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# Bridge pier and embankment foundation real time scour monitoring system development

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ABSTRACT: Bridge pier and embankment caused by floods and foundation scouring have been a severe problem worldwide. In recent years, floods and flash floods in the Taiwan have caused billions of dollars in damage each year. Current early warning systems for bridge pier and embankment collapses are extremely ineffective. This severe problem has also happened in many Asian countries such as India, Taiwan, and Japan etc., because these areas are subject to typhoons, hurricanes, and flood events each year during the summer and fall. However, because of the complex interaction between fluid flow patterns caused by obstructing piers and the erosion of sediment leading to the formation of scour holes, it is extremely difficult to develop a reliable analytical/numerical model that can account for various controlling and interrelated factors without oversimplification. Herein, this paper successfully demonstrated a system combined technologies of internet of things and multiple degrees of vibration based MEMS sensor for flood impact real-time monitoring to provide an early warning mechanism for bridge pier and embankment collapses. With this system, fatal events and damage caused by natural hazards can be reduced at affordable maintenance costs.

## 1 GENERAL INSTRUCTIONS

Taiwan resides on the Tropic of Cancer, and its general climate is marine tropical. In May and June, the rainy season is concurrent with the onset of summer convective thunderstorms, and typhoons are common from June through September. Therefore, Taiwan experiences large rainfall volume throughout the summer season, and its average annual rainfall reaches 2,500 millimeters. Due to the special geographical location and unique terranes, averagely 3.5 typhoon events and dozens of torrential rain events would occur each year on the Taiwan Island, which often trigger severe landslides and flooding. In particular, typhoon-induced flooding impose substantial threats to river-basin bridges by eroding the riverbed in the direct vicinity of bridge piers or abutments and thus causing scour-induced bridge failure. Scour at bridges is a problem of national scope, and scour-induced damages and destruction of highway bridges (Figure 1) can have dramatic impact on economics and on the safety of the traveling public.


Figure 1. Bridge failure due to bridge scour

Moreover, bridge scour is not only a critical problem in Taiwan, it has also been a worldwide issue. Therefore, many worldwide academic and industrial efforts have been devoted to develop scour monitoring systems for monitoring bridge safety. By reviewing and comparing various scouring monitoring schemes, Prendergast and Gavin (2014) suggested that using fixed- or discrete-scour-depth recording instrumentation outperform conventional visual inspection schemes, in which the scour holes may not be timely detected before being refilled as flood subsides. Therefore, various depth-measuring instruments have been developed to monitor the scour depth around bridge piers and abutments, such as single-use devices (Briaud et al., 2011), fiber-Bragg grating devices (Lin et al., 2006), sound wave devices (Fisher et al., 2013; Anderson et al., 2007). However, these scour monitoring techniques have been found to have limited applications due to either high costs, low resistance to natural factors (e.g., temperature, salinity, debris, and turbidity), high susceptibility to noise caused by the turbidity of the flow.

In this context, this paper explored to develop a reliable, real-time, and robust sensor system that can be installed at bridge piers to detect flood-induced scour processes and changes in scour depth at the priers. The proposed sensor system was expected to provide an industrial protocol for bridge safety monitoring and early warning applications.

## 2 DEVELOPMENT OF BRIDGE SCOUR SENSOR SYSTEM

### 2.1 Site description and hydrologic condition

The Da-Chia Bridge on the National Highway No.3 spans the Da-Chia River between two major areas, Miaoli County (northbound) and Taichung County (southbound), in central Taiwan. As the major transportation route with heavy traffic, the 1.2km-long bridge with 38 spans was constructed in 2003 and its piers cylindrical columns (2.7 m in diameter). It is located at 6.57 km away from the mouth of the Da-Chia River which flows westward to the Taiwan Strait. From hydrologic data, the upstream watershed of the Da-Chia Bridge has a natural drainage area of 1981 $km^2$. The river bed slope in the reach of the Da-Chia Bridge is about 1%. According to the report by the Water Resources Agency, Taiwan, the peak discharge of the 100 year return-period flood is estimated 21,000 $m^3\ s^{-1}$ based on the frequency analysis, and the mean annual discharge at the Da-Chia Bridge is around 116 $m^3 s^{-1}$. The main stream flows underneath the Da-Chia Bridge between pier P26 and pier P28L. The monitoring system was installed on the bridge pier P28L as shown in Figure 3. The monitoring data of scour depth at P28L was adopted for numerical model verification. The main objective of the present study was to evaluate the applicability of real-time scour depth estimation by numerical simulation for developing early scour warning system at the Da-Chia Bridge on the National Highway No.3.

