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The Coastal Hazards Warning System Based on the Operational Wave and Storm Surge Models

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ABSTRACT

Taiwan is frequently hit by typhoon and suffers coastal hazards such as coastal flooding, sea dyke breaking, ocean pollution, coastal erosion etc. These disasters cause enormous damage and result into severe consequences due to the over-exploitation of coastal area. The government is responsible to minimize the loss occurring due to maritime hazards in the coastal area.

One of the problems for coastal hazard mitigation is that there is insufficient information for decision making. A decision support system (DSS) for government to prepare and respond to coastal hazards is urgently needed. The DSS contains several components such as the real-time in-situ observation net, the numerical forecasting models and the decision model. These components are probable exist nowadays. However, how to integrate these components to build the decision support system is considerable and necessary. The purpose of this paper is to study the integration of in-situ data and numerical models to establish a coastal hazard decision support system for disaster mitigation applications.

KEY WORDS: Coastal hazard; Operational model; Decision support system

INTRODUCTION

According to the result counted by the United Nations, between 1967 and 1987, various kinds of natural disasters caused 2.8 million people's death in all parts of the world and the direct economic losses were up to several hundred billion dollars. Today, because of population explosion , economic growth , Hi-Tech developing sharply and human destroy the environment wantonly, the intensity of different natural calamity are becoming more serious. So no matter the death toll in different fields,the frequency , the lose caused by the calamity have the tendency to rise day by day. Therefore the United Nation declared that it is the 「the decade of precaution or preparedness against natural calamities」 from A.D. 1990 to 2000. They hoped all countries can promote their engineering level to develop a suitable method for assessing , predicting and disaster relief of disasters by utilizing existing scientific and technology knowledge.

Due to the abundance resources in various kinds ocean offer functions in many ways to mankind, the costal ocean area has been developed the center of economy, society, and culture. Under the circumstances caused by natural factors , such as wind , wave , tide ,and current for a long time, the topographical of coast has changed all the year round and the coast calamity incidents happen frequently. For example, Taiwan is an island type country with the special geographical environment. Coast receives the direct impact by deep sea of billow often in the East; storm surge attacts in the west. In this reason, inundations by the sea always happen in the coastal area when typhoons attact Taiwan. So how to promote the combining relevant work of disaster relief systematically to prevent and reduce the lives and properties that the calamity may cause, have already become one of the present primary work of Taiwanese government.

In order to understand the change of real environment thoroughly is the most important task for reducing natural disaster. The long-range inshore hydrological data is the basis for preventing and curing of coastal disaster. Monitoring of inshore hydrology is the most important reference to deal with an emergency on the sea and maritime activity. Walrus' dynamic prediction is also an important information that the calamity can be prevented even more. In the present stage, understanding of the marine environment can go on form two respects of in-situ measurement and Numerical Forecasting Model The calculation of the numerical model subdivides the grids of model or increases the times of calculate times in order to increase the accuracy of the result. But this process always cost a lot of time in numerical operation. In-Situ measurement is limited to various factors, such as systematic design, transmission channel, power system, etc. So it is unable to offer the in-situ data immediately for rescuing or revising the model's parameter. Hazard warning and rescuing which is a work of racing with time must pay great attention to statute of limitation and mobility. If the offering of the information is unable to go on immediately, it will result in lose of the timing to rescue. Therefore how to make balance between accuracy and statute of limitation and how to offer the in-suit data immediately is the one of difficulty that need to solve against coastal calamities at present. Coastal hazard warning is an issue that has to consider in many aspects and it can't go on with the single opinion. It needs an intact theory which can aim at influencing the factors of coastal hazard in many ways and intersecting analysis in order to get the best decision scheme against coastal hazard. The purpose of this research is utilizing the decision theory and combining the numerical prediction and in-suit data to establish an operational coastal hazard warning system which can provide many aspects information to promote the efficiency of rescuing.

