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Support vector regression methodology for storm surge predictions

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ABSTRACT

To avoid property loss and reduce risk caused by typhoon surges, accurate prediction of surge deviation is an important task. Many conventional numerical methods and experimental methods for typhoon surge forecasting have been investigated, but it is still a complex ocean engineering problem. In this paper, support vector regression (SVR), an emerging artificial intelligence tool in forecasting storm surges is applied. The original data of Longdong station at Taiwan 'invaded directly by the Aere typhoon' are considered to verify the present model. Comparisons with the numerical methods and neural network indicate that storm surges and surge deviations can be efficiently predicted using SVR.

1. Introduction

Storm surge is caused primarily by high winds pushing on the ocean's surface. The wind causes water to pile up higher than the ordinary sea level. Low pressure at the center of a weather system also has a small secondary effect, as can the seabed bathymetry. It is this combined effect of low pressure and persistent wind over a shallow water body that is the most common cause of storm surge flooding problems. Storm surges are particularly dangerous when a high tide occurs together with the surge. In the United States, the greatest recorded storm surge was generated by 2005's Hurricane Katrina, which produced a storm surge 9 m (30 ft) high in the town of Bay St. Louis, Mississippi. While high-impact events will undoubtedly occur in the future, the advent and further improvement of predictions of storm surges may greatly reduce the loss of lives, and potentially reduce property damage.

Storm surge models were developed in the 1950s. Hansen (1956) proposed a fluid dynamic model to describe the storm surge phenomenon in the North Sea. Coarse- and fine-grid cases were considered by Jelesnianski (1965) to calculate storm surges. A special program to list the amplitudes of surges from hurricanes (SPLASH) was developed by Jelesnianski (1972). FEMA (1988) developed a storm surge forecast model using the finite-difference method. Holland (1980) used wind forcing to derive storm surge models. Kawahara et al. (1982) applied a two-step explicit finite-element method for storm surge propagation analysis. Hubbert et al. (1991) proposed an operational typhoon storm surge forecast model for the Australian region. Flather (1991) applied the typhoon model of Holland (1980) to simulate typhoon-induced storm surges in the northern Bay of Bengal. The sea, lake, and overland surges from hurricanes (SLOSH) model (Jelesnianski and Shaffer, 1992) followed SPLASH and considered wetting and drying processes. Emergency managers use this SLOSH data to determine which areas must be evacuated to avoid storm surge consequences. Storm surge forecast systems are based on two-dimensional shallow-water equation models (Vested et al., 1995; Bode and Hardy, 1997). Hsu et al. (1999) developed a storm surge model for Taiwan and arrived at analytical expressions considering both gradient wind and radius. The MIKE 21 hydrodynamic model is a general numerical modeling system for simulation of unsteady two-dimensional flow, developed at the Danish Hydraulic Institute of Water and Environment (DHI, 2002). Xie et al. (2004) introduced a Princeton ocean model storm surge to consider flooding and drying, and further consider nonlinear effects in the surge process. Huang et al. (2005) applied finite-volume method (FVM), a numerical method to simulate typhoon surges in the northern part of Taiwan. Despite close attention of the engineering community, the storm surge problem is still far from its solution, because there are too many unknown parameters to account for, such as the central typhoon pressure, speed of typhoon, rainfall and influence of local topography.

Artificial neural networks (ANNs) are being widely applied to various areas to overcome the problem of exclusive and nonlinear relationships. The back-propagation neural network (BPN) developed by Rumelhart et al. (1986) is the most representative learning model for the ANN. The procedure of the BPN repeatedly adjusts the weights of connections in the network so as to minimize the measure of difference between the actual output vector of the net and the desired output vector. The BPN is widely

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Notations

B	shape parameter (= 1)
C	pre-specified value
L	Lagrange function
H	hidden layer
I	input layer
l	no. of training samples
O	output layer
O_k	output value
P_c	central pressure, hPa
P_n	environmental pressure depression
r	distance from typhoon center
R	the set of real numbers
R_{max}	radius to the point of maximum wind speed
$R(\alpha)$	risk
$R_{emp}(\alpha)$	empirical risk
T_k	target value
W	objective function
K	kernel function
n	dimension of input space
N	the set of natural numbers
X	input space (space of observable states)
Y	output space (space of hidden states)
α^*, α	coefficients
ρ	scale parameter
ρ_a	air density
σ	standard deviation
Ω	Coriolis parameter
ξ^*, ξ	slack variables

applied in a variety of scientific areas—especially in applications involving diagnosis and forecasting.

