STUDY ON INTERACTION BETWEEN THE ESTUARY DYNAMIC AND STORM SURGE INDUCED BY TROPICAL CYCLONE WINNIE(1997) IN YANGTZE RIVER ESTUARY

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ABSTRACT

This paper studied the interaction between the Estuary dynamic and storm surge induced by super tropical cyclone Winnie(1997) in Yangtze River Estuary with nested numerical model, which is driven by meso-scale meteorological model established. And the results indicate that, storm surges have significant influences on the Yangtze River Estuary. The maximum water level increase caused by storm surge can be monitored between Jiangyin and Xuliujing, whose exact position fluctuates owing to effects of the upstream runoff and estuarine tide. Furthermore the general laws about the relationships among astronomical tide, storm surge, and flood are revealed in this paper, and flood water level under storm surge events is predicted also.

Keywords: *the Yangtze River Estuary; Storm surge; Tidal reach; Runoff, Interactions; Increasing water*

INTRODUCTION

Storm surge is induced by strong wind and rapid variation in water level pressure of atmosphere. It may occur in sea or great lake.

Located on the west coast of the Pacific, China is damaged by storm surge frequently with great losses. More than 5 times every year tropical cyclone invades the territorial waters of China, and according to statistics, the economic losses hereby account for over 80 percent of that caused by all marine disasters. The storm surge disaster in China has a growth trend year by year, especially since the mid-1980s. In recent years, the losses by tropical cyclone and storm surge have been more than 10 billion RMB. For example, the direct loss by storm surge in 1996 was up to 20 billion RMB; the storm surge of Winnie(1997) has brought a loss of 51.22 billion RMB, and the direct loss brought by storm surge was more than one billion RMB every year from 1991 to 2000. So the research of preventing and withstanding storm surge is become the important task in disaster prevention and reduction.

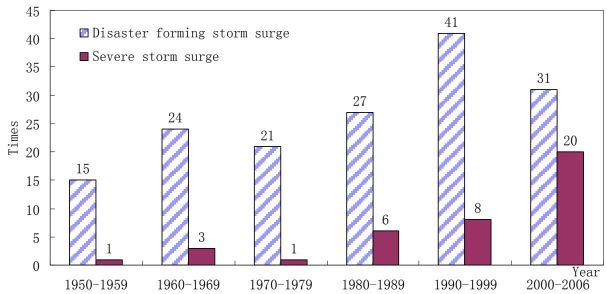

Fig 1 Statistical results of disaster forming and severe storm surge for southeast coast in China from 1950 to 2006[3]

The major areas impacted by storm surge, in China, are costal areas of Fujian Province, Jiangsu Province, Shanghai City, Zhejiang Province, Guangdong Province, Hainan Province and Guangxi Province. And the Yangtze River Delta, which is the most developed area in China, is damaged seriously by the disaster. Statistics show that there are 2~3 times storm surge lands on this area every year.

Fig. 1 is the statistical results of disaster forming and severe storm surge for southeast coast in China from 1950 to 2006. It shows that since 1980 the frequency of disaster forming storm surge has a growth trend, and there are 20 severe storm surges since 2000, with growth trend of proportion(The Bulletin of China Oceanic Disasters 1989-2006).

There are two ways to study storm surge, the first is statistic analysis, the other is numerical simulation. Now day, numerical simulation is the main approach to study storm surge.

Duan Yihong（1997，2005）and Zhou Xubo(2000)studied the mechanism of the interaction between astronomical tide and storm surge in the delta of Yangtsze River, the dynamic of river were not included.

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Zhang Changkuan et al(2004)studied the influence of storm surge on set-up and features of set-up in the Yangtsze River estuary with the integrative numerical model of flood and storm surge in downstream of Jiangyin. It must be pointed out that, because of complexity dynamic of river, it has long tidal reach, the former researches of storm surge model for the Yangtsze River had a short boundary for upstream, the crucial shortage is that it could not estimate the influence of runoff on set-up accurately.

Duan Yihong（1997，2005）and Zhou Xubo(2000)studied the mechanism of the interaction between astronomical tide and storm surge in the delta of Yangtsze River, the dynamic of river were not included. Zhang Changkuan et al(2004)studied the influence of storm surge on set-up and features of set-up in the Yangtsze River estuary with the integrative numerical model of flood and storm surge in downstream of Jiangyin. It must be pointed out that, because of complexity dynamic of river, it has long tidal reach, the former researches of storm surge model for the Yangtsze River had a short boundary for upstream, the crucial shortage is that it could not estimate the influence of runoff on set-up accurately.

