www.sensorsportal.com

Sensors & Transducers

http://www.sensorsportal.com

An Accelerometer-Based Sensor System for Real-Time Bridge Scour Monitoring

Yi-Jie Hsieh, Chih-Chyau Yang, Ssu-Ying Chen, Chen-Chia Chen, Chien-Ming Wu and Chun-Ming Huang
National Chip Implementation Center,
7F, No. 26, Prosperity Rd. 1, Science Park, Hsinchu City, 30078, Taiwan
Tel.: +886-3-577-3693, fax: +886-3-668-7035
E-mail: ccyang@cic.narl.org.tw

Received: 31 August 2015 /Accepted: 15 October 2015 /Published: 30 November 2015

Abstract: With the fast global climate change, many bridge structures are facing the nature disasters such as earthquakes and floods. The damage of bridges can cause the severe cost of human life and property. The heavy rain brought by the typhoon in July and August in Taiwan causes the bridge scour and makes the damage or collapse for bridges. Since scour is one of the major causes for bridge failure, how to monitor the bridge scour becomes an important task in Taiwan. This paper presents a real-time bridge scour monitoring system based on accelerometer sensors. The presented sensor network consists of a gateway node and under-water sensor nodes with the wired RS-485 communication protocol. The proposed master-slave architecture of the bridge scour monitoring system owns the scalability and flexibility and is setup in the field currently. The experimental results in the field show the presented sensor system can detect the bridge scour effectively with our proposed scour detection algorithm in real time. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Bridge, Bridge pier, Scour, Sensor network, Accelerometer.

1. Introduction

Bridges are the important pivots of traffic and the damage of bridges can cause the severe cost of human life and property. With the fast global climate change, many bridge structures are facing the nature disasters such as earthquakes and floods. These nature disasters cause lots of bridge collapse or destruction and thus endanger our daily life.

In Taiwan, many bridges have exceeded their 50-year life span, while many highway bridges are more than 20 years-old [1]. The strength of these old bridges is no longer affordable to the severe nature disasters. In other words, the bridges in Taiwan are likely to suffer from the damage. Scour is one of the major causes for bridge failure [2]. The heavy rain brought by the typhoon in July and August in Taiwan can cause the bridge scour and make the damage or collapse for bridges. Thus, how to monitor the bridge health and real-time diagnose the bridge structure becomes an important task in Taiwan.

Bridge scour has been extensively studied in the world for more than a hundred years. Many methodologies and instruments have been employed to measure and monitor the local pier scour depth, such as bricks, sonar, radar sensor, Time-Domain Reflectometry (TDR), Fiber Bragg Grating (FBG) sensor and accelerometer sensor. The bricks sensors [3-4] are buried in the certain location of the sand before the rain season. After the floods, the bricks are digged out and the number of the remained bricks is calculated. Thus, the bridge scour depth can be obtained. This method can be used only one-time and the scour detection cannot be real-time detected. The sonar and radar sensors [4] provide contactless measurement of streambed scouring near bridge pier and abutments, and usually used to show the final status of streambed after a flood. One of disadvantages of the sonar and radar is that they have limit for measuring status of streambed in real time as rush water contained sands, even rocks during a flood. The time domain reflectometry (TDR) [5-7] measures the reflections that results from a fast-rising step pulse travelling through a measurement cable. The depth of soil-water interface is determined by counting the round trip travel time of the pulse. However, the major drawback of TDR is that accuracy of TDR is strongly dependent on the environment temperature and humidity. Monitoring the scour depth by the fiber Bragg grating (FBG) [5] is dependent on number of FBG elements. However, the cost of monitoring of the scour depth by FBG technique is higher than that of existing methods [5]. The costs of Radar and TDR are expensive due to high-speed hardware requirement. For example, a commercial TDR (Campbell Scientific Inc., TDR100) was used to real-time monitor scour evolution, and its price is high. For FBG, optical devices such as laser, photo detectors and the optical fibers are very expensive. In addition, most of the existing methods used for scour detection are expensive and complicated, which is a major challenge for mass deployment to a lot of bridge piers. The frequency response with Fast Fourier Transform (FFT) and the time domain response with the root mean square (RMS) values of the accelerometer [8-9] are used to detect the scour. Since the accelerometer in [8] does not sense the vibration data by the flow directly, the result of scour depth may be inaccurate due to the unpredictable interferences in the complicated under-water environment. Besides, in order to obtain the frequency response result [9], it may consume the large computations to get the bridge scour. Yang [10] proposed a bridge scouring monitoring system based on accelerometer sensors, this paper utilizes the absolute difference vibration value between current value and initial value of accelerometers to decide the bridge scour in real time. However, this work still lacks of the experimental results in the field.

