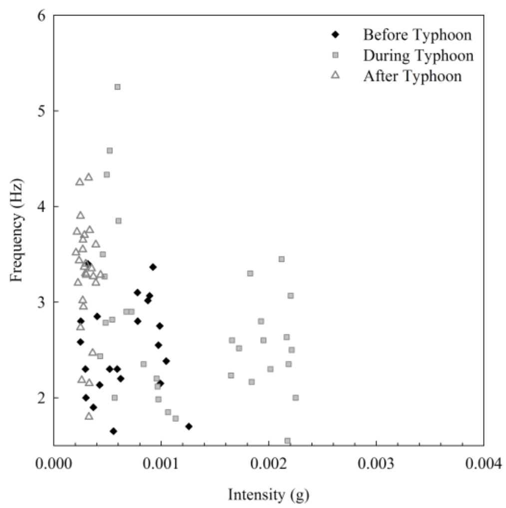
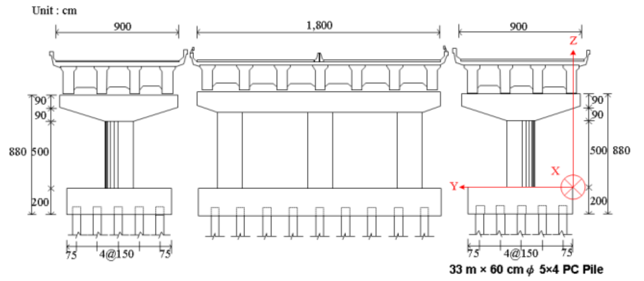


Figure 11 Measured frequencies versus amplitude intensities of Pier 36

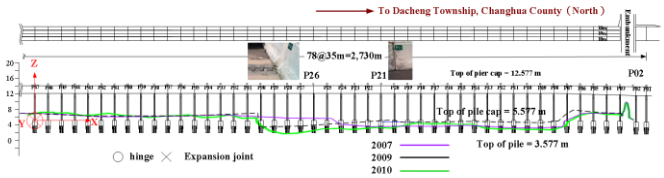
4. CASE STUDY II- XIBIN BRIDGE DURING 2012 FLOOD EVENT

4.1 Basic Information of Bridge

Xibin Bridge is located on Highway 17 crossing Jou Suei River and is the final bridge before the river enters the ocean. The bridge was constructed in 1995. It is a three-span continuous I-girder pre-stressed bridge. Total length of the bridge is 2,730 m across 78 spans (35 m/span). The foundation is composed of pile groups with a total of 20 (5 x 4) pre-stressed piles. Each pile is 33 m long with a diameter of 60 cm. The height of the pile caps is 2 m; the height of the piers is 5 m; and the height of the pier caps is 1.8 m. The total height from the bottom of the pile cap to the top of the pier cap is 8.8 m. Figure 12 shows structural details in schematic drawings and photo of Xibin Bridge.



(a) Cross section



(b) Longitudinal section

(c) Xibin Bridge

Figure 12 Structural details and photo of Xibin Bridge

4.2 Instrumentation Scheme

After successful demonstration on Shi-Tzou Bridge in 2009, the authors had designed a complete instrumentation scheme to monitor performance of the Xibin Bridge in 2011. The developed intelligent monitoring systems were improved and installed to Piers 21 and 26 of the bridge where the mainstream channel of the river located. Pier 21 is located at the middle span of three continuous spans and Pier 26 is located at the expansion joint of a three continuous.

In addition to developed intelligent systems installed on Piers 21 and 26, two scour detectors were also installed for further verification. Pier 21 is equipped with an embedded electro-magnetic scour depth monitoring system. Pier 26 is equipped with a gravity scour depth monitoring system. Water level meter and flow rate meter are installed between Piers 26 and 27. Figure 13 shows the structure of the designed monitoring system. Monitoring data of the systems is firstly collected and analysed within the monitoring boxes located on Piers 21 and 26. A local network was then set up using wifi communication and optical fiber landline for real time display at internet server. Figure 14 shows photos of contents of the monitoring box and installation of system on Xibin Bridge.