Zhang Jinshan(2004)studied the interaction between Yangtsze River estuary dynamic and storm surge with a high accuracy numerical model integrated by the SSM(storm surge model)of East China Sea, the SSM of the Yangtsze River in downstream of Jiangyin, and one dimensional SSM include the all tidal reach from Datong to the estuary, but the unite of two models from 1D to 2D may induce an error in simulation. Zhang Jinshan(2008)studied the interaction between runoff and astronomical tide in Yangtsze River using whole tidal reach model from Datong to the estuary in one 2D numerical model, it covered over 650km in length of river course of downstream of the Yangtsze River. This is the base of this paper research.

NUMERICAL MODEL OF STORM SURGE AT TIDAL REACH OF YANGTZE RIVER

2D numerical model of storm surge at tidal reach in curvilinear orthogonal coordinate

Lies on the junction of Yangtze River and East China Sea, Yangtze River Estuary has a complicated coastline. The 2D numerical model of storm surge in Yangtze River Estuary is established here, with motion equation in curvilinear orthogonal.

The continuity equation is as follow:

$$\frac{\partial\zeta}{\partial t}+\frac{1}{\sqrt{ar}}\left[\frac{\partial}{\partial\xi}(\sqrt{a}Du)+\frac{\partial}{\partial\eta}(\sqrt{r}Dv)\right]=0 \tag{1}$$

and the momentum equation at ξ direction can be written as:

$$\begin{aligned}&\frac{\partial u}{\partial t}+\frac{u}{\sqrt{r}}\frac{\partial u}{\partial\xi}+\frac{v}{\sqrt{a}}\frac{\partial u}{\partial\eta}-\frac{v^2}{\sqrt{ar}}\frac{\partial\sqrt{a}}{\partial\xi}+\frac{uv}{\sqrt{ar}}\frac{\partial\sqrt{r}}{\partial\eta}\\&=fv-\frac{g}{\sqrt{r}}\frac{\partial\zeta}{\partial\xi}+A_H\left(\frac{1}{\sqrt{r}}\frac{\partial A}{\partial\xi}-\frac{1}{\sqrt{a}}\frac{\partial B}{\partial\eta}\right)-\frac{g\sqrt{u^2+v^2}}{C^2D}u-\frac{1}{\rho\sqrt{r}}\frac{\partial p_a}{\partial\xi}+\frac{1}{\rho D}\tau_{S\xi}\end{aligned} \tag{2}$$

and the momentum equation at η direction can be written as:

$$\begin{aligned}&\frac{\partial v}{\partial t}+\frac{u}{\sqrt{r}}\frac{\partial v}{\partial\xi}+\frac{v}{\sqrt{a}}\frac{\partial v}{\partial\eta}-\frac{u^2}{\sqrt{ar}}\frac{\partial\sqrt{r}}{\partial\eta}+\frac{uv}{\sqrt{ar}}\frac{\partial\sqrt{a}}{\partial\eta}\\&=-fu-\frac{g}{\sqrt{a}}\frac{\partial\zeta}{\partial\eta}+A_H\left(\frac{1}{\sqrt{r}}\frac{\partial B}{\partial\xi}-\frac{1}{\sqrt{a}}\frac{\partial A}{\partial\eta}\right)-\frac{g\sqrt{u^2+v^2}}{C^2D}v-\frac{1}{\rho\sqrt{a}}\frac{\partial p_a}{\partial\eta})+\frac{1}{\rho D}\tau_{S\eta}\end{aligned} \tag{3}$$

$$\tau_{s\xi}=\rho_a c_D w_\xi\sqrt{w_\xi^2+w_\eta^2} \text{ 、 } \tau_{s\eta}=\rho_a c_D w_\eta\sqrt{w_\xi^2+w_\eta^2}$$

$$A=\frac{1}{\sqrt{ar}}\left[\frac{\partial}{\partial\xi}(\sqrt{a}u)+\frac{\partial}{\partial\eta}(\sqrt{r}v)\right] \text{ 、 } B=\frac{1}{\sqrt{ar}}\left[\frac{\partial}{\partial\xi}(\sqrt{a}v)-\frac{\partial}{\partial\eta}(\sqrt{r}u)\right]$$

