



WEB-BASED REAL TIME BRIDGE SCOUR MONITORING SYSTEM FOR DISASTER MANAGEMENT

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Abstract. Natural disasters such as typhoons, earthquakes, and especially floods, often cause severe damage in Taiwan. Although bridge engineering technology has matured, the lack of an integrated bridge management system under severe disasters remains a challenge for the government. This research aims to develop a web-based system that displays the real time bridge scour information through combining Global Positioning System and Wireless Sensor Networks technologies for bridges. The system also provides early warnings for bridge safety based on a developed genetic model for estimating scour depth around the bridge piers. The bridge safety monitoring agency utilizes the system as a decision support tool to make the maintenance plan for bridges and block the bridges under severe weather conditions to prevent the damages from bridge collapse.

Keywords: web-based system, real time, bridge monitoring, disaster management.

1. Introduction

In 2009, Typhoon Morakot wrought catastrophic damage in Taiwan, leaving 461 people dead and 192 other missing, with a cost of roughly 110 billion New Taiwan dollars (NTD), what is close to 3.3 billion United States dollars (USD) of damages. The extreme amount of rain triggered enormous mudslides and flooding throughout southern Taiwan. Typhoon Morakot not only tested how the Taiwan government relieved the victims of a severe disaster, but also warned the government to improve the safety of its infrastructure by reducing the impact of disasters. There are over 20 000 bridges located in different counties in Taiwan. As bridges take an important role in traffic, the damage to bridges by scouring not only threatens the safety of users, but also may break-down traffic and cause residents to be locked.

Scouring around bridge piers and abutments is one of the major causes for bridge failure (Melville, Coleman

2000). Real time monitoring of scour depths is a crucial tool to reduce uncertainties in evaluating risk at bridges during flood events (Foti, Sabia 2011). There are several research studies that utilize Wireless Sensor Networks (WSNs) to build structural health monitoring for newly constructed bridges and existing bridges (Chae *et al.* 2011; Lynch *et al.* 2004, 2006). WSNs have the potential to offer significant advantages over traditional wired monitoring systems in terms of sensors, cabling, and installation costs as well as expandability (Hoult *et al.* 2010; Jang *et al.* 2008). Moreover, real-time monitoring of large structures including bridges is now possible using GPS technology (Guo *et al.* 2005).

Although several bridge monitoring technologies have been developed, there are still a lack of integrated bridge management systems that are able to provide real-time information and early warnings to help the government agency monitor over 20 000 bridges in Taiwan,

especially in severe weather conditions. This research aims to develop an integrated web-based management system that provides the real time bridge scour information through combining Global Position System (GPS) and Wireless Sensor Networks (WSNs) technologies to monitor the bridges. Accelerometers and inclinometers were installed with the correction of the GPS function around the substructure and superstructure of the bridge, which is called Chung Sha Bridge over Zhuo-shui River in Taiwan, and figured out the bridge scour monitoring technologies associated with natural frequency. The data of bridge information is transmitted from the wireless sensor to a database server through a 5G-antenna device and the Internet. In the database server a dynamic mathematical model is developed based on long-term monitoring data to estimate the scour depth of the piers of the bridge. The model also displays the early warnings for safety issues to the bridge safety monitoring agency. Finally, the agency utilizes this web-based disaster management system as a reference tool by making the decisions, such as to block the damaged bridges and maintain the unsafe bridges promptly.

2. WSNs for bridge monitoring

The WSNs-based accelerometers and inclinometers, as well as GPS with Non-Iterative Solution for Linear Transformations (NISLT) correction (Han 2010), are installed on the superstructure to obtain complete bridge monitoring information. The GPS and WSNs have been widely employed in civil engineering, especially in structural monitoring and construction safety. To be used in bridge

safety, the time synchronization within the sensor network is required to obtain important correlations between events, such as prevention of equipment collisions. In this work, a high efficient time synchronization method is developed for the ultra-precise localization system to prevent collision accidents on bridges.

2.1. GPS correction

The GPS is utilized to establish a fundamental positioning network as the reference standard in this research. The fundamental network involves a static GPS continuously operating reference station (CORS) and several WSNs sensors with GPS chips. The CORS needs to be set in a stable place in the monitoring area, and utilize a dual frequency transmitter to calculate the precise position of the target as a reference point. This method is also designed to collect observation data lasting 30 to 40 minutes in order to reduce the error of observation to update the position of the station instantaneously.

