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DECISION SUPPORT SYSTEM FOR SAFETY WARNING OF BRIDGE – A CASE STUDY IN CENTRAL TAIWAN

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ABSTRACT
This study aims at developing the decision support system (DSS) for safety warning of bridge. In the DSS, real-time and forecasted radar rainfalls are used to predict flood stage, velocity and scouring depth around bridge piers for one to three hours ahead. The techniques adopted in the DSS include (1) measurement and correction models of radar rainfall, (2) a grid-based distributed rainfall-runoff model for simulating reservoir inflows, (3) models for predicting flood stages, velocities and scouring depths around bridge piers, and (4) ultimate analysis approaches for evaluating safety of pier foundation. The DSS can support the management department to decide whether they should close bridges or not during floods. The proposed DSS gave a test-run during Typhoon Morakot in 2009 in Dajia River Basin, central Taiwan. The results show the DSS has reasonable performances during floods.

INTRODUCTION
Most of the rivers in Taiwan are short and slope steeply towards the sea, which usually causes floods upstream of the basins when typhoons hit. These floods caused by typhoons seriously threaten the safety of the bridges across the rivers. How to prevent the disasters for protecting people’s life and property in the future is seriously considered by the bridge administrative department. This study aims at developing the safety warning of bridge (SWOB) DSS. This paper is organized in two main topics. The first topic describes how SWOB DSS is developed, including a general overview of its main procedures, structure, components and model used in it. The second topic is the application (preliminary test-run) of SWOB DSS in a case study area in central Taiwan to show how it supports decision-making of safety warning of bridge.

SWOB DSS: THE PROPOSED APPROACH
SWOB DSS is the proposed approach to address the issue of safety warning of bridge during floods. It constitutes a structured and instructive tool to help decision makers to issue “Safety!”, “Warning!”, or “No thoroughfare!” for bridges during floods. In order to describe the process of developing this approach, it’s helpful to understand the main steps of the decision making process related to the exercise of judging the safety of bridges during floods.
The process for supporting judging the safety of bridges and issuing the warning during floods is shown in Figure 1.

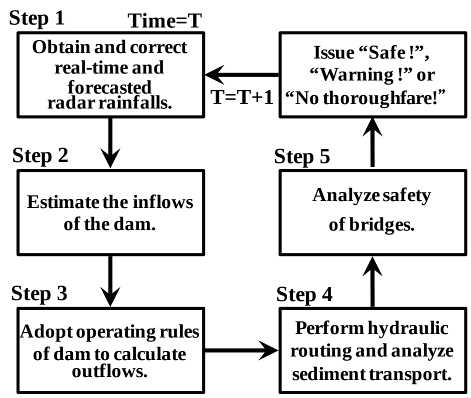


Figure 1. Process for developing and adjusting strategies.

In this process, it's organized into 5 basic steps. Step 1 is to obtain the real-time and forecasted radar rainfalls (one to three hours ahead) and correct their errors. Step 2 uses the corrected radar rainfalls as the input of a grid-based distributed rainfall-runoff model (GDRRM) (Yu and Jeng, 1997[1]; Wang *et al*., 2006[2]; and Wang *et al*., 2008[3]) for estimating the inflows of the control dam (Shihkang Dam). Based on the estimated inflows of the dam, Step 3 adopts the operating rules of the dam to calculate its outflows. Then, Step 4 performs the river hydraulic routing for the downstream of the dam to predict the flood stages and velocities of the downstream bridges, and analyzes the sediment transport for predicting the possible scouring depths around bridge piers during floods. Based on the aforementioned information of scouring depths around bridge piers, Step 5 is to analyze the safety of bridges and decide whether the bridges should be closed or not.

The main components of SWOB DSS are the database, the 5 modules, and the web-GIS platform with a user-friendly interface.

Database: The database provides the input data including the physiographic data upstream of the dam, raingauge rainfalls, radar rainfalls, inflows/outflows of the dam, downstream flow discharge, etc.

Module 1: Error correction for radar rainfalls. The module receives the real-time and forecasted radar rainfalls (one to three hours ahead) and performs the support vector machine regression (SVR) model for constructing the error correction model. For enhancing performances of the SVR, the SVR coupled with the Kriging method was adopted in the DSS.

Module 2: Calculating inflows of the dam. The module receives the corrected real-time and forecasted radar rainfalls (one to three hours ahead) from Module I as the input of the GDRRM for estimating the inflows of the dam.