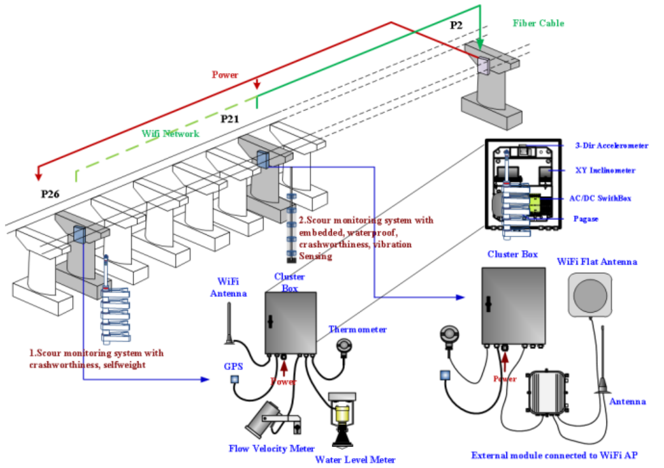


Figure 13 Instrumentation scheme of Xibin Bridge

Figure 14 Installation of the intelligent performance monitoring system on Xibin Bridge

4.3 Performance of Bridge

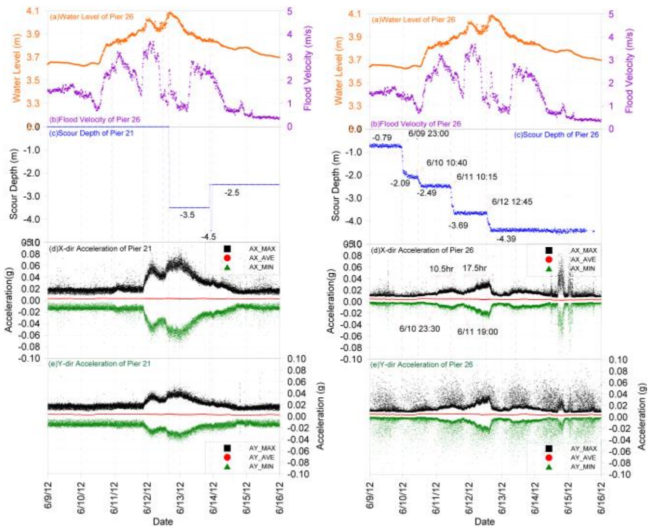
After installation of the developed intelligent performance monitoring system for bridge foundations, there was a heavy rain event during the period of June 9th to 17th 2012, as shown in Figure 15. The developed monitoring system made complete recordings of the acceleration, inclination, water level, flow velocity and scour depth changes during event. Figure 16 shows the relationship between time histories of acceleration amplitude and the water level, flow rate and scour depths recorded at piers P21 and P26. As shown in the figures, water level was increasing constantly to about 4.1m at its highest level, yet flow rate went up and down as a result of combination of river condition and precipitation distribution during the event. Amplitudes of accelerations of Piers 21 and 26 did not just agree to measurements of water level and flow rate in certain aspects, but also gave clear indications of appearances of scours, prior to measurements of scour indicators. The response amplitudes of acceleration of both Piers 21 and 26 increased as water level and flow rate increased combining appearance of scours; they decreased as water level and flow rate descended back to normal flow condition after the event, as riverbed soil also deposited back. The combination effect of bearing capacity loss of bridge foundations due to scour as well as flood pressure acting on bridge foundations could be observed by time history of response amplitude in a reasonable sense.

before the event, 2012/6/8

during the even, 2012/6/13

after the event, 2012/6/17

Figure 15 Condition of Xinbin Bridge during the reported event



Pier 21 Pier 26

Figure 16 Results of monitoring

To further study the performance of bridge foundation during scour, response frequencies of the inclinometers installed on Pier 26 were analyzed and plotted against water level, flow rate, and scour depth measured by scour indicator as shown on Figure 17. The calculated time history of response frequency is capable of describing variation of the flow rate and almost every occurrence of scours during the event. As shown in the figure, there are four occurrences of frequency reductions indicating the corresponding flow rate increases and cumulative scour depth. During scour process, riverbed soil would start to loose its overburden pressure and strength first until soil decompose gradually from top to deeper soil strata. The recorded time history of response frequency gives indications of structural performance of such changes of boundary conditions earlier than scour detector. Moreover, it is always difficult to judge stability of bridge foundations during and after such flood, typhoon, or even earthquake events by judging only water level, flow rate, or scour detector readings. As shown in the figure, time history of response frequency gives clear indications of re-deposition of riverbed soil represented by increases of response frequencies. As response frequencies regained to its original level before the flood event, bridge foundations recovered their stability and ready for re-opening traffic. The proposed method utilizing analyzed time histories of response amplitude and frequency to describe performance stability of bridge foundation during scour is proved to be feasible and more reliable than just measuring scour depth.