The WSNs sensors will be set up on the potential distortion spot of the bridge. The station obtains the position data of the distortion spot from the GPS chip. Considering the total number of bridges in Taiwan is over 20 000, the GPS chip that was chosen in this study is small ($<1 \text{ cm} \times 1 \text{ cm}$) and low-cost ($<30 \text{ USD}$), but with a decent accurate rate (50–65 nanoseconds (ns)). The GPS chip is also the self-timer as a time stamp to ensure the reliability of data analysis.

Different sensors that can be used in bridge monitors are listed in Table 1. The causes of bridge damage consist

Table 1. Table of different sensors

Sensor	Model	Frequency	Accuracy	Limitation	Price, USD
GPS	Topcon GR-3 Static	30 min	3 mm + 0.5 ppmH; 5 mm + 0.5 ppm V		20 000
	Topcon GR-3 RTK	10 s	10 mm + 1 ppmH; 15 mm + 1 ppm V	-20~50 °C	20 000
	Parallax GPS receiver	20~30 ms	15 m without; WA AS: 0.1 m/s	18~78 °C	70
Micro-vibration	Tokyo Sokushin VSE-15D-1	0.1~70 Hz	Velocity: 10 ikine Acceleration: 10^{-4} Gal	± 2000 Gal -10~50 °C	5 000
	Accelerometer	Analog ADXL 322	5.5 kHz	1.34~2.68 Gal	± 2 Gal -20~70 °C
PCB 393B04		0.02~2000 Hz	0.003 Gal	± 5 Gal -18~80 °C	1300
Inclinometer	FAS-A	30 Hz	Pitch, Roll: $\pm 0.7^\circ$	360 °	70
Thermo-hygrometer	SHT1x	Temp.: 5~30 s	Temp.: $\pm 0.5^\circ\text{C}$;	-40~123.8 °C	30
		Humidity: 4 s	Humidity: $\pm 3.5\%$ RH	0~100 °C	
LDV	Polytec PDV-100+	Analog: 0.5~22 kHz		0.2~30 m $\pm 5\sim 40^\circ\text{C}$	30 000
	OFV-505	Digital: 0~22 kHz		MAX distance >300 m	85 000
LIDAR	Trimble GS200	3 mm @ 100 m	1.4 mm @ 5 m~6.5 mm @ 200 m	2~350 m	80 000

mainly of vibration and erosion. Micro-vibration and accelerometer can both be used to monitor vibration in bridges, but due to economic concerns, the accelerometer, which provides less precise measurements, is chosen. As for erosion, no suitable sensor has been found, thus an analysis on dynamic models is conducted to determine relationship between frequency and erosion. The frequency information measured by the accelerometer is used to estimate the amount of erosion. This method allows using a low cost sensor to determine both vibration and erosion. Furthermore, to synchronize the monitoring data of the accelerometers at each node, a low precision GPS, which nevertheless has accurate timing function, is chosen for this task.

The accuracy of the original calculating method for the C/A code with a single position is around 10 m and cannot deal with the observation error efficiency. In order to solve the problem of an unacceptable observation error, this study utilizes NISLT which was developed by Han 2010 to reduce the system error and then improve the data accuracy to 0.01 m.

2.2. Integration of GPS and WSNs

This study utilizes the integrated WSNs-based ultrasonic localization system that was developed by National Taiwan University (Lin *et al.* 2010). The advantages of this system include low-cost, high-accuracy data collection, flexible network structure and transmission. The system also can easily add other chips, such as accelerometers and pluviometers, to collect other data simultaneously. Combining with GPS correction technology and the WSNs-based ultrasonic localization system is a new approach to develop an integral bridge monitoring system.

The monitoring system is divided into two major parts. The first is a permanent network which is composed of a high accuracy static GPS observation station and several Real Time Kinematic (RTK) receivers. The static station is set in the stable area in the network, and the RTK receivers are installed in the places with potential deflection to monitor the deformation of bridge. The detailed information of GPS equipment chosen in this paper is listed in Table 2. The accuracy level of the static station is around 3 mm horizontal to 5 mm vertical. The accuracy level of RTK receivers are around 10 mm horizontal to 15 mm vertical.