$$a=x_\eta^2+y_\eta^2 \text{ 、 } r=x_\xi^2+y_\xi^2 .$$

In which, *u* and *v* show respectively the velocity components in ξ direction and η direction; $D = h + \zeta$ shows the total water depth; $f = 2\omega \sin\varphi$ is Coriolis parameter (ω is geotropic angular velocity); h is the depth under the hydrographic datum; ζ expresses water level; A_h is horizontal eddy diffusivity; C is Chezy coefficient; g is acceleration of gravity; p_a is atmosphere; ρ_a is the air density, $\tau_{s\xi}$ and $\tau_{s\eta}$ are wind stresses respectively. A simulation system of tide dynamic is established here, which is composed with wind stress, barometric gradient, bed friction and Coriolis force. It can simulate well the movement of current, tide, storm surge and the interactions between wave and current.

The sea surface wind and pressure often be determined by empirical model, the famous models like that Fajita T.(1952.), Jelesnianski C P.(1965), Holland J.(1980) and Myers V A.(1957). Zhong Zhong and Zhang Jinshan et al. used MM5 to simulate tropical cyclone, and using this wind and pressure to simulate storm surge and get a excellent results(Zhang Jinshan 2004,2009.). In this paper, the wind and pressure also be used.

The boundary of outside in East China sea is got from the model of East China Sea storm surge(Zhang Jinshan,2004]. The boundary of upstream is determined by the fixed flow rate.

Owing to the location, the Yangtze River Estuary has a complicated coastline, with long and narrow channel, wide outsea, changeful landform and current. For the obvious neritic and nonlinear traits here, the horizontal 2D nonlinear motion equation (1) and (2) can't be linear, that is the linear model can't be employed here to research storm surge.

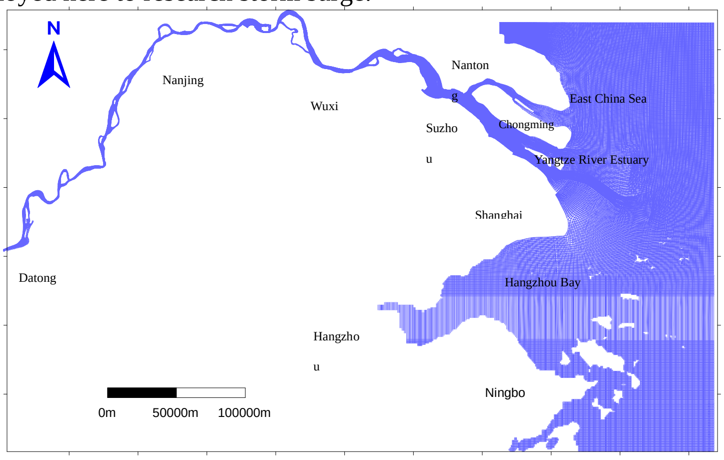

Fig2 Mesh diagram of 2D horizontal storm surge model for the Yangtze River tidal reach and estuary

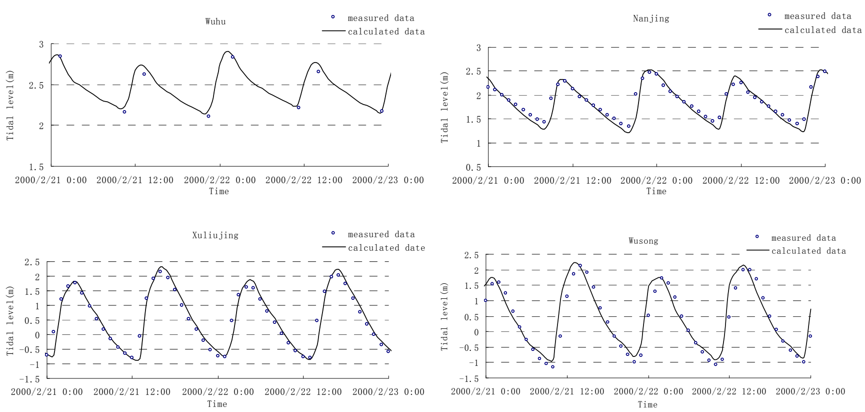

Fig 3 Water level verification of dry season for numeral model in February 2002

- Geographic range and the mesh

The model geographically covers the whole Yangtze Estuary and Hangzhou Bay. As shown in Figure 3.1, the modeling ranges transmeridionally from Datong, the limit of tide, to Longitude 123°E, and longitudinally from the south side of Radial Sandbar – Qidong to the south of Xiangshanwan.

