

Maximum tidal range analysis of radial sand ridges in the southern Yellow Sea

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Received 2 September 2013; revised 21 February 2014

Radial Sand Ridges sea area is significantly affected by tidal action. Around this area, tidal range is commonly higher and the historical record can reach 9.28m in Xiaoyangkou station. Within two years from 2010 to 2012, four new tide stations were built in the core region of Radial Sand Ridges. In October 17, 2012, the maximum tidal range of 9.39m was observed by the Xintiaoyugang station in the south of Tiaozini. It has set a new record. For further analysis of the hydrologic characteristics, a two-dimensional hydrodynamic model, based on the measured tide level data, was applied to simulate the spring-neap cycles of tidal level changes. And then, the quantitative analysis of the spatial distribution of the tidal range in RSR region was carried out in this study. The result showed that the tidal range isoclines fanned out from inshore to offshore with Tiaozini as the central apex. The maximum tidal range occurred in the south of Tiaozini area because of the unique tide system “movable standing tidal wave.” A quantitative spatial distribution of maximum tidal range and an updated record of 9.39m are the main innovations of this study.

[**Keywords:** Maximum tidal range, Radial Sand Ridges, Tiaozini, movable standing tidal wave]

Introduction

Radial Sand Ridges (RSR), a special continental shelf sand body is located off the central part of Jiangsu coast. RSR is fan-shaped with an apex at Tiaozini stretching seawards with a central angle of about 160° and covering an area of 20,000 km² in the southern Yellow Sea (Fig.1). The two important characteristics of the RSR area are the strong tidal flow and large tidal ranges^{1,2,3,4}. The large vertical difference between the high tide and the succeeding low tide often occurred in narrow harbors and estuaries, such as the Hangzhou Bay, Bay of Fundy, Amazon, and Red Mouth. However, the appearance of large tidal range in RSR area is unique in the entire coastal area of China including the Southern Yellow Sea. For decades, the studies on tidal range are often a qualitative description rather than a quantitative analysis because of the lack of long continued measured tide level data. The historical tidal range record of 9.28m observed in Xiaoyangkou in the 1980's is still in use^{1,4}. Moreover, according to the previous studies (Liu, Z.X., 1989⁵; Zhang, D.S., 1996⁶; Zhu, Y.R., 1997⁷; Yan, Y.X., 1999⁸; Zhang, C.K., 1999⁹; Tao J.F., 2005¹⁰; and Xing F., 2011¹¹), numerical models were used to simulate the hydrodynamic environment of this sea area. However, the a fore

mentioned studies only have some qualitative description on tidal range and rarely involved quantitative analysis due to the lack of measured tide level data. Besides, Wu (2008) developed the formula to calculate the maximum possible tidal range using the improved G. Godin's tidal level harmonic analysis and prediction procedures¹². However, the accurate value of the largest tidal range and precise position were not obtained by using this method. Further, the tidal range of 9.28m has long been questioned. In this study, the tidal range of 9.39m, observed in the Xintiaoyugang tide-gauge station is employed for the quantitative description of the spatial distribution of tidal range and also for exploring the cause of large tidal range in the RSR sea area.

Materials and Methods

From October 2010 to October 2012, four new tide level automatic telemetry stations have been completed around Tiaozini. They are Dafeng (DF), Dongdagang (DDG), Xintiaoyugang (XTYG), and Yangkou (YK) stations (Fig.1). The tide level automatic telemetry station contains an outdoor sea monitoring equipment and an interior information collection system. The support platforms of the outdoor sea monitoring equipment are of two types: a Column Tower

made of steel (XTYG and DDG) and the trestle of the pre-existing port (DF and YK) (Fig. 2). Moreover, mobile communications are used to achieve data synchronization between outdoor equipment and interior system (Table 1). Along with the data from the four new tidal stations, tidal level data from the two pre-existing stations SY and Lvsi were also collected employed for the verification of the hydrodynamic model, which was used to analyze the distribution characteristics of tidal range in RSR sea area.