### *2.2 Instructions for sections and insertions*

A sensor unit was formed by first fixing an accelerometer sensor (STM, LSM303DLHC) between two stacked octagonal printed circuit boards (PCBs), and then enclosing the structure with a plastic case. Subsequently, the sensor unit was sealed in a steel hollow ball for waterproof purpose (Figure 2). The power module mounted onto the top PCB generates 1.2–5 V outputs from the 48 V input to supply the power to the sensor unit. Each sensor unit was connected to a Power-over-Ethernet (PoE) switch (TI, TPS2376DDAH), through which the sensor signal is retrieved by a data logger.

To monitor the scour process of a bridge pier or abutment in a timely manner, a sensor matrix consisting of the sensor units can be deployed onto bridge piers length wisely. The accelerometer enclosed in the sensor unit detects the steel ball's vibration triggered by water motion in the river, and then the accelerometer signal is received by the data logger through the PoE switch.


Figure 2 Sensor Design

## 3 FIELD DEPLOYMENT AND RESULTS

The scouring system was installed on the bridge pier P28L in the main channel of the Da-Chia River where the greatest scour depth had occurred during the flood (Figure 3). All the sensor systems including the wireless station were fabricated in the laboratory factory. The scouring system was subject to floating debris impact. The signal and performance of all the sensors corresponding packaged waterproof and long-term durability were tested and analyzed before being used in the field.

As shown in Figure 4, signal data of sensor monitoring were collected over the period of time from May 17 through 26 at P28L. The duration of the flood event can be separated into three periods: T1 is the time before scouring, T2 has the strong scouring processes, and T3 is the period of flood recession. The datum of the scour depth measurement is set as the original river bed elevation, which is about the top of the pier foundation. There were five vibration-based sensors, named S1 (located at -1.55m) to S5 (located at -3.55 m). The distance between each sensor was 0.5m. They were packaged within a waterproof steel ball as a scour positioning indicator, which were protected in a steel reinforcement cage and deployed beside the pier foundation (Figure 4). Once the scour monitoring sensor emerges out of the riverbed, it will send vibration signal as it vibrates by the turbulent flow. Sensors S1 and S2 were initially exposed to air due to the previous flood event erosion, which were then able to detect flow turbulence to reveal signal fluctuations.

It is obvious to observe the strong signal fluctuations both from Sensors S1 and S2 before noon on May 19 in the T1 period, which could be induced by the fast rising flow during the period of flood. At the early stage of T2 period around 20:00 on May 19, the signal readings from Sensor S3 vibrated significantly, presenting a strong erosive impact at the first peak discharge. The noticeable fluctuations in the readings showed strong interactions between the sensor and the flow turbulence/sediment transport around the peak flow. However, after the first peak discharge in the period between midnight and 12:00 on May 20, the flood flow receded and the readings showed weak fluctuations indicating that S3 was once again buried due to sediment deposition. At the meantime, Sensors S1 and S2 having readings were still in the flowing water. The readings varying strongly again after 14:00 on May 20 indicating apparent scouring processes detected by Sensors S1-S3. From the S3 signal responses read at 12:00 on May 21, it showed weaker fluctuations which might indicate the S3 buried partially to reduce its vibration. Until the third peak discharge arrived at 14:00 on May 21, Sensor S4 emerged and was exposed in the flood water for about 4 hours. From the S4 sensor responses, it was recorded that there was a maximum scour depth of 1.0 m during this flood event. The maximum scour depth at P28L was confirmed by field investigation after the flood as shown the photo in Figure 4. After T2 period on May 22, the continuous flat signal readings may indicate that the Sensors S3 and S4 should had been buried again by sediment deposits in the T3 period.