This paper presents a sensor system with accelerometer sensors to real-time detect the bridge scour with our proposed simple scour detection algorithm. The presented sensor system consists of a gateway node and under-water sensor nodes with the wired RS-485 communication protocol. The proposed master-slave architecture of the bridge scour monitoring system owns the scalability and flexibility for mass deployment. The experimental results in the field show our sensor system can detect the bridge scour effectively with our proposed scour detection algorithm in real time.

In Section 2, the proposed algorithm of scour bridge detection is introduced. In Section 3, the overview of our proposed architecture is presented. In Section 4, the experimental setups and the experimental results are illustrated. Finally, we conclude this paper in Section 5.

2. The Proposed Algorithm for Bridge Scour Detection

In this paper, the accelerometer sensor system is presented to real-time detect the bridge scour. The accelerometers are buried into the sand of riverbed in advance. During the season of typhoon, the heavy rain that comes with typhoon causes the river full of water. The sand of the riverbed is scoured and it causes the accelerometers exposed. The accelerometers are scoured and thus vibrated due to the river water flow. The accelerometer owns the characteristics of low-cost, high sensitivity, small form factor, and low power compared with those in other instruments. With the accelerometers, the vibration can be detected easily no matter the river water is clean or mixed with sand. Moreover, it is easy to setup in the field without the direction alignment.

The main purpose of the under-water sensors is to monitor the scouring condition of the bridge pier and riverbed. Fig. 1 shows the concept of the scour detection with accelerometer sensors. The under-water sensors are arranged equidistance and vertically fixed on the steel shelf. The under-water sensors are then buried deeply in the riverbed close to the bridge pier.

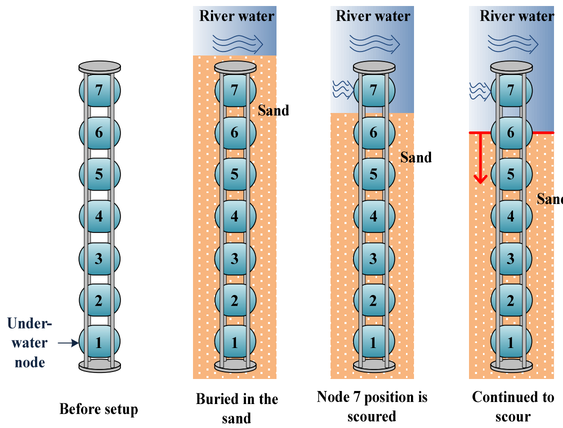

Fig. 1. The operation of under-water sensor node to detect the bridge scour.

In the normal condition, the sand of the riverbed can fully cover the under-water sensors, and the sensor nodes are in a steady state condition. When the water of the river becomes rapid due to the storm or heavy rain, it washes away part of the riverbed and the sensors originally buried in the sand become exposed and vibrated due to the scouring. The deeper the riverbed gets scoured, the more sensors are exposed. The vibration data of each sensor will be real-time sent to the data logger through the Ethernet and the host program helps to identify the scouring degree. To keep track of the scouring condition of the riverbed in long terms, the host program provides reference information of the stability of the bridge pier, and achieves the purpose of disaster prevention.

Table 1 illustrates our proposed algorithm to detect the bridge scour with accelerometers. The algorithm consists of scour detection loop for each sensor node. Each sensor node executes the scour detection loop. The host program acquires the N-point accelerometer values first in the detection loop. These N-point values are averaged and then subtracted by the initial accelerometer value to obtain the absolute difference value. If the absolute difference value between current accelerometer and initial accelerometer exceeds the threshold value, the sensor node is labeled as the status of scoured. Otherwise, the sensor node is labeled as the status of non-scoured. If the position of the scoured sensor node exceeds the position of alarm threshold, the alarm is triggered. Note that the threshold value and the alarm threshold position are obtained from the experiment in the laboratory. Fig. 2 illustrates the flow chart of the proposed algorithm for bridge scour detection loop.