The second is the data transmission network that is structured by WSNs nodes. The C/A code chip and additional sensory elements including accelerometer, inclinometer, and GPS chip installed on the WSNs sensors (Fig. 1) are used to collect environment-related data with precise timing. The WSNs are able to transmit those data to the database effectively. Model SDI 1221L with 2000 mV/g resolution as the accelerometer was chosen, and VTI SCA103 as the inclinometer with 0.001° resolution in this study.

3. Genetic algorithms for estimating scour depth

Scouring around bridge piers is the important safety issue of bridge management since it often leads to bridge slanting

Table 2. The information of GPS equipment

Type	Model	Sampling frequency	Accuracy of observation
GPS	Topcon GR-3 Static	20 min	3 mm +0.5 ppm horizontal; 5 mm + 0.5 ppm vertical
	Topcon GR-3 RTK	10 s	10 mm + 1 ppm horizontal; 15 mm + 1 ppm vertical

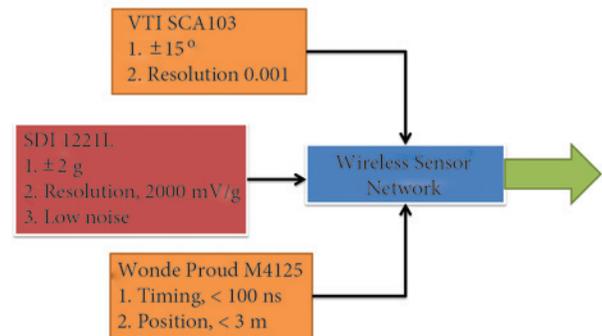


Fig. 1. Integration module of WSNs

and collapsing. Many researchers have tried to estimate the scour depths around bridge piers by simulating the bridge model with the consideration of various factors, such as depth of water, average velocity of flow, and diameter of sand (Dargahi 1990; Firat, Gungor 2009; Johnson, Dock 1998; Johnson, Niezgodna 2004; Melville, Raudkivi 1996; Yanmaz, Altinbilek 1991). However, most of models require predefined conditions and can only be applied to certain types of bridges. In this study, a model that combines genetic algorithms and simulation technology is developed to estimate the scour depth around bridge piers by using the natural frequency of the bridge structure. The genetic algorithms are used to find the fitted generic formula that defines the relationship between the scour depth and natural frequency. In this chapter, using finite element analysis simulation of bridge natural frequency is introduced in the first part. Adoption of genetic algorithms to find the fitted generic formula between the bridge natural frequency and exposure depth is then described in the second section.

3.1. Simulation of bridge natural frequency

The structure natural frequency calculation is a motion of a dynamic problem, and the equation is:

$$M\ddot{X} + C\dot{X} + KX = F, \tag{1}$$

where M , C , and K – mass, damping, and stiffness matrices, respectively; X – the displacement vector; F – the external force vector. If the damping and external force is neglected, one obtains:

$$M\ddot{X} + KX = 0. \tag{2}$$

The displacement vector is assumed to be $X = \Phi e^{i\omega t}$, and Eq (2) changes to:

$$(K - \omega^2 M)\Phi = 0. \quad (3)$$

Eq (3) is a standard eigenproblem, where ω – natural frequency and Φ – modal shape.

To simulate the eigenproblem of bridge accurately, the foundation and soil cannot be ignored, since the bridge foundation often contains a large portion of the total structure. Especially for the scoured bridge, its natural frequency is sensitive to the exposure of the bridge foundation.

The total number of natural frequencies and modal shape is the same as the total number of degrees of freedom (NDF) of the finite element mesh. The subspace iteration method was used to solve the eigenproblem of Eq (2). The major advantage of this method is that the first N eigenvalues and eigenvectors can be obtained, where N is decided by users. For a finite element problem with large degrees of freedom, such as million or over, the subspace iteration method is efficient, since it is often required only by the first several modes, such as 40 to 60 modes. When the mode shapes of soil, foundations, and superstructures may be coupled together, but the measurement devices installed on the superstructures are able to obtain the natural frequencies of the superstructures. In this study, the effective mass above the soil surface is used to determine the natural frequencies of the superstructures. Further, the effective mass ratio represents the importance of this mode under the seismic load. If this value is large, such as 30%, this mode is categorized as a mode shape in that direction. The results are verified by the field experiment. Errors in the x direction and y direction are 2.64~4.58% and 1.42~4.99%. The finite element results are in an acceptable accuracy.