Module 3: Calculating outflows of the dam. This module uses the operating rules of the dam to calculate its outflows based on the inflow from Module II. The operating rules of the dam can be gained from its management authority and are programmed into "if-then" statements to relate the inflow and the outflow.

Module 4: Predicting stage, velocity and scours. This module performs the river hydraulic routing (CCHE1D model) for the downstream of the dam to predict the flood stages and velocities of the downstream bridges, and performs the sediment transport model for getting possible scouring depths around the bridge piers during floods.

Module 5: Analyzing safety of bridges. The ultimate analysis approaches were used to evaluate the safety of pier foundation for providing failure envelops considered scouring depth, river velocity and water level. In the module, the failure envelop for each pier is embedded for assessing the safety of bridge.

Web-GIS platform: The platform integrates the former 5 modules and has a user-friendly interface for controlling all the module functions and displaying the real-time and forecasted results of the flood stages and velocities of the downstream bridges, possible scouring depths around the bridge piers during floods, and the essential information for the decision-support of issuing the warning.

SWOB DSS procedures and structure are displayed as shown in Figure 2. The proposed SWOB DSS can be used to support judging the safety of bridges and issuing the warning during floods.

STUDY AREA

The study area is Dajia River Basin (Figure 3). Dajia River is a river in central Taiwan and experienced frequent floods during typhoons and heavy rain. The main bridges across Dajia River are the bridges of Taiwan Provincial Highway No.1 (BR1), National Freeway No. 1 (BR5) and No. 3 (BR3), Taiwan Railways (BR2 and BR6), and Taiwan High Speed Rail (BR4). In the basin, there are six reservoirs/dams, from the west to the east including Techi Reservoir (R1), Ching-Shan Dam (R2), Kukuan Reservoir (R3), Tienlun Dam (R4), Maan Dam (R5), and Shihkang Dam (R6). These reservoirs/dams are mainly used for generating hydroelectric power.

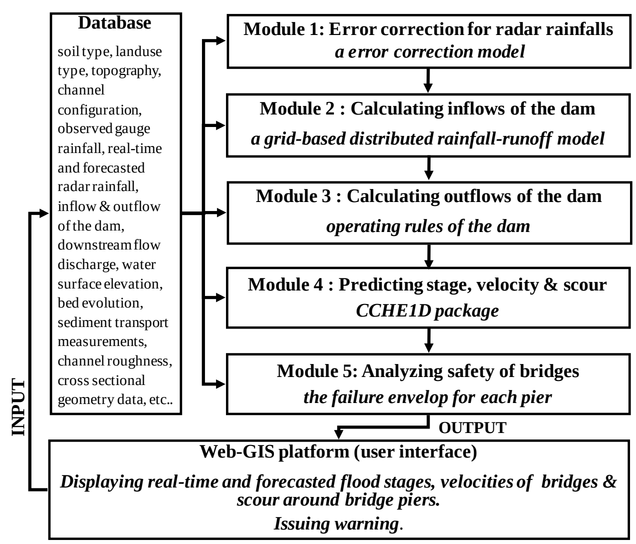


Figure 2. Overview of SWOB DSS procedures.

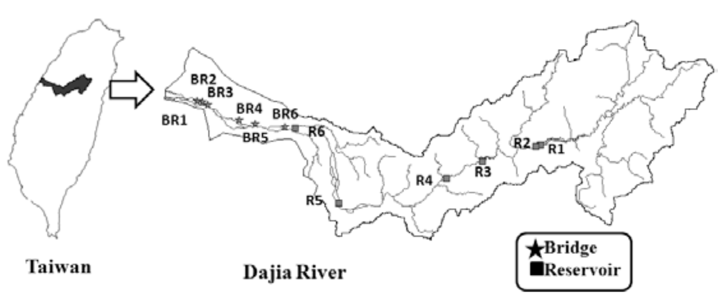


Figure 3. Study area.

RESULTS OF DSS PERFORMANCE

1.The error correction model for radar rainfalls

Radar rainfall estimates have a spatial resolution of about 1.25×1.25 km^2, and a temporal resolution of 10 min. The present radar rainfall estimates were underestimated, despite the facts that the precipitation estimation system already used algorithms to remove noise effects and continuous improvements are made. In the study area, hourly rainfall data from 14 ground raingauges provide the ground-truth data for adjusting the radar rainfall estimates. Table 1 lists nine typhoon events, which have noticeable rainfalls in the study area.