Table 1. The algorithm for bridge scour detection loop.

Scour Detection Loop
LOOP
FOR t=0 TO (N-1)
Node(Ax, Ay, Az) = **GetAccInfo();**
($\mu x, \mu y, \mu z$) = **GetMean (**Ax, Ay, Az**)**;
$\Delta\mu x = \lvert \mu x - \mu x0 \rvert$; $\Delta\mu y = \lvert \mu y - \mu y0 \rvert$; $\Delta\mu z = \lvert \mu z - \mu z0 \rvert$;
IF(($\Delta\mu x > \mu ThD$) OR ($\Delta\mu x > \mu ThD$) OR ($\Delta\mu x > \mu ThD$))
Node_Scoured =ON;
ELSE
Node_Scoured =OFF;
IF (i >= Alarm_ThD) THEN
AlarmTrigger();
GOTO LOOP

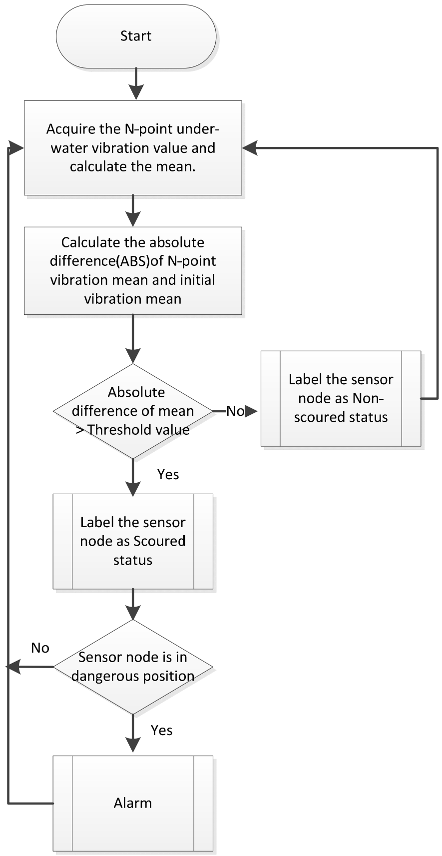

Fig. 2. The flow charts for the detection of the bridge scour with accelerometers.

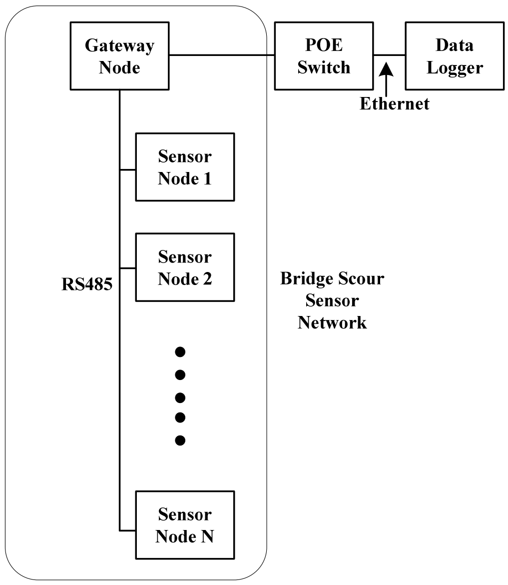

Fig. 3. The architecture of real-time bridge scouring monitoring system.

3. Development of Real-Time Bridge Pier Scour Monitoring System

3.1. Architecture of Our Sensor System

The presented sensor network shown in Fig. 3 consists of a gateway node and under-water sensor nodes with the wired RS-485 communication protocol. The architecture of our bridge scour monitoring system is based on master-slave configuration. A master sends commands to slave for controlling sensor nodes and accessing sensor data. The data logger sends the command to the gateway through Power over Ethernet (POE) switch. When the gateway receives the command, the gateway converts the Ethernet command to RS485 command.

After converting the command, the gateway broadcasts it to all the sensor nodes. To avoid the data collision on the RS485 bus, only the specific sensor node with corresponding sensor ID can return the sensor data to the data logger. The POE switch is connected with 48V battery (3 packs in series for 48 V with individual 16 V lithium iron phosphate battery).