- Initial conditions and boundary conditions

The open boundary conditions are supplied by the modal of East China Sea, and the upstream boundary conditions come from the current and water level at Datong station. The wind field condition of storm surge is tropical cyclone drive, in meso-scale model of MM5(Zhang Jinshan 2004,2009.).

Verification and calibration of the model

Considering the dynamic conditions, the model simulates the interaction between estuarine dynamics and oceanic dynamics in tidal reach and estuary, and achieves the dynamic transition from both sides of the estuary to the open sea. As for the tide movement, the model can simulate rotative tidal wave outside the estuary and the rectilinear current inside the estuary. The tidal wave is distorted after entering the estuary, and intrudes upstream, with shortened period of flood tide and prolonged period of ebb tide. Then the low water falls and the high water rises, namely the tidal range increase. Further more the oceanic dynamics decrease and the runoff increase along with the distance from the estuary.

- **Verification of tidal wave in flood reason and dry season**

As for the tidal reach and the estuary, the astronomical tide in this model is verified at Datong, Wuhu, Nanjing, Jiangyin, Tiansheng port, Xuliujing, and Wusong stations in flood and dry seasons.

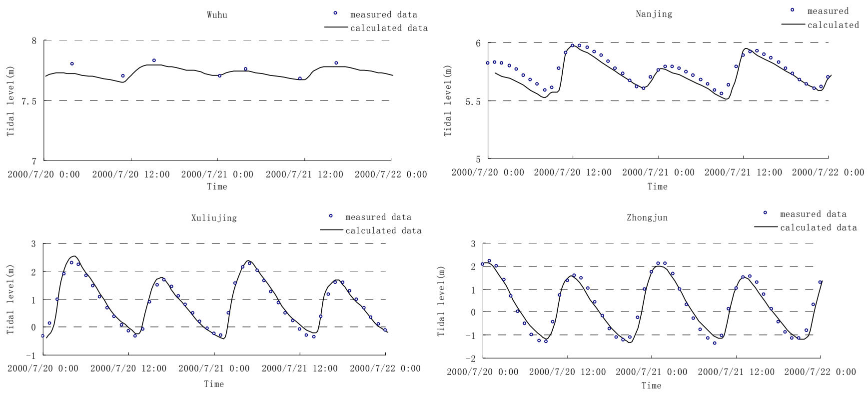

Fig 4 Water level verification of flood season for numeral model in July 2002

And Fig 3 and 4 show the verification results of flood season and dry season at some stations. It is obvious from the figures that the simulated results meet the measured data quite well, with reasonable parameters.

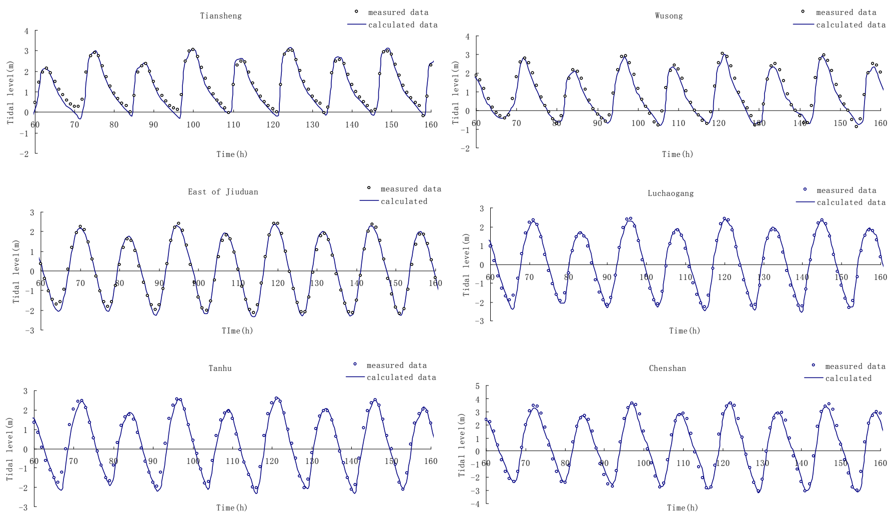

Fig 5 Tidal wave verification of astronomical tide near the Yangtze River Estuary

- **Verification of astronomical tide**

The astronomical tide data of the storm surge of Winnie(1997) is employed for the verification of the Yangtze Estuary. The data comes from harmonic analysis of tide forecast, which has adequate precision.