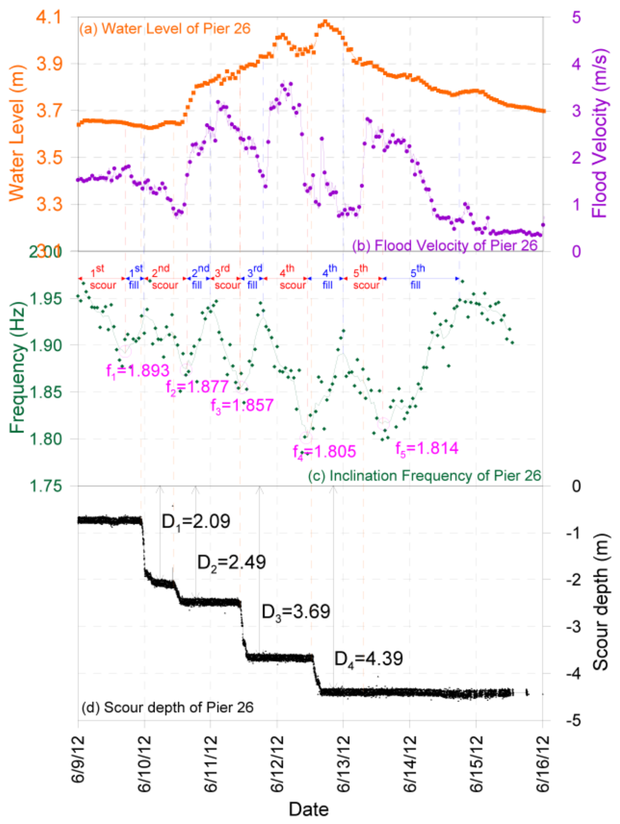


Figure 17 Analysis for scour versus response frequency

5. APPLICATIONS TO EARLY WARNING OF BRIDGE SAFETY UNDER MULTI-HAZARDS

Major advantage of the developed intelligent monitoring system of bridge foundations is that structural performance including response acceleration amplitudes and response frequency could be monitored in real time. Response amplitude and frequency could be ideally used to describe structural deformation caused by external forces, overall external forces acting on structure, overall structural stiffness, and boundary conditions of monitored structural members. Table 1 further illustrates performance indices that could be used to describe structural stability during multi-hazards. The developed intelligent monitoring system is cable of monitoring performance of bridge foundations during natural hazards that would cause changes of above-mentioned structural performances in real time using time histories of response amplitude and frequency. The developed system was able to report instability of bridge foundation earlier and more efficient than existing scour detectors and flow condition instrumentations.

The other advantage of the developed system is that it could be integrated with environmental monitoring. The proposed early warning scheme for bridge safety is to set up a "watershed" monitoring network structure by combining the developed systems, rainfall stations, and flow monitoring systems along the monitored river watershed. Rainfall data obtained in the upstream area of the monitored bridge could give earlier flow information such as when water level and flow rate will start to increase, how fast water level and flow rate would increase. Structure performance indices could be then effectively monitored via the developed system at downstream bridge sites. In the studied cases, bridge warning could actually be activated two hours earlier than conventional scour detectors did.

Table 1 Performance indices that could be used to describe structural stability during multi-hazards

Performance Index	Response Amplitude		Response Frequency	
Multi-Hazards	Structural deformation caused by external forces	Overall external forces acting on structure	Overall structural stiffness	Boundary condition
Flood	✓	✓	✓	-
Scour	-	-	-	✓
Debris Flows	✓	✓	✓	✓
Earthquake	✓	✓	✓	-

6. CONCLUSIONS

In this paper, two successful case studies were presented to demonstrate performance monitoring of bridge foundation during flood and scour events. In Shi-Tzou Bridge case, performances of two bridge piers with different foundations, one old foundation suffering from serious scours, the other newly retrofitted foundation seated in main river channel. Performances of both piers during 2009 Typhoon Morakot were studied. It was found that response amplitude of the monitored piers could describe well the combined effects of water flow pressure and scour acting on bridge foundations. Moreover, response frequency could present actual boundary conditions of bridge foundation including scour and re-deposition of riverbed soil. By analyzing monitoring results of the retrofitted pier and that suffered scour, the proposed retrofit method to strengthen bridge foundations by enlarging the size and prolonging the depth of bridge foundations appears to be an effective measure for bridge against server hazards caused by climate change.