3.2. The Gateway and Sensor Node

Fig. 4 shows the pictures of PCBs for the gateway node and sensor node. The gateway node is comprised of two stacked PCBs – a power module and a core module. The top board is the power module, which operates as a DC-DC converter for generating 1.2~5 V outputs from the 48 V input. An Ethernet PHY (TI, DP83640) is used to send/receive Ethernet data from POE switch, and send/receive the signals and power to sensor nodes through RS485 interface (ADI, ADM2682E). The core module is composed of a Cortex-R4 Microcontroller Unit (MCU, TI, RM48L952) and a Field Programmable Gate Array (FPGA, Xlilinx, Spartan-6). Ethernet data and RS485 data are processed by the Cortex-R4 MCU and the FPGA, respectively. The FPGA mainly is used to translate the sensor data from serial format to parallel format. Three signals (Int, Rdy, En) are used to control the operations between the FPGA and the Cortex-R4 MCU. The FPGA receives the sensor data in 8-bit as a unit. After the FPGA collects 8-bit data, the FPGA deposits to register, then sends Int signal to the Cortex-R4 MCU, and notifies the Cortex-R4 MCU to receive sensor data. After the Cortex-R4 MCU receives 8-bit data, the Cortex-R4 MCU sets the Rdy signal and sends it to the FPGA. The FPGA En Signal is set to "0" to indicate that the sensor data has been transferred completely.

Fig. 4. The pictures of printed circuit boards of gateway (left) and sensor node (right).

The configuration of sensor node is similar to that in the gateway node (see Fig. 4). The Cortex-R4 MCU is used to access sensor data through Serial Peripheral Interface (SPI) interface and the FPGA is used to process RS485 data. The block diagram of the FPGA in sensor node is shown in Fig. 5.

The FPGA parses the received commands, executes part of commands, and responses to the data logger. The Cortex-R4 MCU takes charge of collecting sensor data. Fig. 6 describes the processing sequence of the FPGA and the Cortex-R4 MCU. In Fig. 6, the steps with blue color are tasks of the FPGA, those steps with purple color are memory related tasks, and those steps with red color are the tasks of the Cortex-R4 MCU. In the case that the data logger requests sensor data, the FPGA will receive a Read command. After the FPGA parses and decodes the command, the FPGA puts this command in memory and notifies the Cortex-R4 MCU with an interrupt. The Cortex-R4 MCU reads command from memory via I2C interface, and then collects sensor data and stores them in memory. After the data collection is done, the Cortex-R4 MCU notifies the FPGA by a General-Purpose Input/Output (GPIO) signal. Then, the FPGA reads data from memory and generates response to the data logger.

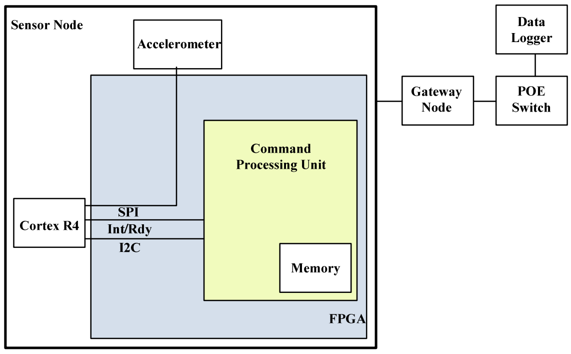

Fig. 5. Block diagram of FPGA in sensor node.

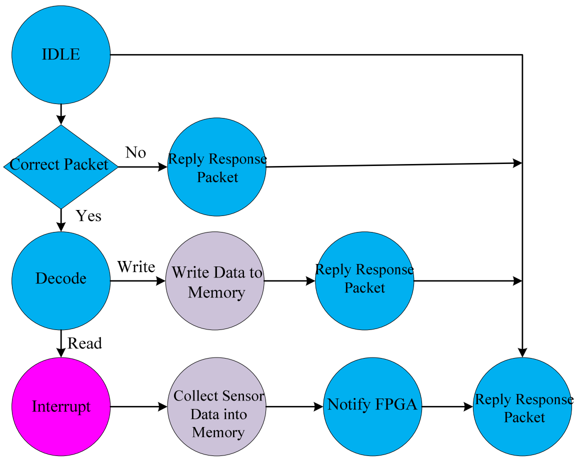

Fig. 6. Processing sequence of FPGA and MCU.