3.2. Genetic algorithms for fitting formula

From the above simulation method, one can change the parameters, such as soil distribution, foundation dimensions, and pier condition, to perform numerous finite element analyses and get bridge natural frequencies. However, huge numbers of data will be generated and will make it difficult to generate a universal formulation to predict the scour depth. Genetic algorithms (GA) are then applied to find an approximate relationship between the bridge natural frequency and the scour depth. GAs are search algorithms developed by Holland (1975), which are based on the mechanics of natural selection and genetics to search through decision space for optimal solutions (Goldberg 1989). In GAs, a string (chromosome combination) represents a potential solution to a problem. Each string is evaluated on its performance with respect to the fitness function (objective function). The crossover and mutation schemes will exchange the information (gene) between strings to produce various solutions, and a selection scheme such as roulette selects the strings (solutions). That string with the higher performance will be selected with higher probability.

The general form of equation is shown as:

$$Y = (X, \theta) + \varepsilon, \quad (4)$$

where Y – the dependent variable; X – a vector of independent variables; θ – parameter vector; ε – a random error.

(X, θ) can be displayed in various forms such as Eq (5) to make the fitting function more suitable.

$$Y_i = \theta_0 \sin(X_i^{\theta_1}) + \varepsilon_i. \quad (5)$$

As a result, a GA string that represents a potential solution for a fitting formula is used to determine the variables including θ , numerical parameters to adjust the dependent variable, and the transform functions such as the trigonometric function. The numerical parameter (θ) is displayed as Eq (6):

$$\theta = \alpha \cdot 10^\beta. \quad (6)$$

Set α is a number around -1 to 1 with acceptable precision, such as 6 decimal places. Also set β within an acceptable range, such as 0 to 3 and accurate to 3 decimal places. As a result, α and β are coded in binary. Then, the GA strings of θ are defined. For example, the bits (string length) required for α in this case are 21, since α equal size range is smaller than or equal to 221. The calculation formulation is shown in Eq (7):

$$2^{m-1} < (b-a) \cdot 10^d \leq 2^m, \quad (7)$$

where m – the required bits; b and a – the upper and lower bound of the range; d – the decimal places.

For the selection of transform functions, a one hundred percentage number is divided into equal parts to represent each of the transform functions. Then, a random number between 0 and 1 is used to determine the selection of transform functions by means of the location of the percentage. The random number is then coded in binary as the GA strings for transform functions selection.

Root mean square error (RMSE) is finally used to measure the performance of the GA solution. The fitness function is displayed as Eq (8):

$$\gamma = \sqrt{\frac{\sum E_i^2}{n}}, \quad (8)$$

where γ – RMSE; $E_i = (estimate\ value, Y_0 : real\ value)$; n – the number of data.

The error means the different between the result of the fitting formula and the scour depth which is simulated by finite element analysis. When the error is lower than an acceptable level, the GA process finishes and the formula is conducted.

A model that combines genetic algorithms and simulation technology to estimate scour depth of bridge piers by calculating natural frequency is introduced in this section. Using the natural frequency of bridge structure is an available way to prevent the devices under water destroyed by the flood. In order to build the model, a finite element mesh of the bridge is used; and through a series of

computer simulations by setting different conditions of the bridge, large numbers of natural frequencies are generated. Genetic algorithms are then applied to find an approximate relationship between the bridge’s natural frequency and the scour depth based on the simulation data and then by conducting the formula. Thus, the scour depth of the bridge is able to be computed in the field experiment by using natural frequency. The simulation results of bridge’s natural frequencies that change with scour depth are shown in Fig 2.

4. Web-based system structure

After the WSNs method and genetic model for bridge monitoring were developed, the aim of this study was to establish a web-system to combine those technologies. All monitoring information is integrated to develop a comprehensive assessment of indicators that effectively monitor bridge safety. The web-based system is developed through Analytic Network Process (ANP) with a 3-layer structure as shown in Fig. 3.

a. Resource access layer

The major objective of the resource access layer is to collect data from different chips to establish an integrated database. In the sub-structures the survey-based database contains the information of GPS observation, satellite time adjustment, and Doppler frequency measurement. This data is recorded as documentation. The WSNs-based database contains all the information collecting from the WSNs sensor with additional chips, such as accelerators, inclinometers, frequency, and coordinates. These data are transmitted from notes to the integrated database through control points. For the bridge management database, the information contains the fundamental information, the damage type of bridges, historic statistic data, and the suggested strategies.