Nine radar rainfall estimates at the adjacent grids corresponding to the raingauge (Liu *et al*., 2001[4]), the coordinates of latitude and longitude of the raingauge, the distance between the raingauge and radar are as the input variables for error correction. Model performance is assessed by two indices: the root mean square error (RMSE) and the correlation coefficient (CC) of the observed ground rainfalls and the adjusted radar rainfalls.

After correcting by the SVR, the CC increased from 0.5 to 0.72 and the RMSE decreased from 10.81(mm/hr) to 7.93(mm/hr), which reveals that the SVR can correct the underestimation of radar rainfall volume for the calibration events. In the validated events, the CC increased from 0.51 to 0.61 and the RMSE decreased from 11.01(mm/hr) to 8.92(mm/hr). For improving the performance by using the SVR, the Kriging method was used to execute the second correction. The rainfall data at 35 raingauges (i.e., calibration raingauges) in or nearby Dajia River Basin were used for spatial error correction by the Kriging method. The other 5 raingauges were used for validation. During Typhoon Matsa, only the correction results during 19-22 hours were demonstrated (Table 2) and revealed that the correction performances are apparently improved by using the Kriging method. Therefore, the SVR coupled with the Kriging method was adopted in Module 1.

Table 1. Calibration and validation events for the SVR

Typhoon		Period (year-month-day-hour)
Calibration	Matsa	2005-08-04-05~2005-08-05-04
	Fung-Wong	2008-07-28-03~2008-07-29-02
	Jangmi	2008-09-28-17~2008-09-29-16
Validation	Haitang	2005-07-18-24~2005-07-19-23
	Talim	2005-08-31-16~2005-09-01-15
	Bilis	2006-07-13-12~2006-07-15-11
	Sepat	2007-08-18-20~2007-08-19-19
	Krosa	2007-10-06-05~2007-10-07-04
	Sinlaku	2008-09-14-05~2008-09-15-04

Table 2. Comparisons of raingauge rainfall and radar rainfall before and after correction for calibration and validation events, respectively, by the kriging method.

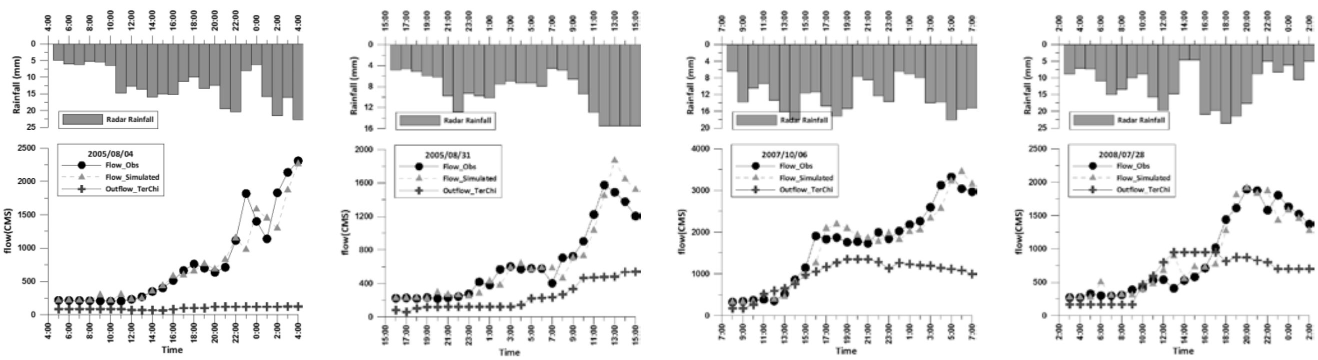
		The 19th hour		The 20th hour		The 21st hour		The 22nd hour	
		before	After	before	After	before	After	before	After
Calibration events	CC	0.29	1.00	0.42	0.99	0.67	1.00	0.44	0.98
	RMSE(mm)	6.61	0.52	4.56	0.57	21.51	2.09	16.49	3.09
Validation events	CC	0.99	0.97	0.93	0.99	0.63	0.92	-0.39	0.87
	RMSE(mm)	7.24	2.68	5.89	2.39	14.81	10.35	21.63	8.17

2.Grid-based rainfall runoff model

The study chose the upstream catchment of Shihkang Dam for rainfall-runoff modeling. The GDRRM was used for simulating the inflows of Shihkang Dam. The model was calibrated and validated by using historical typhoon events.