The accelerometer (ADI, ADXL345) which is integrated in the core module of the sensor node is used in this study. Fig. 7 shows the top-view and bottom-view pictures of the accelerometer module. The accelerometer value is read by Cortex-R4 MCU via the SPI interface. The sensor data is then sent back to data logger for the further analysis.

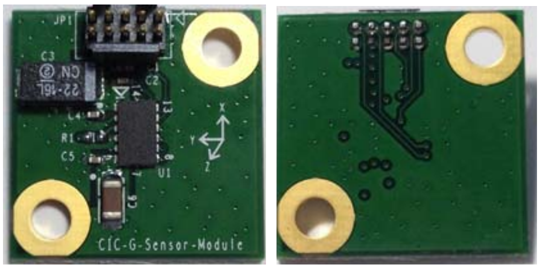

Fig. 7. Top and bottom-view pictures of the accelerometer module.

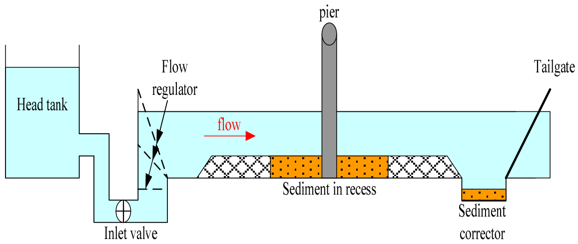

Fig. 10. Partial layout of recirculating laboratory flume.

4. The Experimental Setup and Results

The accelerometer module is fixed on thin metal strip with thickness of 0.3 mm, as shown in Fig. 8. The accelerometer module is filled with silicon to be water-proof. Fig. 9 shows the picture of setup of real-time bridge scouring monitoring system. The accelerometer sensor module is installed alone the pier model. The 48 V battery, control circuits of gateway and sensors nodes and cables are setup near the laboratory flume.

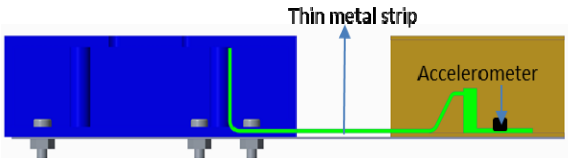

Fig. 8. The drawing house for accelerometer module.

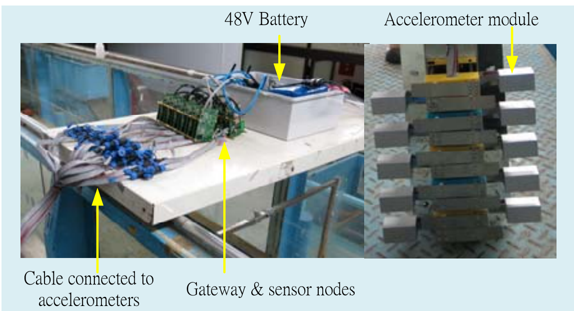

Fig. 9. The photos of setup for the real-time bridge pier scouring monitoring system.

The monitoring bridge scour erosion detection is carried out in a recirculating laboratory flume (length = 36 m, width = 1 m, depth = 1.1 m) at Hydrotech Research Institute of National Taiwan University, Taiwan [11]. The layout of the flume and experimental setup are shown in Fig. 10. A false test bed has a sediment recess (length = 2.8 m, width = 1 m, depth = 0.3 m) which is filled by nearly uniform sediment. A 15-cm-diameter hollow cylindrical pier made of Plexiglas is located at the middle of the recess. An inlet valve and a tailgate are used to regulate depths of flow and flow speed.

Fig. 11 shows the experimental results. The left figure shows the time-domain vibration raw data while the right figure shows the absolute difference vibration data.