DECISION MAKING SYSTEM OF COASTAL HAZARD WARNING AND RESCUE

An excellent decision system of coastal hazard warning can offer meteorological situation of coast while coastal hazard happens. If the system can propose warning before the hazard takes place, it can avoid calamity or lighten the severity of calamity. So the decision making system of coastal hazard warning developed in this paper is based on the decision theory. It is combined with the observed data and numerical simulation results to offer the intact coastal meteorological phenomena. Now it carries on the simple explanation to every factor in the system applied in this text, including the in-situ measurement system, numerical model and decision theory.

In-Situ Measurement

On technical level, coastal marine environment monitoring system comprises two subsystems: In situ realtime monitoring network subsystem and data management subsystem. Of which the former transmit the data measured on the field to the data centre. The later undertakes data quality control, database pooling, operational prediction and data report service at the data centre.

The approaches of coastal marine monitoring could be categorized as the remote sensing and In-Situ measurements, as shown in Table 1. The satellite remote sensing has its limitations on the operational monitoring due to its long return periods. The airborne operations are comparably costy. As the underwater wireless data communications are restricted, the bottom mount instrumentations are not capable of deliver the data in realtime. Considering the previous mentioned requirements of operational coastal watch network, the data buoy is regarded as the most frequent used instrumentations. The moored data buoy has the following characteristics over other methods to be regarded as the main observation method: (1) data buoy can be applied in water depths ranging from thousands to tens of meters; (2) floating on the surface, buoy can fully benefit from satellite communication and broadband wireless data transmission technology for deployment in any ocean region; (3) data buoy need not depend on submarine lifeline to provide energy, and has sufficient buoyancy to carry the weight of various instruments, equipped with high expendability.

Concerning the wave monitoring, the six degree of freedom accelerations and inclinations that record buoy movement with wave can yield wave directional spectrum via cross-spectrum analysis, describing wave energy's distribution characteristics on frequency and propagation direction, providing greater precision in building weather forecast model and the application of data assimilation technology.
As the intensity of wireless radio wave for communication quickly abates in water, to assure realtime data transmission from interruption in extremely adverse sea conditions due to excessive signals from moisture and spray, planning of the monitoring system should be emphatic of multi-route data transmission mechanism, allowing data to choose one channel from wireless transmission, GSM wireless communication, broadband bluetooth communication or satellite communication to send the data back to the control centre as shown in Figure 1.

Table 1 Methods of Coastal Environment Observation

	Payload	Observations
Remote Sensing	Satellite	SAR
		Altimeter
	Airborne	Scattemeter
		Stereophotography
	Lane Based Marine Radar	X-band Radar Images
In-Situ Measurement	Platform	Directional Waves
		Tide
	Data Buoy	Current
	Ship	Marine-Meteorological Factors
		Water Quality
		Bio/Ecological Factors
		Waves
	Bottom Mount	Current Profile
		Sedimentation

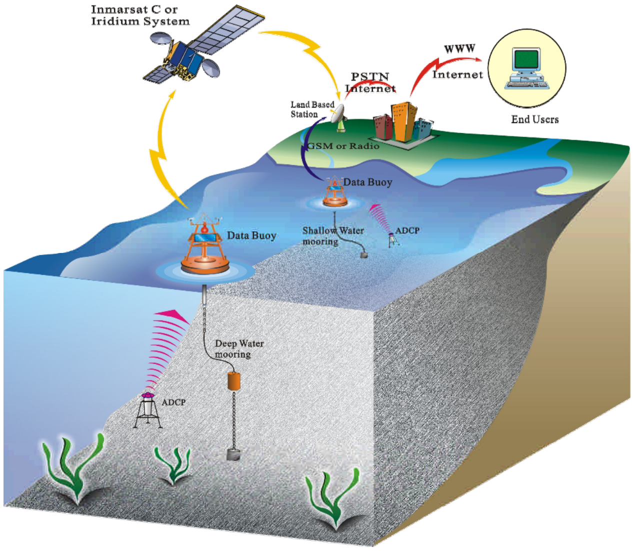

Figure 1 The Multi-routes Real-Time Data Transmission

Numerical Forecasting Models

In order to describe the change of coastal water level, we define the water level as total of half of wave height, astronomy tide and storm surge. Therefore the models we apply in this text are included with wave model and tide model. Those models are all public and free.

