La mer 38 : 227-231, 2000
Société franco-japonaise d'océanographie, Tokyo

The influence of the drag coefficient on the simulation of storm surges

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Abstract : Wind stress plays a major role in the formation and propagation of storm surges. In numerical simulation of the storm surge, wind stress is expressed by empirical formula as a power law of wind speed, where the drag coefficient decides the rate of momentum transmission from air into water. Observations show that the drag coefficient increases gradually with the increase of wind speed and is a function of surface roughness and atomspheric stability. In this paper, sever proposed formulae of the drag coefficient varying with the increasing of wind speed have been examined by numerical simulation of the storm surge. The elevations simulated with varying drag coefficient coincide much better with the observed value than those for the constant drag coefficient. The best result is obtained when the formula proposed by SMITH(1980) is adopted.

Key words : *storm surge, drag coefficient, Bohai Sea, Yellow Sea*

1. Introduction

Wind stress plays a major role in the formation and movement of storm surges. In numerical simulation of the storm surge, wind stress is expressed by an empirical formula as 2-power law of wind speed, where the drag coefficient (C_d) decides the rate of momentum transmission from air into water. The drag coefficient in the empirical formula is usually considered as a constant, that is, the sea surface roughness does not vary during the process of a storm surge. In this condition, the results of numerical simulation cannot really reflect the process of a storm suge.

Numbers of observations showed that the drag coefficient increases gradually with the increase of wind speed and should be a function of surface roughness and atmospheric stability. In the present paper, several formulae proposed to represent the drag coefficient varying with the increase of wind speed have been examined by numerical simulation for the storm surge in the Bohai and Yellow Seas caused by Typhoon Rita(No.7203) in 1972.

2. Numerical model

Two-dimensional storm surge model is employed. The goverining equations are:

$$\frac{\partial\zeta}{\partial t}+\frac{\partial}{\partial x}[(\zeta+h)U]+\frac{\partial}{\partial y}[(\zeta+h)V]=0,$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}-fV$$
$$=-g\frac{\partial\zeta}{\partial x}-\frac{1}{\rho}\frac{\partial P_a}{\partial x}+\frac{(\tau_{x,a}-\tau_{x,b})}{\rho(\zeta+h)},$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+fU$$
$$=-g\frac{\partial\zeta}{\partial y}-\frac{1}{\rho}\frac{\partial P_a}{\partial y}+\frac{(\tau_{y,a}-\tau_{y,b})}{\rho(\zeta+h)},$$

where ζ is the surfece elevation relative to the undisturbed water depth h, (U, V) are the transport components in the (x, y) direction, f is Coriolis parameter, g is gravitational acceleration, P_a is the atmospheric pressure, ρ is the density of sea water, (τ_{xa}, τ_{ya}) are the components of wind stress $\vec{\tau}$ and $\vec{\tau}_a=C_d\rho_a\vec{W}|\vec{W}|$, in which $\vec{W}$ is the velocity of wind, ρ_a is the diensity of air, C_d is the drag coefficient of wind stress, (τ_{xb}, τ_{yb}) are the components of bottom stress $\vec{\tau}_b$ and $\vec{\tau}_b=C_f\rho\vec{V}|\vec{V}|$, in which $\vec{V}$ is the velocity of current, C_f is the friction coefficient of bottom.

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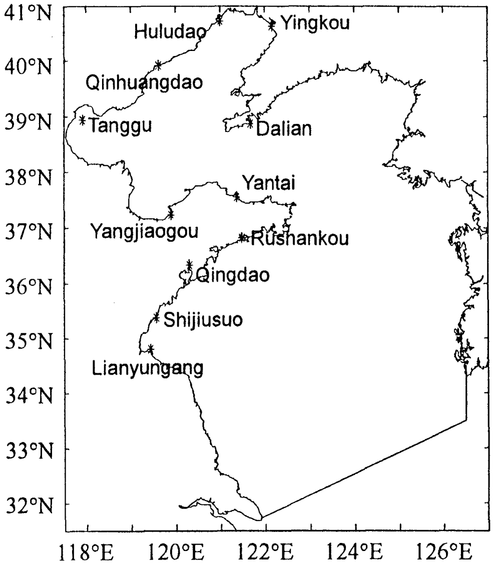

Fig. 1. Locations of the tide gauge stations

The numerical scheme is based on a finite difference used by LEENDERTSE (1967) on an Arakawa C-grid. This is an alternating direction implicit (ADI) technique, which generates solutions space and time. The computational domain is the Bohai Sea and the Yellow Sea (see Fig. 1) and the horizontal resolution is$(1/12)^\circ$. The zonal distance (Δx) between two adjacent grid points is varying with the latitude, while the meridianal distance (Δy) is equal.