First, we discuss the time-domain vibration data obtained in the scouring experiment. At first, the sensors of G4, G5, G6, G7, G8, G9 and G10 are buried in the sand. At the time of Ti, the Gk sensor starts to be scoured by water and exposed from the sand; Ti refers to the times {T1, T2, T3, T4, T5} and Gk refers to the sensor nodes {G4, G5, G6, G7, G8}, respectively. The accelerometer data of G7 and G8 starts to change little from T4 and T5 respectively. We find the G7 and G8 are scoured and exposed from the sand; however it's not easy to obtain the correct scouring information from the vibration raw data in the time domain. For the sensor of G9 and G10, they are buried in the sand in this experiment, so that we cannot observe the change of the vibration data for these two accelerometers.

The right figure of Fig. 11 shows the absolute difference vibration data. We utilize our proposed algorithm in Table 1 to detect the bridge scour. The threshold value of absolute difference of vibration data is set to 0.01 according to the experiment results. At the time of Ti, the Gk sensor starts to be scoured by the water and starts to be exposed from the sand. The value of absolute difference vibration data for Gk sensor node starts to be larger than the threshold value from Ti. Ti refers to the times {T1, T2, T3, T4, T5} and Gk refers to the sensor nodes {G4, G5, G6, G7, G8}, respectively. By using the proposed algorithm shown at Table 1 and the proposed flow chart shown in Fig. 2, the bridge scour detection can be easily realized. This sensor system with the proposed algorithm is currently setup in the Da-Chia-River Highway Bridge to detect the bridge scour.

Table 2 shows the experimental results of the under-water sensor system in Da-Chia-River Highway Bridge in Taiwan. The initial value data is measured on March 18, 2014 while the vibration data during the flood is measured on May 15, 2014. According to the algorithm in Table 1, the absolute difference vibration data of X, Y and Z axis can be obtained. From the experiment results in the laboratory, the threshold value is set to 0.01 to decide whether the bridge is scoured or not. From the Table 2, we found the top 4 under-water nodes are scoured.