The developed system was then further verified at the second case study Xibin Bridge. Scour detectors were installed on the same monitored piers as the developed systems on Xibin Bridge for comparison. It was found that the combination effect of bearing capacity loss of bridge foundations due to scour and flood pressure acting on bridge foundations could be observed by time history of response amplitude and frequency in a reasonable sense. The proposed method utilizing analyzed time histories of response amplitude and frequency to describe performance stability of bridge foundation during scour is proved to be feasible and more reliable than just measuring scour depth. Finally, application schemes of the developed system to bridge safety under multi-hazards including flood, scour, and possible debris flows, were also proposed. It was hoped that results of this study could offer a new concept of safety monitoring and performance analysis of bridge foundation under critical natural hazards.

7. REFERENCES

Chung I Yen, Chin-Kuo Huang, Wei F. Lee, Cheng-Hsing Chen, Ming-Cheng Chen, Yi-Ching Lin (2014), "Application of High-Tech Bridge Safety Monitoring System on the Monitoring Performance of Xibin Bridge." Proceedings of the Forensic Engineering, proceedings of the Institution of Civil Engineers (ICE), ICE Journal Forensic Engineering, Vol. 167, No. 1, page 38-52, February.

Kong X, Cai CS, Hou S (2013) Scour effect on a single pile and development of corresponding scour monitoring methods. Smart Materials and Structures 22(5): 1-13.

Ko YY, Lee WF, Chang WK, Mei HT and Chen CH (2010) Scour evaluation of bridge foundation using vibration measurement. International Conference on Scour and Erosion (ICSE-5), San Francisco, CA, USA, pp. 884-893.

Lin YB, Lai JS, Chang KC, Chang WY, Lee FZ,and Tan YC (2010) Using MEMS Sensors in The Bridge Scour Monitoring System. Journal of the Chinese Institute of Engineers, ASCE, 33(1): 25-35.

Lin YB, Chang KC, Chen CC, Wong SC, Lee LS, Wang YK, Gu MH (2011) Integrating real-time bridge scouring monitoring system with mobile location-based services. International Journal of Automation and Smart Technology 1(2): 51-62.

Wei F. Lee, Kenji Ishihara, C. H. Chen, (2010)," Performance of bridge foundations under extreme natural hazards." Proceedings of Bangladesh Geotechnical Conference 2010, Natural Hazards and Countermeasures in Geotechnical Engineering, Dhaka, Bangladesh, page 67-74.

Wei F. Lee, (2011), "Bridge Monitoring and Safety Evaluation using a Vibration Technique," US pattern No. US 8,290,718, Japan pattern No. 5148589

Wei F. Lee, (2012a), "Method for Analyzing Structure Safety," US pattern No. 8,640,544 B2, Japan pattern No. 5514152, and Taiwan pattern 449883

W. F. Lee (2012b), "Bridges at Risk from Multi-hazards," Forensic Engineering, Proceedings of Institution of Civil Engineers, London, United Kingdom, Vol. 165, No. 4, page 157 –159, November 2012.

W. F., Lee, M. Abe, M. Cubrinovski, C. I. Yen, M. F. Wu, C. F. Chen, (2013), "Forensic Investigation and Performance Analysis for Bridges under Extreme Natural Hazards." Keynote Address, Forensic Engineering: Informing the Future with Lessons from the Past, Proceedings of ICE Fifth International Conference on Forensic Engineering, Institute of Civil Engineers, London, United Kingdom, page 29-48.

W.F. Lee, T.T. Cheng, C.K. Huang, C.I. Yen, H.T. Mei (2014), " Performance of A Highway Bridge under Extreme Natural Hazards – A Case Study on Bridge Performance during 2009 Typhoon Morakot." Journal of Performance of Constructed Facilities, ASCE, Vol. 28, No. 1, page 49-60, January/February.

Zarafshan A, Iranmanesh A and Ansari F (2012) Vibration-Based Method and Sensor for Monitoring of Bridge Scour. Journal of Bridge Engineering, ASCE 17: 829-838.