Wave Model

The recently developed SWAM model for near-shore wave simulation is selected for this present study. In SWAM wave model the evolution of the wave spectrum is described by the spectral action balance equation for Cartesian coordinate as follows:

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial x}C_x N+\frac{\partial}{\partial y}C_y N+\frac{\partial}{\partial \sigma}C_\sigma N+\frac{\partial}{\partial \theta}C_\theta N=\frac{S_{total}}{\sigma} \qquad (1)$$

Where σ is the relative frequency, θ is the wave direction, N is the wave action density and is equal to the energy density divided by the relatively frequency: $N(\sigma,\theta)=E(\sigma,\theta)/\ \sigma$, and $E(\sigma,\theta)$ is the wave energy density. Eqs. 1 is an approximation with simple bottom topography and current distribution. In Eqs. 1, the first term of left-hand side represents the local rate of action density in time. The second and the third terms represent propagation of action in geographical space with propagation velocities C_x and C_y in x- and y- space, respectively. The fourth term represents shifting of the relative frequency due to variations in depths and currents with propagation velocity C_σ in σ-space. The fifth term represents depth-induced and current-induced refraction with propagation velocity C_θ in θ-space. The term S_{total} at right hand side of the action balance equation is the source term in terms of energy representing the effects of generation, dissipation and nonlinear wave-wave interactions.

In this study, all default values of physical parameters in SWAM model are adopted since the primary object of this study is to generally evaluate the applicability of SWAN for typhoon waves. The integration of the action balance equation has been implemented in SWAN wave model with finite difference schemes in all five dimensions (time, geographic space and spectral space).

Tide Model

POM, which was proposed by George L. Mellor & Alan Blumberg in 1977, is a fully three dimensional ocean circulation model. The computational scheme of splitting mode is applied in POM to integrate the barotropic (external mode) and baroclinic (internal mode) equations at their respective time steps so as to reduce the computation time. Based on the assumptions of static equilibrium and Boussinesq approximation, the simplified governing equations in the Cartesian coordinate can be expressed as Eqs. 2 and Eqs. 3.

The equation of continuity:

$$\nabla \cdot \vec{V} + \frac{\partial W}{\partial z} = 0 \tag{2}$$

The equation of momentum:

$$\frac{\partial U}{\partial t} + \vec{V} \cdot \nabla U + W\frac{\partial u}{\partial z} - fU = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(K_M \frac{\partial U}{\partial z}\right) + F_u \tag{3}$$

$$\frac{\partial V}{\partial t} + \vec{V} \cdot \nabla V + W\frac{\partial V}{\partial z} + fV = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(K_M \frac{\partial V}{\partial z}\right) + F_v \tag{4}$$

$$\rho g = -\frac{\partial p}{\partial z} \tag{5}$$

Decision Support System

Decision support system proposed by G.A. Gorry and M.S. Scott Morton in 1970’s. It was defined as 「interaction computerized system that help policymaker to solve the non-structural problem by utilizing materials and models」. In other words, it’s main characteristic is a interactive computer-based system to help policymaker to solve the non-structural problem by utilizing materials and models. Therefore decision support system can help policymaker for obtaining materials and attempting on the methods of different settlement during the process of solving the problem.

Decision support system is a kind of limited analytical method. On the premise of some limiting conditions, it can bring up different solution to paint the rout of reaching the goal. Decision support system is the combination of tools, materials, and technology. The propose is to help the administrator to extempore decision. The meaning extempore refers to during the process of making policy and making, change some specific and unable to predict in advance information needed because of the situation.