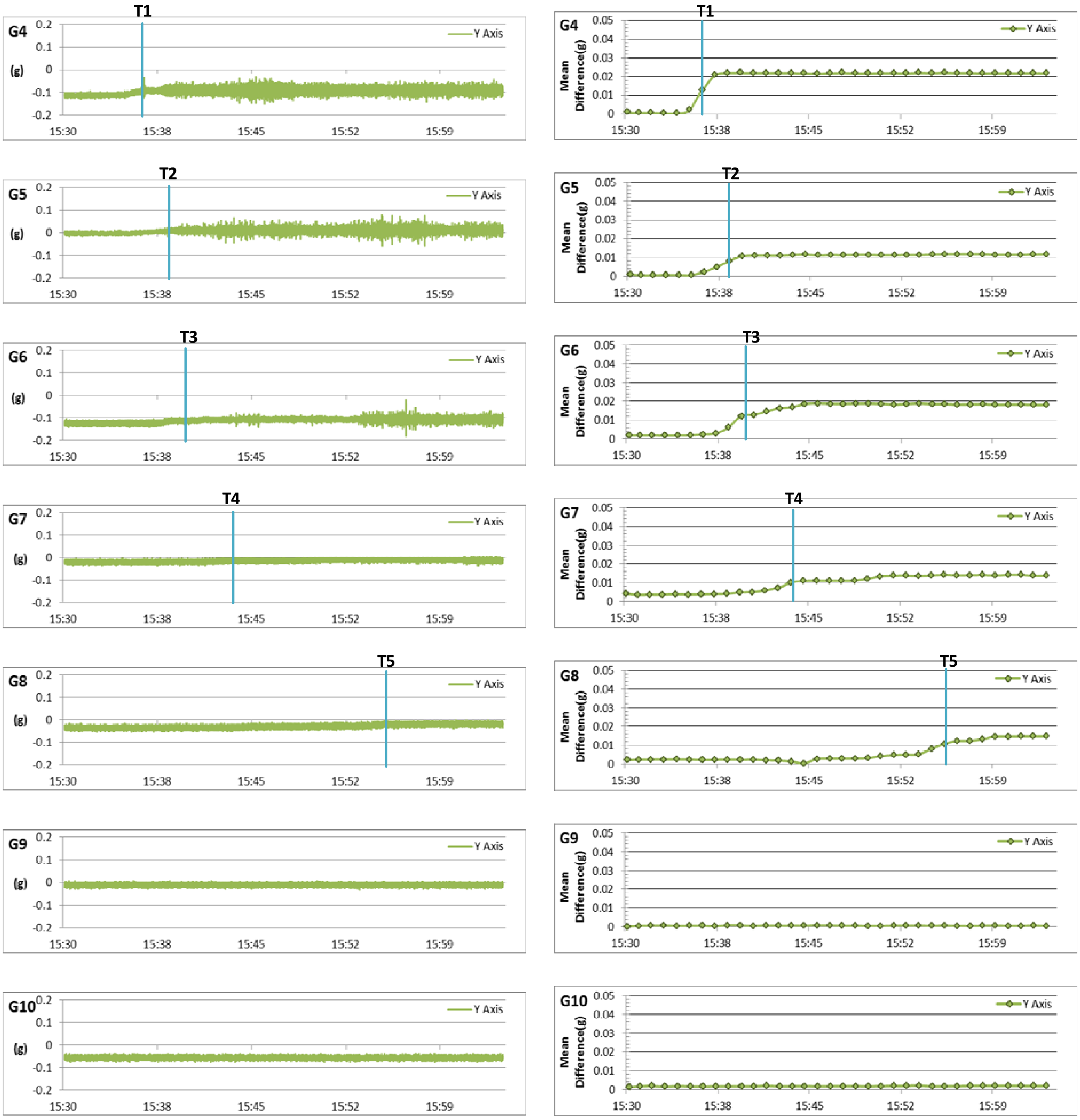

Fig. 11. The experimental results of time-domain vibration raw data and absolute difference vibration data.

Table 2. The experimental results of under-water nodes in the field.

Node Number	2014/03/18(Initial Value) Accelerometer Vibration Data			2014/05/15(During the Flood) The Accelerometer Vibration Data			Absolute Difference Vibration Value		
	X Axis	Y Axis	Z Axis	X Axis	Y Axis	Z Axis	X Axis	Y Axis	Z Axis
Node1	2.60E-01	-7.31E-03	9.99E-01	2.86E-01	-3.99E-04	9.86E-01	2.60E-02	6.91E-03	1.31E-02
Node2	3.02E-01	5.68E-02	1.01E+00	3.48E-01	6.20E-02	9.88E-01	4.54E-02	5.15E-03	2.53E-02
Node3	2.09E-01	2.11E-02	9.97E-01	2.35E-01	3.32E-02	9.89E-01	2.58E-02	1.20E-02	7.93E-03
Node4	1.06E-01	5.47E-02	1.01E+00	1.12E-01	6.07E-02	1.00E+00	5.66E-03	5.92E-03	1.08E-02
Node5	2.04E-01	-4.92E-03	9.83E-01	1.99E-01	3.30E-03	9.80E-01	4.76E-03	8.22E-03	3.19E-03
Node6	4.83E-01	4.96E-02	8.87E-01	4.90E-01	5.06E-02	8.81E-01	6.86E-03	9.90E-04	6.01E-03
Node7	3.67E-01	8.59E-02	9.63E-01	3.72E-01	8.56E-02	9.60E-01	4.55E-03	3.45E-04	2.15E-03

Fig. 12 shows the picture of the under-water nodes in the field, we found the top 4 under-water nodes are exposed. The results between the laboratory and the field are consistent.

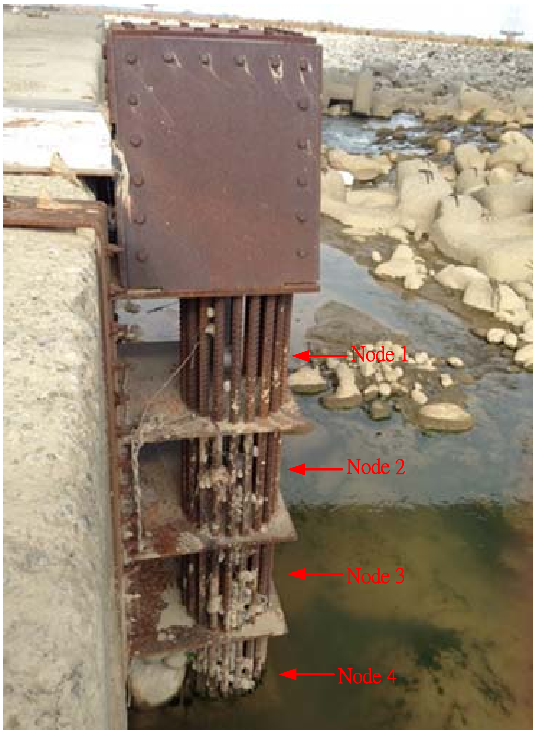

Fig. 12. The results of bridge scour in the field.