At the open boundary, the water levels are taken to $\text{bes}=(P_\infty - P_a)/\rho g$ in which P_∞ is the environmental pressure.

According to the feature of the wind field of Typhoon, the elliptical wind field model (WANG, 1999) is adopted, which is derived from JELESNIANSKI (1965) circle wind field model.

$$\vec{W}=\begin{cases} \frac{r}{R+r}(V_{ox}\vec{i}+V_{ay}\vec{j})+W_R\left(\frac{r}{R}\right)^{3/2} \\ \cdot\frac{1}{r}(A\vec{i}+B\vec{j}), \quad (r\le R) \\ \frac{r}{R+r}(V_{ox}\vec{i}+V_{ay}\vec{j})+W_R\left(\frac{R}{r}\right)^{1/2} \\ \cdot\frac{1}{r}(A\vec{i}+B\vec{j}), \quad (r>R), \end{cases}$$

$$P_a=\begin{cases} P_0+\frac{1}{4}(P_\infty-P_0)\left(\frac{r}{R}\right)^3, \quad (r\le R) \\ P_\infty-\frac{3}{4}(P_\infty-P_0)\left(\frac{R}{r}\right)^3, \quad (r>R), \end{cases}$$

where $A=\cos(\alpha+\varphi+\theta)$ and $B=\sin(\alpha+\varphi+\theta)$, in which α is the inclination angle of major axis against x axis, φ is the angle of tangent in calculated point, and θ is the inflow angle; (V_{ax}) are the x-and y-components of velocity at the typhoon center respectively; W_R is maximum wind velocity at the distance R from the typhoon center; $\vec{W}$ is wind speed at the distance r from the typhoon position; P_a is air pressure on sea surface; P_o is air pressure at the typhoon center. These parameters are obtained from annals of typhoon, and some properties are modified for some parameters.

3. Simulation and analysis of results of it

The numerical simulations are performed using Typhoon Rita (No.7203) that had strong influence on the Bohai and Yellow Seas; the path of Rita is shown in Fig. 2. Typhoon Rita originated in the Western Pacific Ocean near the Equator (9.5 N, 150.5 E) on 5 July 1972 and moved northwestward and reached to its peak intensity on 11 July with an estimated central

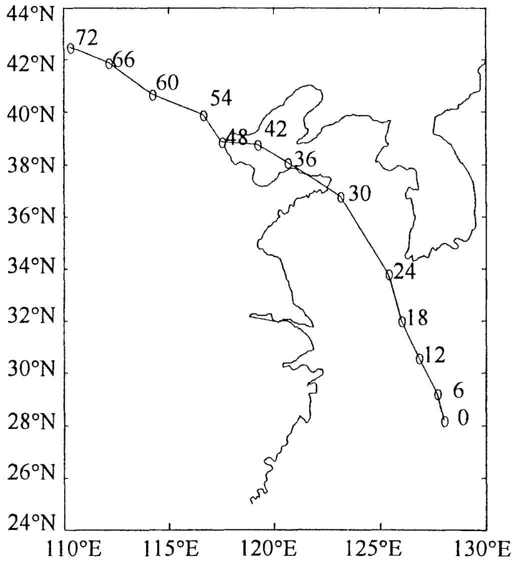

Fig. 2. Track of Typhoon Rita(No.7203) from 1972/7/25 08:00 to 1972/7/28 08:00

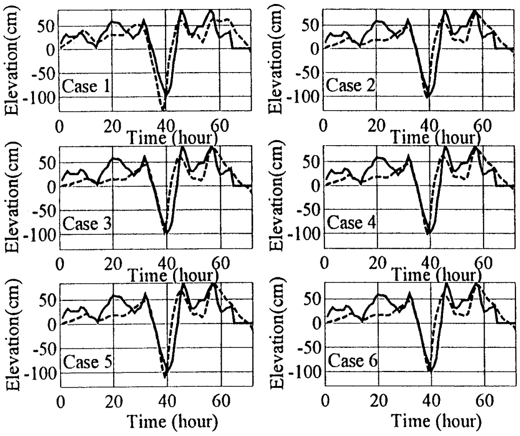

Fig. 3. Temporal change of observed elevation and that simulated at Lianyungang (Solid line: Observed value; dash line: Simulated value; Time: 1972/7/25 08:00 to 07/28 08:00)