Among many kinds of decision support system, the systematic dynamics was developed by Jay W. Forrester in 1950’s, which combined system theory, cybernetics, servo-mechanism, information theory, decision theory and computer simulation. Systematic dynamics is a research method which leads by process, and it is good at dealing with a large number parameter, high-order non-linear research of system. The feedback relation of cause and effect in the system is intimate. For example, the 「World Dynamics Model」 which is to study questions , such as world population , activity in production , polluting , natural resources ,etc. (Forrester, 1973), study city develop dynamic ' city dynamics way ' (Forrester , 1969) ,etc.. The application of this systematic dynamics is very extensive, including ecology, economy, society, organization , management , environmental protection ,etc..

OPERATION OF NUMERICAL FORECASTING MODELS

The prevent and rescue of coastal hazards emphasize the statute of limitation, so an operation of warning system must control all message as soon as possible. Generally speaking, the higher of the analysis degree of numerical models, the more correct of the simulation result is. However the cost of calculation time will increase relatively. So how to obtain the accurate numerical simulation result in order to reach the operation degree within limited time is the main question of this text.

Model Accuracy

The SWAN model includes more flexible options on the parameters for processes such as non-linear wave-wave interactions, wind wave generation, energy dissipations by breaking and friction, frequency shifting due to local topographical conditions. Many researches have given suggesting parameters for SWAN. However, it’s difficult to find one set parameter good enough for all the cases. For example, the topography is much different between eastern and western coasts and the marine environment is also much different during monsoon season and during typhoons.

For post-research purpose, people can adjust the parameters case by case to find the perfect simulation results. However, for the operational purpose, there is not enough time to try and find the best parameters. To decide one set parameter which considers the model overall accuracy is very important for model operational.

Therefore we put the different parameters into the SWAN to find out the best parameters used in simulating the wave around Taiwan water. For example, the Fig 2 and Fig 3 are the results by using Komen’s recommendation on whitecapping parameter. The Fig. 4 and Fig. 5 are the results from Janssen’s parameters. In these figures, the solid points are the in-situ filed data, the line is the simulation result from models. The Fig. 2 and Fig. 4 are results from Chiku station and the Fig. 3 and Fig. 5 are the comparison results from Hsinchu station. All of them were during typhoon Cheibi in year 2001.

From Fig. 2 and Fig. 3, it is found that the root mean square error which is 12% at Chiku is better than which is 24% at Hsinchu by using Komen’s whitecapping parameter; however, inverse result is found when uses Janssen’s suggest parameter. In other words, if we use Komen’s parameter, we obtain better wave simulation result for southern Taiwan coast but low accuracy result for northern Taiwan coast, there is reverse results by using Janssen’s parameter.

Therefore, how to decide one feasible parameter set should be faced. For operational model, we think the parameter set that can lead to average good performance at all stations is the best. By similar study, different parameter sets are used to find the best one. The result is shown in this table 2. By using the suggesting parameters, no certain station has very high validation errors and also no certain station has very low errors. For several typhoons validation, the lowest root mean square error is 8% and highest error is 24%. This Fig. 6 and Fig. 7 are the validation example during typhoon BILIS. This error level is still within the acceptable range for an operational model.

Table2 The parameters are used in this paper

Source terms	Theory of source terms of SWAN
Linear wind growth	Cavaleri & Malanotte-Rizzoli(1981)
Exponential wind growth	Komen et al.(1984)
Whitecapping	Komen et al.(1984)
Quadruplet interaction	Hasselmann et al.(1985)
Triad interaction	Eldeberky(1996)
Depth induced breaking	Battjes & Stive(1985)
Bottom friction	Hasselmann et al. JONSWAP(1973)

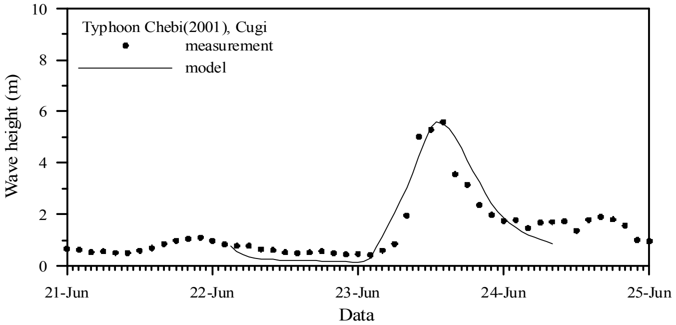

Figure 2 The results using Komen's recommendation on whitecapping parameter are in Chiku during typhoon Chebi.