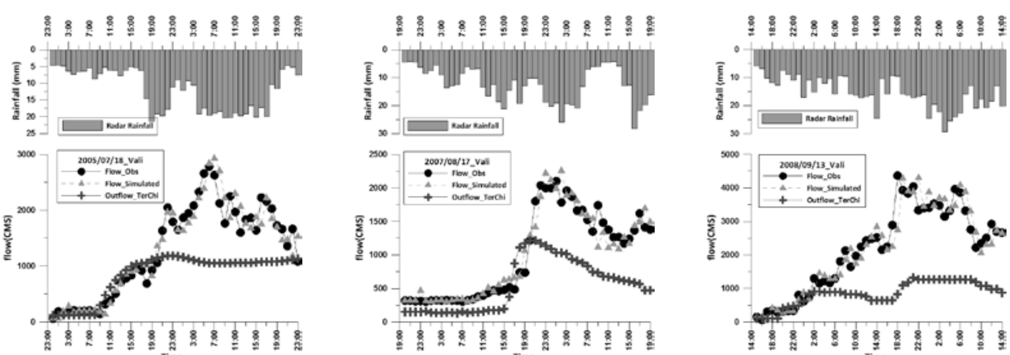
The GDRRM (Yu and Jeng, 1997[1]) includes three components: estimation of watershed characteristics, infiltration model and flow governing equations. The catchment was divided into a 1km×1km grid-based mesh. Rainfall data for each grid were provided by radar. The GIS software was adopted to determine catchment characteristics (i.e., soil type and land use) and the geometry (i.e., topography and channel configuration) for each grid. The land use classification data analyzed by FORMOSAT-2 satellite images. Both of the soil type and land use in each grid can be used to determining Manning's roughness coefficient (Manning's n) and infiltration capacity for the model. The digital elevation data are used for determining topography. Details of the GDRRM can be found in the literatures of Yu and Jeng (1997)[1], Wang *et al*. (2006)[2], and Wang *et al*. (2008)[3].

The study used four typhoon events, including Matsa, Talim, Krosa and Fung-Wong for model calibration. The coefficient of determination, R^2, between observed inflows and simulated inflows is higher than 0.7 for each calibration events. The calibration results are reasonable (Figure 4). Further, the study used the typhoons, Haitang, Sepat and Sinlaku, for model validation. The validation results are also reasonable and shown in Figure 5.



(a) Typhoon Matsa (b) Typhoon Talim (c) Typhoon Krosa (d) Typhoon Fung-Wong

Figure 4. Calibration results of the GDRRM.



(a) Typhoon Haitang (b) Typhoon Sepat (c) Typhoon Sinlaku

Figure 5. Validationresults of the GDRRM.

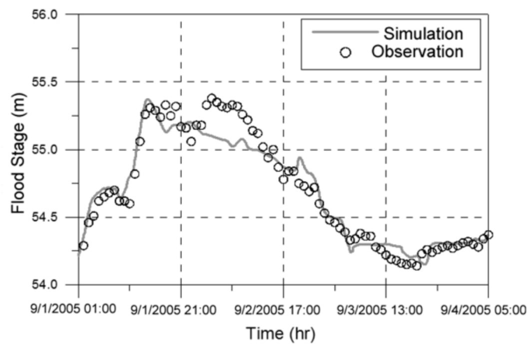


Figure 6. Observed and simulated hydrographs of water level during Typhoon Talim.

3.CCHE1D

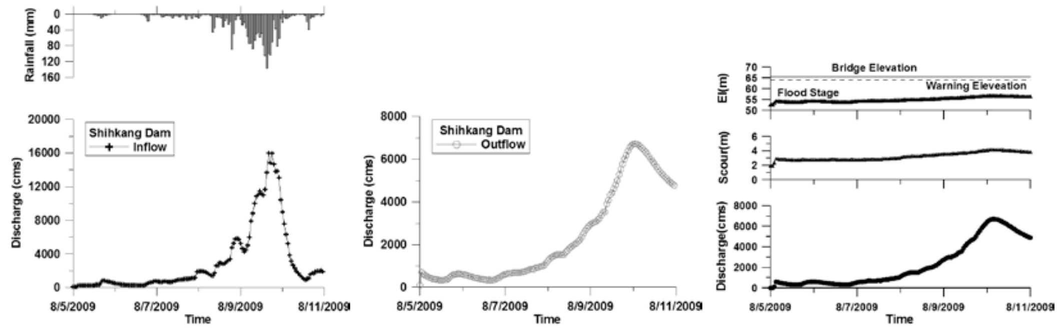
Module 4 comprises the execution files of CCHE1D package. CCHE1D has the dynamic flow model for flood routing and the sediment transport model.