Figure 3 Sensor installation at the Da-Chia Bridge

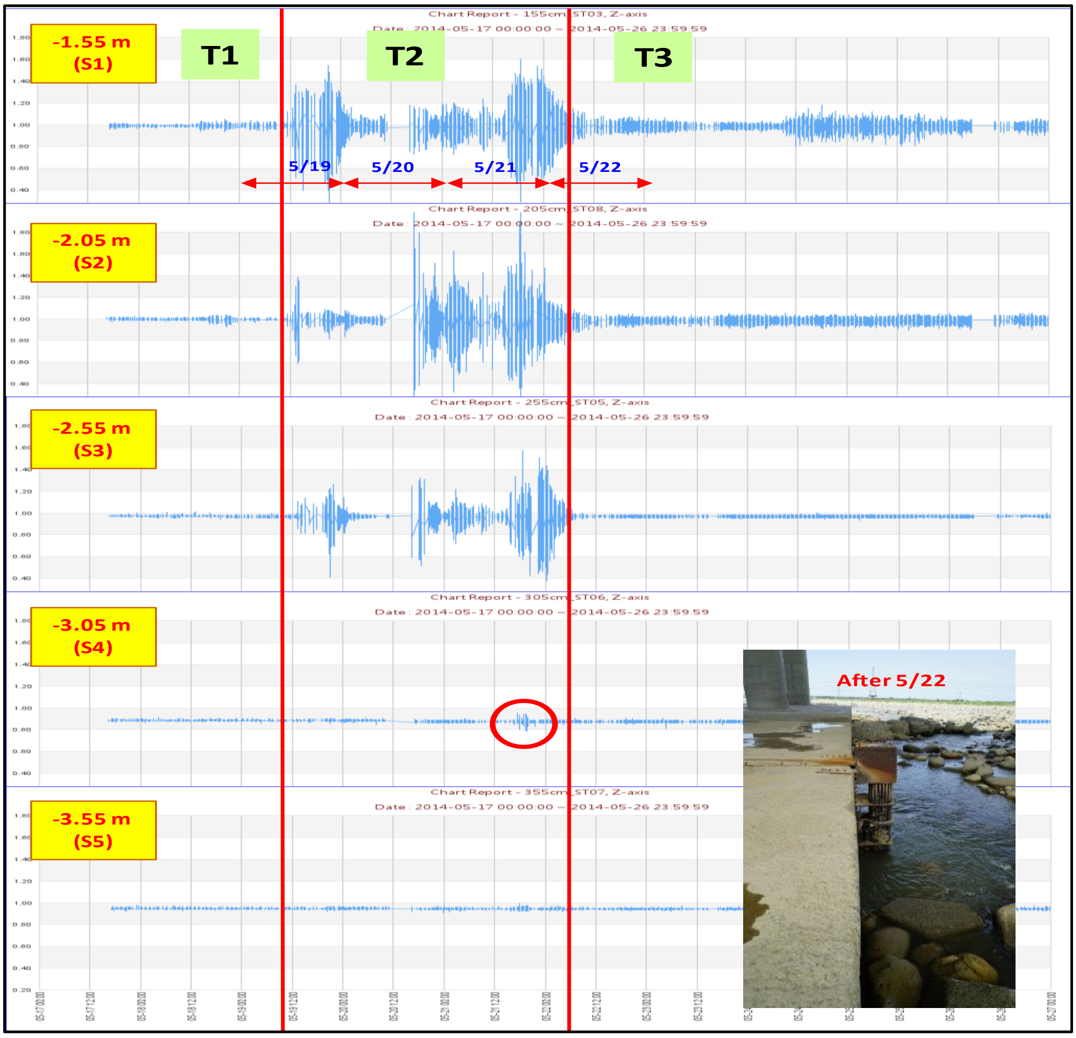


Figure 4 Responses of sensors during the scouring/deposition processes

## 4 SUMMARY

Scouring around bridge piers remains a major cause of bridge failure. Without prior warning to the bridge pier structure, scour failure tends to occur suddenly and result in major public disruption and life losses, particularly in a flood event. It is important to monitor in situ scour depth changes in order to prevent catastrophic failure. In the present study, the proposed novel technique of real-time bridge scour monitoring that is more resilient to harsh environments and is capable of measuring both scouring and deposition processes.

The scour monitoring system consisting of five vibration-based sensors was installed on pier P28L of the National Highway No.3 in the Da-Chia River, Taiwan. The system was subject to harsh flooding environments. Packaged within a waterproof steel ball and protected in a steel reinforcement cage, each sensor was tested and analyzed before being used in the field for long-term durability.

The system was applied and evaluated in the flood event with heavy rainfall. The flood event had a multiple-peak discharge and water stage hydrographs. The measured data in the scour and deposition processes were collected and analyzed. As a scour positioning indicator, the sensor exposed to running flow was able to detect flow turbulence to reveal signal fluctuations. From the sensor responses of vibration readings, a maximum scour depth of 1.0 m occurred near the highest peak discharge in this flood event was recorded. This maximum scour depth at P28L was confirmed by field survey investigation after the flood. Afterward in the period of flood recession, the continuous flat signal readings indicate that the sensors should have been buried again by sediment deposits. The field measurements of total scour depths have shown quite reasonable results for the scouring and deposition processes.

For practical purposes, one may select a proper scour formula for a specific bridge pier through validation processes by comparing with the data measured by the in situ installed vibration-based sensors. The in situ scour depth data collected in the present study will be very helpful in assisting engineers to improve the accuracy of the early warning system for predicting the total scour depth evolution.

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