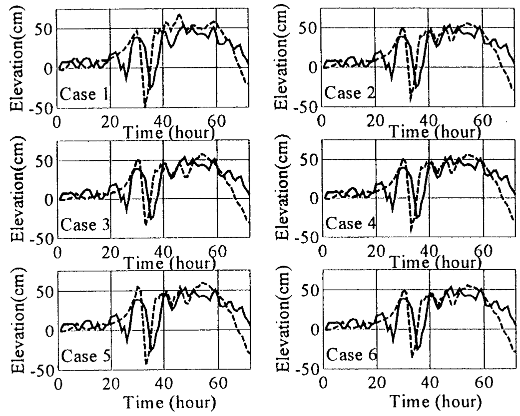

Fig. 4. Temporal change of observed elevation and that simulated at Rushankou (Solid line: Observed value; dash line: Simulated value; Time: 1972/7/25 08:00 to 07/28 08:00)

pressure of 911hPa and a maximum wind speed of 65 m s^{-1}. About 25 July it got into the Yellow Sea with a central pressure of 957hPa with a maximum wind speed of 35 m s^{-1}. It crossed the eastern coast of the Bohai Sea on 27 July and then weakened as it moved to the inland.

In numerical simulation, the different fromulae of the drag coefficient are examined. The formulae are as follows:

case 1 : $C_d = 0.0026$ (Const),
case 2 : $C_d = (0.8 + 0.0065 \times U_{10}) \times 10^{-3}$
$0 < U_{10} < 50$ (WUJING, 1982),

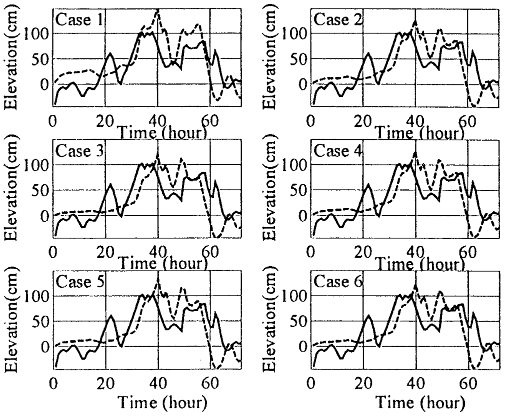

Fig. 5. Temporal change of observed elevation and that simulated at Yangjiaogou (Solid line: Observed value; dash line: Simulated value; Time: 1972/7/25 08:00 to 07/28 08:00)

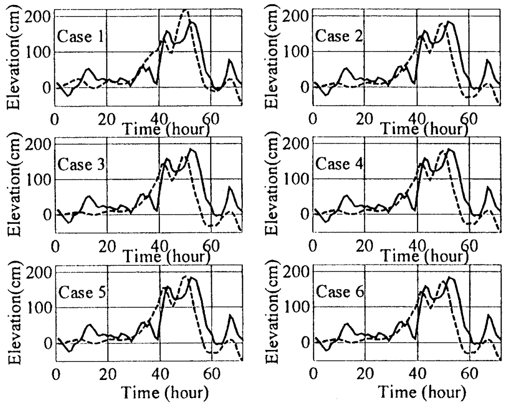

Fig. 6. Temporal change of observed elevation and that simulated at Tanggu (Solid line: Observed value; dash line: Simulated value; Time: 1972/7/25 08:00 to 07/28 08:00)

case 3 : $C_d = (0.61 + 0.063 \times U_{10}) \times 10^{-3}$
$6 < U_{10} < 22$ (SMITH, 1980),
case 4 : $C_d = (0.75 + 0.067 \times U_{10}) \times 10^{-3}$
$3 < U_{10} < 21$ (GARRATT, 1977),
case 5 : $C_d = (0.577 + 0.085 \times U_{10}) \times 10^{-3}$
$4 < U_{10} < 24$ (GEERNAERT, 1987),
case 6 : $C_d = (0.8 + 0.0065 \times U_{10}) \times 10^{-3}$
$0 < U_{10} < 6$
$(0.29 + 3.1/U_{10} + 7.7/U_{10}) \times 10^{-3}$
$3 < U_{10} < 21$
$(0.6 + 0.07 \times U_{10}) \times 10^{-3}$
$6 < U_{10} < 26$ (MARGARET, 1996),

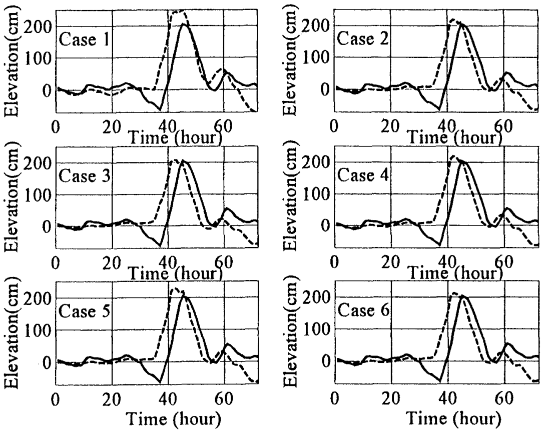

Fig. 7. Temporal change of observed elevation and that simulated at Huludao (Solid line: Observed value; dash line: Simulated value; Time: 1972/7/25 08:00 to 07/28 08:00)