The river range for the dynamic flow model for flood routing is from the outlet of Shihkang Dam to the river mouth, which has a length of 23.24 km. The gauge under Dajia River Bridge of Taiwan Provincial Highway No.1(BR1) during Typhoon Talim in 2005 was used for calibrating the dynamic flow model. It's found that the observed and simulated hydrographs of water level are close as shown in Figure 6, which reveals the dynamic flow model has reasonable simulation for flood routing.

Pier scour includes general scour, local scour, and constriction scour. The sediment transport model was calibrated here before application. The calibration data are as follows. The historical scour data were collected from the spot experiment of washing out bricks under BR1 during Typhoon Sinlaku. The scour depth was 2.3 meters. The sediment transport formula derived by Wu *et al*. (2000)[5] was chosen and has been tested to have reasonable prediction results in Dajia River. The estimated maximum general scour downstream of the experimental spot was 2.5 meters, which was close to the measured value of 2.3 meters. It reveals that the sediment transport model can reasonably predict the scour of the river.

4.Test Run of DSS for Typhoon Morakot

Typhoon Morakot during 2009/08/05 to 2009/08/10 hit Taiwan badly and brought torrential rain which broke the highest record of the southern Taiwan. The case study used the approach of storm transposition to transpose Typhoon Morakot from its occurring position (a storm center in Mountain Ali in southern Taiwan) to this study area. The objective of the test run is to examine the early warning ability of SWOB DSS and check the safety of bridges in Dajia River under the hypothesized scenario (i.e., the storm center of Typhoon Morakot occurs in the study area).



(a)Rainfall and Inflow of Shihkang Dam

(b)Outflow of Shihkang Dam

(c) Flood stages, Discharges, and Scouring Depths of BR1

Figure 7. Hydrogram during the Hypothesized Typhoon.

During the hypothesized typhoon, SWOB DSS received the real-time radar rainfalls and corrected the radar rainfalls as the input of the GDRRM for calculating the inflows of Shihkang Dam. The rainfall histogram in the catchment of Shihkang Dam and the inflow during the hypothesized typhoon are shown in Figure 7(a). After the inflows of Shihkang Dam were estimated, the operating rules of the dam were used to calculate its outflows as shown in Figure 7(b). Then, CCHE1D was performed for the downstream of the dam to predict the flood stages and velocities (or discharges) of the downstream bridges, and possible scouring depths around the bridge piers. Among the bridges across Dajia River, BR1 is illustrated here to display the flood stages, discharges, and scouring depths as shown in Figure 7(c). Ultimate analysis were used to evaluate the safety of pier foundation for providing failure envelops considered scouring depth, river velocity and water level. Fortunately in this case, the analytical results reveal that all the piers of bridges across Dajia River were safe under the hypothesized scenario, which means the bridges designed for Dajia River were able to endure this kind of huge flood.

CONCLUSIONS AND FUTURE STUDIES

This study proposed a SWOB DSS for safety warning of bridge. In the DSS, real-time and forecasted radar rainfalls are used to predict flood stage, velocity and scouring depth around bridge piers for one to three hours ahead. The analytical information of the DSS can be provided to the bridge administrative department for the early warning of bridge damage, or say, to decide whether they should close bridges or not during floods. The proposed DSS gave a test-run during Typhoon Morakot in Dajia River Basin, central Taiwan. The results show the DSS has reasonable performances during floods and all the piers of bridges across Dajia River were safe under the hypothesized scenario (i.e., the storm center of Typhoon Morakot occurs in the study area).

The presented paper reinforces the importance of constructing a DSS for safety warning of bridge and demonstrating a case study of the DSS. Future works may consider the other basins for further test the practicability of the DSS.

Acknowledgments, appendices, and references

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