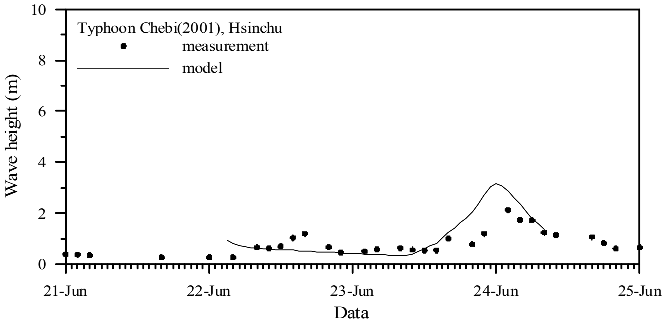

Figure 3 The results using Komen's recommendation on whitecapping parameter are in Hsinchu during typhoon Chebi.

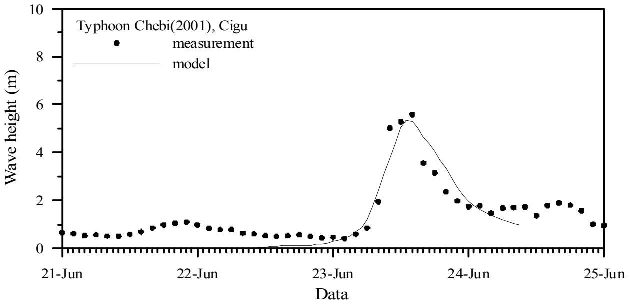

Figure 4 The comparison results from Chiku station are used Janssen's suggest parameter during typhoon Chebi.

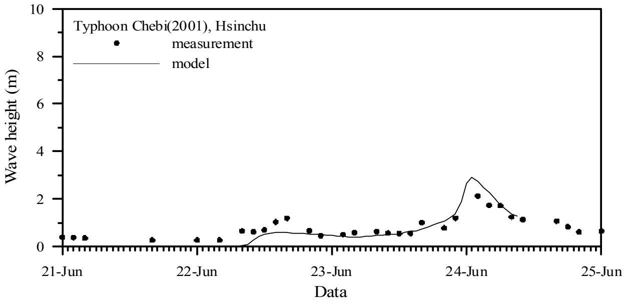

Figure 5 The comparison results from Hsinchu station are used Janssen's suggest parameter during typhoon Chebi.

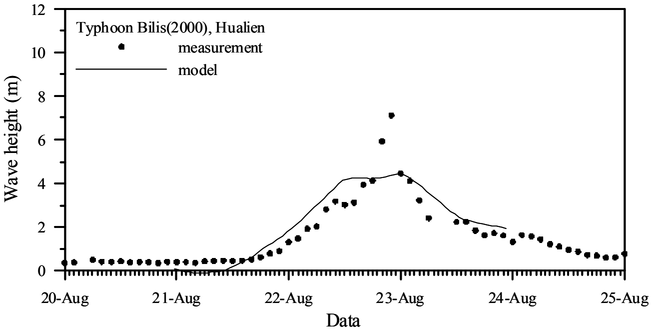

Figure 6 Simulation result of wave height(at station Hsinchu during typhoon BILS, 2000)

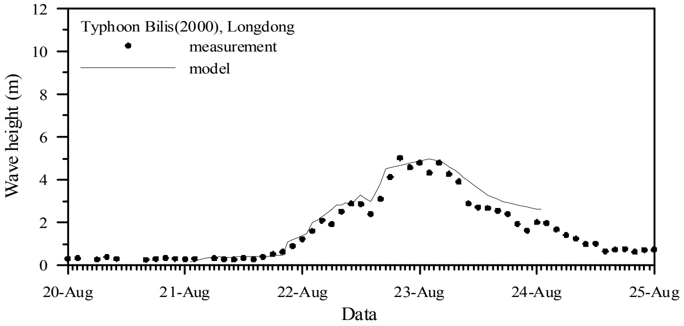

Figure 7 Simulation result of wave height(at station Longdong during typhoon BILS, 2000)

Model Operation Time

The main purpose of this paper is to establish an operational decision making support system for coastal hazard rescuing. We hope this system can simulate the coastal wave level correctly. Therefore to ensure the system can work stably and save the calculating time when the models are running. We discussed computer hardware of system, time step of model and the grid size.