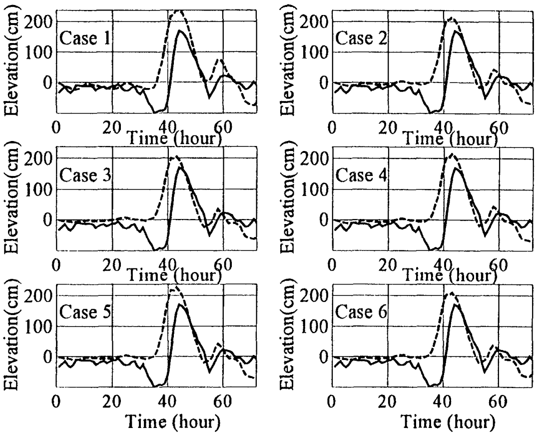

Fig. 8. Temporal change of observed elevation and that simulated at Yingkou (Solid line: Observed value; dash line: Simulated value; Time: 1972/7/25 08:00 to 07/28 08:00)

Table 1. The maximum elevations at 11 tide gauges in the Bohai and Yellow Seas

		The maximum elevations of the storm surge at 11 tide gauge stations											
Tide gauges		Lian	ShiJS	Qing D	RuSK	YanT	YangJG	TangG	QinHD	HuLD	YingK	DaLian	SD
Observation		84	59	64	53	118	101	183	181	204	168	127	
Case	1	53.8	61.9	62.4	68.6	103.2	149.0	218.6	256.9	250.3	236.0	149.1	32.33
	2	75.4	70.7	59.8	56.0	100.6	126.7	178.9	221.7	218.4	213.8	145.8	20.23
	3	73.4	68.6	57.1	54.4	93.7	117.2	163.9	204.8	205.3	200.5	136.7	**17.57**
	4	75.8	71.0	59.7	56.2	100.7	126.2	178.0	220.9	218.0	213.4	145.9	20.03
	5	80.9	75.6	63.3	59.5	109.3	133.2	187.4	234.0	229.1	224.8	157.0	22.22
	6	77.7	72.3	60.4	55.7	98.6	122.5	171.6	214.4	213.1	208.4	143.2	18.61

Table 2. Standard deviations between observed and simulated elevations at 11 tidal stations.

Case	Standard deviations of the storm surge at 11 tide gauge stations											
	LianYG	ShiJS	QingD	RuSK	YanT	YangJG	TangG	QinHD	HuLD	YingK	DaLian	Mean
1	25.74	23.43	16.14	20.05	19.35	34.35	37.91	43.24	53.95	58.45	23.65	32.39
2	24.85	21.71	15.76	18.62	20.36	35.30	38.63	41.39	52.92	57.51	22.92	31.82
3	25.26	21.90	16.21	18.02	20.01	34.82	38.34	39.52	52.13	56.58	22.37	**31.38**
4	24.92	21.76	15.83	18.63	20.43	35.39	38.72	41.46	53.00	57.58	22.97	31.88
5	25.31	22.21	16.16	19.51	21.53	36.71	40.10	44.44	54.82	59.49	24.22	**31.14**
6	25.14	21.95	16.25	18.48	20.39	35.21	38.94	41.19	53.16	57.70	22.96	31.94

here U_{10} is the wind speed at 10m over sea surface. In these models, if the U_{10} is out of the range of these formulae, the drag coefficient is considered as a constant corresponding to the general value of $C_d=0.0026$. In this paper we adopt $C_f=0.0016$, $P_\infty=1020$ hPa and $\theta=20°$ for the case of Typhoon Rita.

The temporal changes of elevation observed at 6 tide gauges in the Bohai and Yellow Seas and the corresponding results of simulation for the case 1~case 6 are shown in Fig. 3~Fig. 8, respectively. From these figures, we can see that the simulated results in the case 2～case 6 are more in agreement with the real processes of the storm surge than that in case 1.

The results of simulations are analyzed by two methods. The first is comparison of the maximum elevations due to the surge between observations and simulations at 11 tide gauges along the coast of the Bohai and Yellow Seas. The results of comparison are listed in Tabel 1. The last column (SD) is the standard deviation of the difference between observed and simulated maximum elevations at these stations. The Table 1 indicates that the best results are obtained by adopting the Smith's formula. The second is to examine the standard deviation (SD) of the difference between observed and simulated elevations; the SD values are listed in Table 2. The mean values of SD are lowest in the case 5 and secondary lowest in the case 3.

4. Conclusion

By comparison of the results simulated by different C_d formulae, it has been clarified that the Smith's formula works better than others. Thus we conclude that the Smith's formula is the better selection for the numerical simulation of a storm surge.

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Received on January 11, 2000
Accepted on October 23, 2000