b. Logic access layer

In the logic access level, those data collected in the resource access layer need to be transferred to useful information through appropriated application. The GPS and network mechanism are integrated as a survey module; the WSNs module contains wireless transmission, note configuration, and safety encryption mechanisms. The bridge integration module includes static and dynamic mechanic calculation, bridge structure analysis, and soil mechanic analysis. This system combines these logic calculation modules to develop the functions for users in the following presentation layer.

c. Presentation layer

There are three major functions including bridge searching, data monitoring, and safety warning in the presentation layer. The bridge searching module provides the foundational information and historic data of bridges. The historic data contain the reasons of the bridge disaster and the recovery and maintenance strategies. In the data monitoring module, the integrated database with the genetic calculating model provides the real time monitoring data, such as acceleration, deformation, and frequency. In the safety warning function, the bridge control chart involves the acceptable value of indicators for bridge safety evaluation.

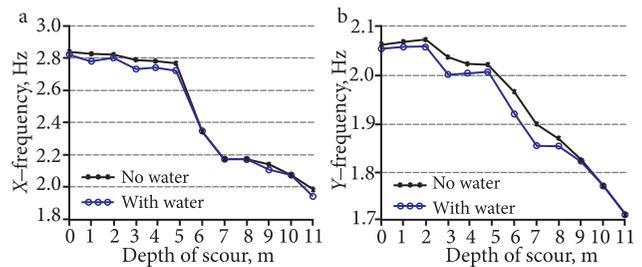


Fig. 2. Bridge natural frequencies changing with the scour depth: a – X direction (longitudinal direction); b – Y direction (transverse direction)

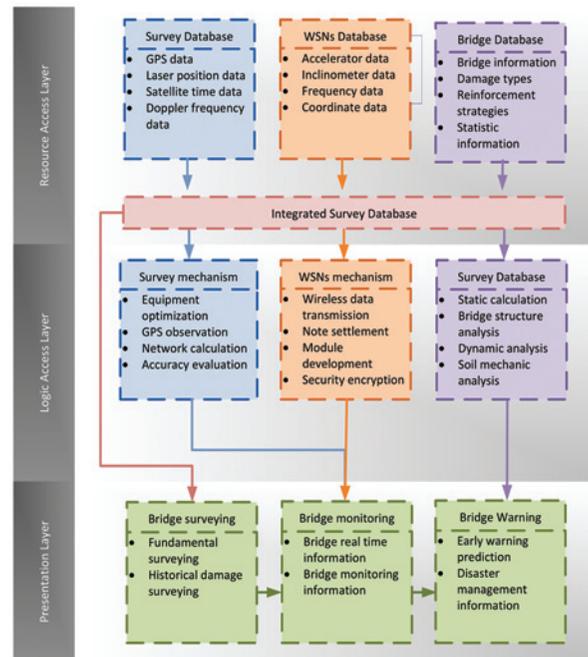


Fig. 3. Web-based bridge scours monitoring system structure

The system not only displays an early warning when the bridge is close to collapse, but also provides the response strategies needed to help managers to make decisions.

5. System application

The next step is to apply the integrated system to a real case. First, how to install the WSN sensors on the bridge is explained; then, the data from the sensors will be collected and converted from RS232 format to RJ45 format by a computer in the coordinator box. Through the 5G antenna device, the data will be transmitted from the coordinator box to the control room in a nearby police department. Finally, these data will be transmitted to the database server in the research institution through the Internet from the computers in the control room. The scour depth at the piers of the bridge will be estimated based on the data from the sensors by the genetic model in the database server. The calculating results of scour depth will be uploaded online immediately so that the engineers and the governors can realize the instant situation of the bridge.