In the modeling area, there are 6 measurement stations inside of the Yangtze River Estuary, namely Tiansheng port, Baimao, Shidongkou, Changxing, Wusong, and Hengsha; and 6 measurement stations outside of the estuary, namely Zhongjun, East of Jiuduansha, Luchao port, Tanhu, Dajishan and Chenshan Island. See from the verification results, the phase error in large scope is less than 10 minutes; both tidal range error and the mean tidal level error are less than 0.15m respectively. The verification results meet well the measurement data, and the modal can simulate well tide movement in large scope. Figure 5 shows the verification of 6 representative stations.

Increasing water and decreasing water verification of storm surge

The astronomic tidal level subtracted from measured tidal level is considering as the increasing water of storm surge at present. This method is employed in this paper also. The current and tidal level are calculated first with the astronomic conditions, and then calculated with the storm surge conditions, and the increasing water is calculated in the end. In order to verify the increasing water, calculated data of 16 stations located from Tiansheng Port to Yangtze Estuary and Hangzhou Bay are compared with the measured data. The process of increasing water of part stations are shown in Figure 6.

From this figure, the process of storm surge is well simulated in this model. The error of maximum water level increase is small, and no more than 0.20m. The time error of maximum water level increase is less than 0.5h, except at the Wusong station. As for the water lever increase process, the meso-scale meteorological model is employed for storm surge forecast, and the result is meet well not only the master-vibrating, but also the initial-vibration and after-vibrating of setup.

According to the simulation results, the numerical model of storm surge in this paper has simulated well the process of the storm surge of Winnie(1997), and can forecast the storm surge movement in Yangtze River Estuary. So it can supply sustainment to disaster prevention and reduction of this area.

Fig 6 Verification of water level increase caused by Winnie(1997) storm surge

INTERACTION OF RUNOFF AND STORM SURGE

According to the Statistics, to research the interaction between the current and storm surge, three types of runoff are used here: the discharge of 17000m^3/s in dry year, the discharge of 45500m^3/s in average year, the discharge of 82300m^3/s in rainy year.

Distribution of water level under different upstream inflow conditions

Figure 7 shows the distribution of high water level for each downstream station under three inflow conditions. See from the figure, taking no account of typhoon the high water level is declined gradually down the river, under the interaction between the current and the tide. And the water level increases in proportion to increasing discharge upstream.

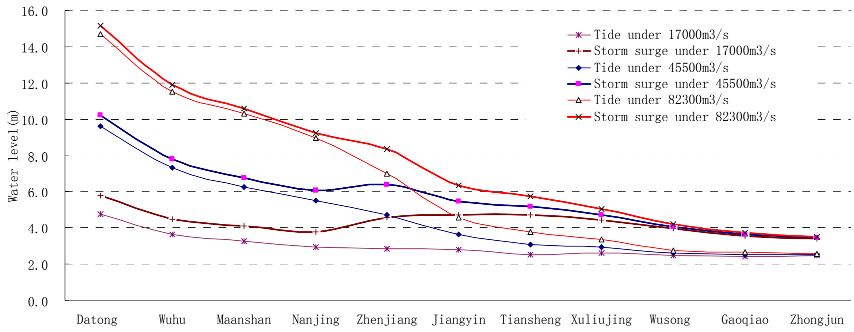

Fig. 7 Distribution of water level and high water level caused by Winnie(1997) storm surge for each downstream station under different upstream inflow conditions

The high water level, with discharge of 82300m^3/s , at Datong station, has 5m more than that with discharge of 45500m^3/s, and has 10m more than that, with discharge of 17000m^3/s. Near the Wusong station, the high water levels under different inflow are approximative.

The high water level upstream Wusong station lies on the inflow upstream. The more distant from the estuary, the more intense the impact on the water level of the inflow. The runoff has a large impact on the high water level upstream Jiangyin station, and has little impact on it downstream the station. The high water level outside Wusongkou is controlled mainly by tide from out sea.