ANN has been widely applied in various areas (Daniell, 1991; French et al., 1992; Karunanithi et al., 1994; Grubert, 1995; Minns, 1998; Tsai and Lee, 1999; Lee et al., 2002; Nagy et al., 2002; Lee and Jeng, 2002; Coppola et al., 2003; Jeng et al., 2004; Lee, 2004, 2006; Makarynskyy, 2005; Bateni et al., 2007). Recently, Lee (2008) forecast a storm surge using neural networks (NNs). However, the estimated results still need to be improved.

In fluid dynamic models, the accuracy of storm surges depends on the fineness of the grid. The storm surge forecast model using finite-difference method involved the solution of a large number of equations. Explicit finite-element methods for storm surge propagation analysis are not very accurate compared to implicit methods. The storm surge forecast system cannot be applied to deep-water equation models. In FVMs, similar to finite-difference methods, values are evaluated at discrete places on a meshed geometry. In this method, the typhoon model is always represented in terms of relatively simple parametric model, the distribution of wind velocity and pressure. These methods also involve five equations and many boundary conditions and the method is conservative. This work was carried out by the third author and the calculated computer time was 9.6 h on an Intel Pentium IV 2.6 GHz personal computer. Since there are too many unknown parameters to account for, predictions of storm surges by NN and support vector machine (SVM) will be useful. BPN model was adopted by the third author to predict storm surges by using one hidden layer with three hidden neurons with a learning rate of 0.07 and momentum factor of 0.9, and the network was trained for 10,000 epochs. The training time was 50 s for every case based on an Intel Pentium IV personal computer with a 2.6 GHz CPU and 1 GB DRAM. Hence one needs to determine the number of hidden layers, number of neurons in a hidden layer, momentum factor, learning rate, sigmoidal gain, etc., whereas in SVM, if a proper kernel is selected, two parameters such as C and ε are required to achieve the desired accuracy. Therefore, the support vector regression (SVR) model considered for forecasting storm surges and surge deviations is desired and considered in this paper.

2. Numerical storm surge model

In general, numerical methods are often applied to establish an efficient storm surge forecasting system, such as FVM and finite-difference method. Many different analytical models were proposed in the literature for generating realistic air pressure and surface wind distributions (Dube et al., 1994). Common to all these analytical models is that they require information in terms of the following typhoon characteristics: (i) maximum wind speed, (ii) central pressure, (iii) radius of maximum wind, and (iv) parameters describing the shape of pressure and wind distributions. Often some of these parameters are related using empirical formulae derived from historical typhoon data. The analytical storm surge models are based on different formulations of surface wind and pressure fields.

Comparing with the measured and simulated results of the SVR model to storm surge, the most suitable storm surge model can be applied for Taiwan. In this storm surge model, two-dimensional shallow-water equation models based on three-dimensional Navier–Stokes equation as the hydrodynamic model (Vested et al., 1995) are used. The factors affecting the fluid field, such as the tide, wind, Coriolis force, bottom friction, fluid shear stress, and topographical boundary conditions must be considered in this model. Natural typhoon wind fields are usually intense, spatially inhomogeneous and directionally varying. The large gradients in wind speed and rapidly varying wind directions of the typhoon vortex can generate very complex ocean wave fields, but for practical applications the wind fields are always represented in terms of relatively simple parametric models. In this paper, the air pressure distribution form is assumed to be an exponential relation that can be expressed as (Hubbert et al., 1991)

$$P_r = P_c + (P_n - P_c)\exp\left(-\left(\frac{r}{R_{max}}\right)^{-B}\right) \tag{1}$$

where P_c is the central pressure, P_n the ambient or environmental pressure depression, r the radius (distance from the typhoon center), R_{max} the radius to the point of maximum wind speed, and B is a shape parameter. The value of shape parameter B can be assumed as 1–2.5 for the most favorable results (Hsu et al., 1999).

The wind speed distribution is usually derived using a gradient wind model or simply by using an empirical expression. The storm surge model, where analytical expressions of both the gradient wind and the radius, derived from the governing momentum equation using the air pressure distribution in Eq. (1), is given by

$$V_g = \left[\frac{P_n - P}{\rho_a}\frac{R_{max}}{r}\exp\left(-\left(\frac{r}{R_{max}}\right)^{-B}\right) + \left(\frac{1}{2}\Omega r\right)^2\right]^{1/2} - \frac{1}{2}\Omega r \tag{2}$$

in which Ω is the Coriolis parameter, ρ_a the air density, and the shape parameter B is 1 in this paper.