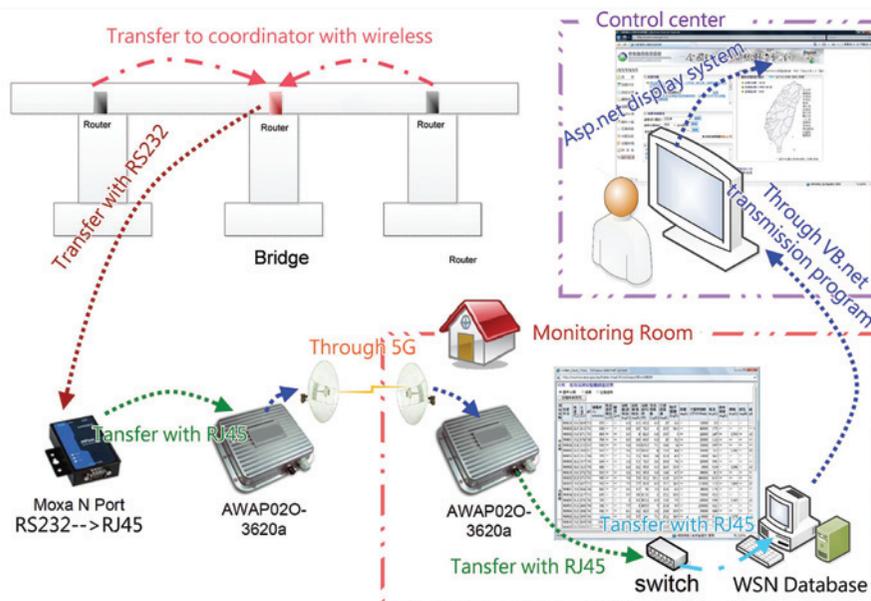


Fig. 4. The processes of the bridge scour monitoring system

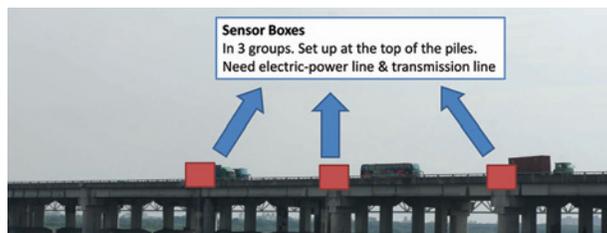


Fig. 5. The deployment diagram of the sensors

The detail developing processes of the scour monitoring system are described in the following sections and are shown in Fig. 4.

5.1. The experimental bridge

This study carried out a test of the scour monitoring system on Chung Sha Bridge (Fig. 5) which is located in Dou-nan Town of Yunlin County in Taiwan. The fundamental descriptions of the bridge are shown in Table 3. There are

two major reasons for selecting this bridge for the test. First, Chung Sha Bridge is one of the exposed foundation bridges caused by scouring recently, and thus it matches the scope of the research for developing a real time bridge scour monitoring system. Second, the National Center for Research on Earthquake Engineering of Taiwan (NCREE) is also preceding the related experiment in the bridge. The benefit of choosing Chung Sha Bridge as the experimental bridge in this study is to minimize the traffic disturbance through setting up the measuring instruments with NCREE together.

5.2. Sensor installation

In the sensor installation process, the information from the bridge was collected to know the scour depth at the piers of the bridge through bridge vibrating frequency. The accelerometers and inclinometers and GPS sensors are installed on the bridge deck, not on the piers of the bridge to prevent that the sensor will be damaged by flood. There

Table 3. Fundamental descriptions of Chung Sha Bridge

Latitude	23.818	Width of rectangular bridge piers	5.8 m
Longitude	120.477	Height of bridge piers	9.45 m
Construction year	1978	No. of foundation piles	26 piles
Structure type	Beam bridge	Material of foundation piles	Concrete
No. of Span	67 spans	Shape of foundation piles	Circular
Length	2355 m	Diameter of circular foundation piles	1 m
Type of bridge deck	Reinforced decks	Length of foundation piles	25 m
Width of bridge deck	15.22×2 m	Type of bearing	Elastomeric bearing
Angle of attack with flow	90 degrees	Type of foundation	Pile foundation
Material of bridge pier/pillar	Reinforced concrete	Type of channel	Braided channel
Material of bridge pier	Reinforced concrete	River land	P15-P27
Shape of bridge pier	rectangular	Soil property	Sandy soil layer

are a total three sensor groups in different locations. Each group includes 3-axis accelerometers, an inclinometer, and a GPS sensor. The deployment diagram of the sensors is shown in Fig. 5.