Figure 7 shows also, gradient difference of discharge is obvious in proportion to the discharge from Zhongjun station to Datong station. But downstream Jiangyin station, the gradients are approximative. Namely current effect is strong upstream Jiangyin station while tide effect is strong downstream the station.

The effect of the storm surge of Winnie(1997) on the high water level

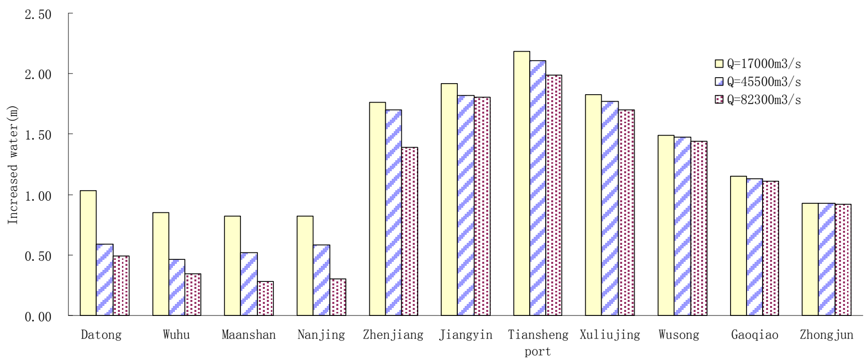

Fig. 8 Distribution of set-up caused by Winnie(1997) storm surge for each downstream station under different upstream inflow conditions

Water level in Yangtze River is controlled by both the runoff upstream and the tide downstream. Under general condition (astronomic tide), the water level is in proportion to the runoff, especially upstream Jiangyin station. Under the action of storm surge, the water level of storm surge is in proportion to the discharge also, namely the water level is highest under discharge of 82300m^3/s.

Considering the impact of water level, the water level increases largely with small inflow upstream. With the discharge type of 17000m^3/s, the water level caused by tropical cyclone is the largest; and that with the discharge type of 82300m^3/s is the smallest. The interaction between estuary dynamic and current is obvious that the impact of current dynamic increases along with the decrease of estuary dynamic.

Figure 7 can also shows that with normal discharge less than 45500m^3/s and normal weather, the water level from Datong to the estuary is declined with gentle gradient; but with flood of 82300m^3/s, there is a point of abrupt fall between Zhenjiang and Jiangyin, which is disappeared by the impact of storm surge. This is the discontinuity phenomenon under the interaction between the current and tidal, which is related with the runoff, riverbed cross section, tide and storm surge.

Figure 8 is the distribution of set-up down the river under different upstream inflow conditions. Corresponding to the highest tidal level, the water level increases firstly and then decreases from Datong to Zhongjun, and the decrease trend is obvious downstream Jiangyin station.

From Datong station to Zhenjiang station, the water level increases with gentle gradient. The increase changes from 0.80m ~ 1.20m, with the discharge of 17000m^3/s; the increase changes from 0.50 ~1.20m with 45500m^3/s; and the increase is from 0.30m ~ 0.60m with discharge of 82300m^3/s. It shows that upstream Jiangyin, the set-up is in inverse proportion to the discharge, indicating the balance between the upstream and downstream dynamics.

With three inflow conditions, the increasing water differs from Jiangyin to the Yangtze River Estuary, indicating the asymmetry actions of storm surge.

CONCLUSIONS AND DISCUSSION

The laws and characteristics of storm surge are analyzed in this paper, especially the interactions between runoff and storm surge in tidal reach of Yangtze River Estuary. The numerical model of storm surge is established and is verified well also.

Researches indicate that the maximum set-up occurred from Jiangyin to Xuliujing, and its position was effected by the interaction between runoff , wind storm and astronomic tide, namely the area of high increasing water moved downstream when the tidal dynamic weakened. In addition, under severe flood conditions, the whole water level increased, and the set-up by storm surge was not obvious.

ACKNOWLEDGMENTS

This was financially by the Special Research Project for off-shore Deep Harbor in the Ministry of Transport of the PRC. China(Grant No.200632800003-03), and national nonprofit project: impact of climate change on water security and adaptative strategy in China (No. 200801001) jointly support.

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