5. Conclusions

Bridges are the important pivots of traffic, and the damage of bridges can cause the severe cost of human life and property. The heavy rain that comes with typhoon occurs in July and August in Taiwan often causes the bridge scour and makes the damage or collapse for bridges. Since scour is one of the major causes for bridge failure, how to monitor the bridge scour becomes an important task in Taiwan. This paper presents a real-time bridge scour monitoring system based on accelerometer sensors. The proposed sensor network consists of a gateway node and under-water sensor nodes with the wired RS-485 communication protocol. With the proposed scour detection algorithm, the system can detect the bridge scour effectively in real time. The proposed master-slave architecture of bridge pier scour monitoring system has scalability and flexibility for mass deployment. The experimental results in the field show the presented sensor system can detect the bridge scour effectively with our proposed scour detection algorithm in real time.

References

[1]. T. Y. Liu, W. L. Chiang, C. W. Chen, W. K. Hsu, L. C. Lu, T. J. Chu, Identification and Monitoring of bridge health from ambient vibration data, *Journal of Vibration and Control*, Vol. 17, No. 4, 2011, pp. 589-603.

[2]. J. A. Puleo, J. T. Hayden, A Near Real-time Scour Monitoring System at Indian River Inlet, Delaware, USA, in *Proceedings of the IEEE Bilox-Marine Technology for Our Future: Global and Local Challenges (OCEANS'09)*, Oct. 2009, pp. 1-10.

[3]. J. Lu, J. Hong, C. Su, C. Wang, J. Lai, Field Measurements and Simulation of Bridge Scour Depth Variations during Floods, *Journal of Hydraulic Engineering*, Vol. 134, No. 6, 2008, pp. 810-821.

[4]. H. C. Yang, C. C. Su, Real-time River Bed Scour Monitoring and Synchronous Maximum Depth Data Collected During Typhoon Soulik, *Hydrological Processes*, Vol. 29, 2015, pp. 1056-1063.

[5]. L. J. Prendergast, A review of bridge scour monitoring techniques, *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 6, No. 2, 2014, pp. 138-149.

[6]. H. Wang, S. C. Hsieh, C. Lin, C. Y. Wang, Forensic Diagnosis on Flood-Induced Bridge Failure. I: Determination of the Possible Causes of Failure, *Journal of Performance of Constructed Facilities*, Vol. 28, 2014, pp. 76-78.

[7]. J. Tao, X. Yu, X. B. Yu, Real-time TDR Field Bridge Scour Monitoring System, in *Proceedings of the Structures Congress*, 2013, pp. 2996-3009.

[8]. J. L. Briaud, S. Hurlebaus, K. Chang, C. Yao, H. Sharma, O. Yu, *et al.*, Realtime Monitoring of bridge scour using remote monitoring technology, FHWA/TX-11/0-6060-1, *Texas Transportation Institute*, Austin, USA, 2011.

[9]. M. Fisher, S. Atamturktur, A. Khan, A Novel Vibration-based Monitoring Technique for Bridge Pier and Abutment Scour, *Structure Health Monitoring*, Vol. 12, No. 2, 2013, pp. 114-125.

[10]. C. C. Yang, Y. J. Hsieh, S. Y. Chen, W. C. Chen, C. T. Kuo, C. C. Chen, C. M. Wu, C. M. Huang, A real-time bridge scouring monitoring system based on accelerometer sensors, in *Proceedings of the 9th International Conference on Sensor Technologies and Applications (SENSORCOMM'15)*, Venice, Italy, 23-28 August 2015, pp. 152-156.

[11]. Y. B. Lin, J.-S. Lai, K. C. Chang, W.-Y. Chang, F.-Z. Lee, Y.-C. Tan, Using MEMS Sensor in the Bridge Scour Monitoring System, *Journal of the Chinese Institute of Engineers*, Vol. 33, Jan. 2010, pp. 25-35.