Due to the fact that the testing bridge in this research is in the intermediate part of a highway, how to maintain the sensors without blocking the traffic and keeping workplace safety are the important issues. There are two problems needed to be solved to avoid the chance of maintenance. The first one is how to keep the source of the power support of the sensors stable and transmitting the data consistently. Then, since the traffic will be disturbed when replacing batteries, a power switchboard was set independently for the monitoring system to provide power persistently. The other problem is how to make sure that the sensors have enough weather resistant ability to prevent damages by severe weathers, such as heavy rain and strong wind. In order to protect the sensors, a specially designed waterproof box (Fig. 6) made by fibre glass is used in this study. The box has a thickness of 4 cm for its bottom, 1.5 cm for its protection layer, and $-40\text{ }^{\circ}\text{C}\sim 110\text{ }^{\circ}\text{C}$ for its thermo stability.

5.3. Data transmission in coordinator box

The data from the sensors will be collected to the coordinator box with RS232 format in this process. There is the 5G antenna device included in the box. The installation process of the coordinator box is shown in Fig. 4. The coordinator combines the data from three sensor groups into a single file, and converts it to RJ45 format, and then transmits it via 5G antenna device and the Internet. For the same reason, the chance of maintenance was reduced in the previous section, and these devices were installed in a metallic box to improve the weather resistant ability of the equipment. This metallic box is also with a ventilation design below to avoid over-heating of the computer.

5.4. Data transmission in control room

After preliminarily processing the data, the computer in the coordinator box will transmit these data to the 5G antenna device. Although the 3.5G high-speed downlink packet access (HSDPA) has been developed for years, the stability of the signal is not as stable as the 5G antenna device. The 5G antenna device will send the data signal from the bridge to the control room in a nearby police department. Then the computer in the control room will transmit the data to the database server in the research institution through the Internet (Fig. 7).

There are two major advantages of setting the control room in a police department. First, the police department is open 24 hours a day and 7 days a week, thus, data collection and device maintenance can be done anytime. Second, the police department can be a local command centre. The decision maker can decide to evacuate, block the bridge, or execute other necessary actions in advance based on the information from the developed system.

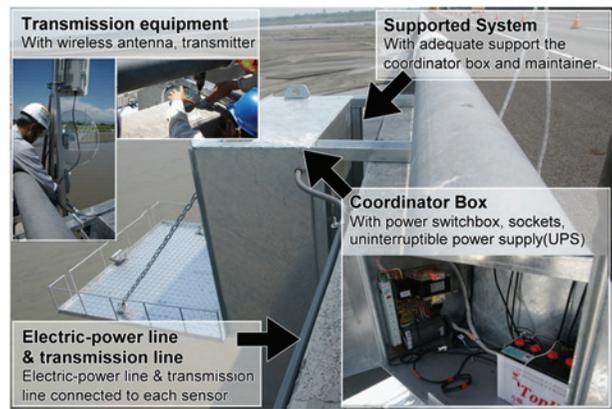


Fig. 6. The coordinator box diagram



Fig. 7. Data transmit process

5.5. System database server

A dynamic mathematical model is developed to estimate the scour depth at the piers of bridge by calculating the vibrating frequency of the bridge in the database server.

The result from the model will be shown on the web page of the scour monitoring platforms built on the database server. The sample result from the prototype of developed model is shown in Fig. 8.

6. Conclusion

Under extreme weather, the bridge is likely to collapse because of the long-standing scour at the piers. An instant bridge scour monitoring system is necessary to evacuate. This study builds a web-based real time scour monitoring system to provide action suggestions to engineers and bridge safety monitoring agency in government. The system is a decision support reference. The web-based system concept accomplishes the goal of real time data exchange. The genetic model for calculating scour depth provides the warning signal instantaneously; and the Wireless Sensor Networks are a flexible and powerful tool to ensure consistent data transmission during extreme weather conditions. The Global Positioning System with Non-Iterative Solution for Linear Transformations correction provides a high-accuracy and low-cost method for data collection. This study not only provides the results from laboratories, but also applies the developed



Fig. 8. The platforms of web-based bridge scour monitoring system

system in a real case. A number of obstacles were solved when the system was installed on the bridge. The experience of installation processes would be a valuable reference for future research. Although this study provides a novel research methodology for bridge scour monitoring, there are some limitations required to be overcome. First of all, the standards of warning still need to be clarified. The system works perfectly both in the laboratory and in bridge, but it can still be improved after collecting data on site. According to real data collection from the bridge, one is able to revise the proposed genetic model to provide calculation results and early warnings more precisely. This system provides a new structure of bridge scour monitoring system for disaster management. Finally, it is suggested that the future research focus on improving the system installation processes, such as better power supply, new Global Positioning System sensor and Wireless Sensor Networks technologies.

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