Generally speaking the grid solution is higher, the change of topography can be reflected more accurate. The time that is model working needs increases relatively. The operational warning system must control limiting of time, so we must get the balance between the correction and limiting of time. Therefore in this text we compare the correction of predicted result and the time of model used on the different grid setting. Table 3 and Fig. 8 show the compared result. It is found since the error for forecasting next 1 hour waves is only 12% when the grid size is 9km, but it takes 5.3 minutes computation time.

By using 36km grid size, it takes only 0.6min, but the error is up to 48%. By general adjustment, 18 km is the best grid size for this case.

Table 3 The computation time and root mean square error for various model grid size

Item \ Grid solution	20’	10’	5’
Computation time	0.6 min	1.2 min	5.3 min
Root mean square error (%)	48 %	14 %	12 %

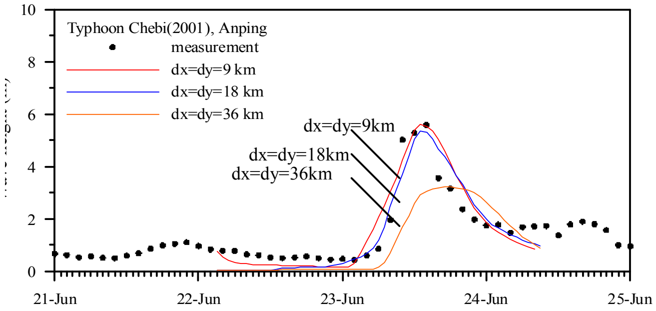

Figure 8 Comparison of model results by various grid size

Coastal Water Level Warning System (COWLEWIS)

It is necessary to setup an interface to “use” the model results, even in-situ measurements, especially for decision-making people who are always don’t much know technology. A Coastal Water Level Warning System, called COWLEWIS, is established under the support from Water Resources Agency of Taiwan. The main page of the system is shown in Fig. 9. It is a Chinese and Homepage-based version. This system includes four parts. The first part is located in the middle of the interface. They are the real-time field data which are measured from the national coastal ocean monitoring network. The field data contain wave, tide, current, wind, water and air temperature, pressure, etc. It updates every hour. The second part of the interface is the coastal water level estimated from numerical models by formula (6). The results are shown in the upper left and right table of the interface. The coastal water level is compared with the height of sea dyke (also shown in the interface) to assess if it will be flooded at certain location along Taiwan coast.

$$\begin{aligned} \mathit{Coastal\ water\ level} &= \mathit{wave\ height}/2 \\ &+ \mathit{astronomu\ tide\ height} \\ &+ \mathit{storm\ surge\ height} \\ &+ \mathit{wave\ set-up\ height} \\ &+ \mathit{wave\ run-up\ height} \end{aligned} \tag{6}$$

The third part of this interface is the experiences from historical hazard event induced by typhoons which have similar path and strength. The information is shown in the lowest area of the homepage. Sometimes, experiences are more referenced than numerical results. The last part of the system is the real-time live video from the field site. It is easily found in the interface. COWLEWIS integrates the real-time in-situ data and video, numerical forecasting results and historical experiences. It is used by Water Resources Agency of Taiwan for one year. The decision maker can receive any information by this system via Internet.

Operational requirements

The flowchart of operational route of the coastal water level warning system is shown in Fig. 10. It is begun from the input of wind field. The wind field is forecasted by atmospheric model which is supported by the Central Weather Bureau. It is the requirement data for numerical wave model and storm surge model. In this study, the storm surge is also estimated by an alternative statistical model. The total water level is estimated by formula (6). Besides water level estimation, the in-situ data, video and historical event (from a database) are inputted to COWLEWIS at certain time. This system (homepage) updates every one hour. Therefore, all units are not allowed to be broken at any time. If it is possible to break during operation, the alternative method is necessary, such as the storm surge estimation in this study. For stable operation, this system is based on the Linux operation system.

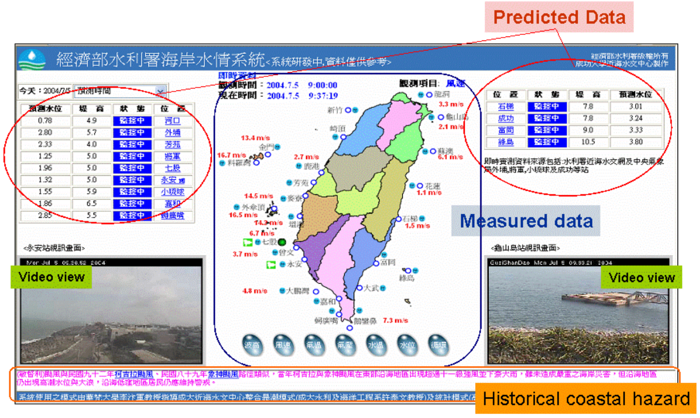

Figure 9 The Interfaces of Coastal Water Level Warning System (in Chinese, Homepage version)Middle: real-time in-situ data; Upper left and right: forecasting water level from models; Lower left and right: Live videos from sites; Lowest: historical coastal hazards events for reference

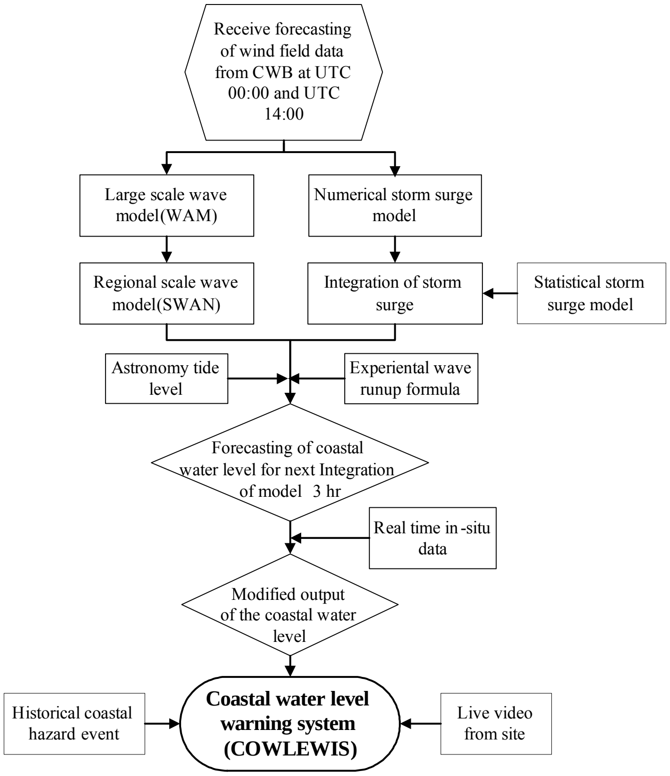

Figure 10 The flowchart of the operational route of the coastal hazards warning system

CONCLUSION

Measurements and models which researched and developed nowadays are used for hazards mitigation finally. This paper presents a Coastal Water Level Warning System which is assembled by real-time in-situ measurement, numerical models, statistical models, live video and experiences of historical events. The key point of the system is not how accuracy of the measurements and models. To integrate the existing models and measurements sometimes is more difficult then development. An Internet-based decision support system is established. One technical support term is necessary to support all requirements for the operation of this system. The decision-maker needs only to use the information to make decisions for coastal hazards warning or mitigation. Since the government decision-maker cannot make decision without reference information, stable and long-term operation system is the most important.

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