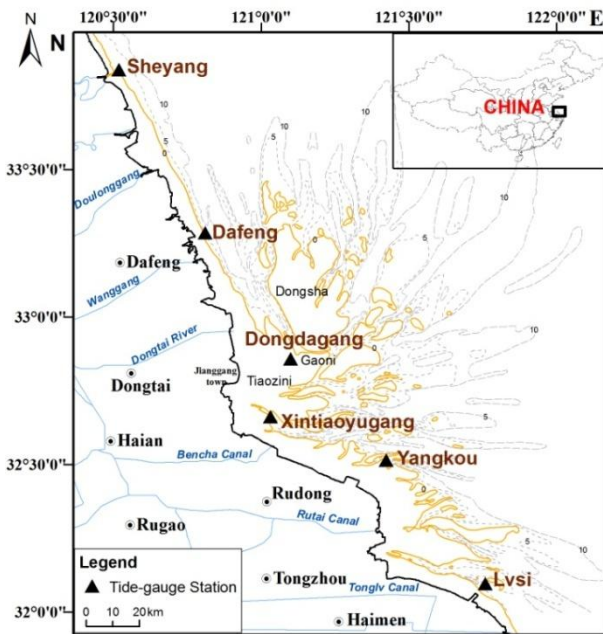


Fig. 1—Six tide-gauge stations in RSR area

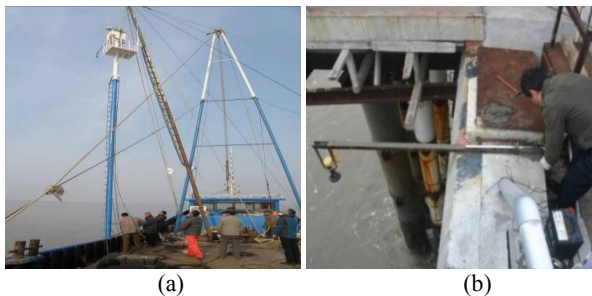


Fig. 2—(a) Column tower type. 2 (b) Trestle type

Table1—Details of four newly built tide-gauge stations				
Name	DF	DDG	XTYG	YK
Build time	2010.10	2012.10	2012.10	2010.10
Latitude/°	33.3	32.9	32.7	32.5
Longitude/°	120.8	121.1	121.0	121.4
Station platform	Pier	Column steel tower		Pier
Distance / km	8	11.1	9.1	13
Low tide water depth / m	10	3	3	12
Limnimeter	Water level ranging radar			
Radar altitude/m	6.9	15.1	15.5	8.5
Observation accuracy	±1mm	±1mm	±1mm	±1mm
Transmission	Mobile network synchronous			

Based on the six tidal stations, tide level data of the whole year of 2012 was used as the main materials in this paper. However, DDG station and XTYG station only had the measured data of two months (from October to December in 2012). So, in this paper, we carried out the harmonic analysis based on the water level data from the two stations in the two months. Through the harmonic calculation, the year-round tidal level data would be obtained. The water level at a certain location as a function of time is expressed by the following formula:

$$\eta(t) = a_0 + \sum_{n=1}^N a_n \cos(\omega_n t - \alpha_n) \tag{1}$$

Where: $\eta(t)$ is the measured (or predicted) tidal level with reference to a fixed level a_0 is mean level, a_n is amplitude of component number n , ω_n is angular velocity of component number n , α_n is phase angle of component number n , t is time, N is number of harmonic components. Contrary to the traditional harmonic analysis, the frequencies ω_n are known here, having been derived from astronomical considerations. The phase angles α_n have to be derived from observations as they are extremely site specific. This applies to the amplitude a_n as well. Tidal analysis for a certain location therefore is the determination of amplitudes and phases.

At each tide station, 11 main harmonic constituents showed in Table 2 have been computed by a least-squares regression without inference. It is typically regular semi-diurnal tide and the M_2 harmonic constituent assumes absolute superiority in southern Yellow Sea area.

Table 2—Main constituents of the tide at two tidal stations in RSR sea area

Component	Amplitude H(cm) / Phase lag g(°) ref. to MET	DDG	XTYG
M2	H(cm) / g(°)	218.01 / 356.7	246.9 / 8.6
S2	H(cm) / g(°)	78.18 / 62.3	103.43 / 56.7
N2	H(cm) / g(°)	36.61 / 329.4	43.75 / 348
K1	H(cm) / g(°)	23.11 / 81.6	18.08 / 132.1
K2	H(cm) / g(°)	21.26 / 67.6	28.13 / 60.6
M4	H(cm) / g(°)	18.47 / 215.3	5.86 / 210.2
MU2	H(cm) / g(°)	17.01 / 79.4	5.11 / 115.5
O1	H(cm) / g(°)	16.93 / 10.9	9.48 / 56.4
MS4	H(cm) / g(°)	13.69 / 293.4	10.17 / 268.5
L2	H(cm) / g(°)	11.09 / 9.8	9.27 / 21.1
2MS6	H(cm) / g(°)	8.55 / 139.7	7.2 / 53.0

A two-dimensional numerical hydrodynamic model (HD) was set up using MIKE 21 Flow Model (MIKE 21 HD) to simulate the water level variations in the RSR area. MIKE 21 HD is a general modeling system for the simulation of water level variations and flows in estuaries, bays, and coastal areas¹³. It simulates unsteady 2D flows in one layer (vertically homogeneous) fluids and has been applied in a large number of studies. The following equations, which show the conservation of mass and momentum integrated over the vertical, are used in the HD model to describe the flow and water level variations¹⁴:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \quad (2)$$

$$\begin{aligned} \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left(\frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left(\frac{pq}{h} \right) + gh \frac{\partial \zeta}{\partial x} + \frac{gp\sqrt{p^2 + q^2}}{C^2 h^2} \\ - \frac{1}{\rho_w} \left[\frac{\partial}{\partial x} (h\tau_{xx}) + \frac{\partial}{\partial x} (h\tau_{xy}) \right] - \Omega q \\ - fVVx + \frac{h}{\rho_w} \frac{\partial}{\partial x} (p_a) \\ = 0 \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{\partial p}{\partial t} + \frac{\partial}{\partial y} \left(\frac{p^2}{h} \right) + \frac{\partial}{\partial x} \left(\frac{pq}{h} \right) + gh \frac{\partial \zeta}{\partial y} + \frac{gp\sqrt{p^2 + q^2}}{C^2 h^2} \\ - \frac{1}{\rho_w} \left[\frac{\partial}{\partial y} (h\tau_{yy}) + \frac{\partial}{\partial x} (h\tau_{xy}) \right] - \Omega q \\ - fVVy + \frac{h}{\rho_w} \frac{\partial}{\partial y} (p_a) \\ = 0 \end{aligned} \quad (4)$$

where $h(x,y,t)$ is the water depth, $C(x,y)$ is the Chezy resistance, $f(V)$ is the wind friction factor, $\Omega(x,y)$ is the latitude-dependent Coriolis Parameter, $P_a(x,y,t)$ is the atmospheric pressure, $\zeta(x,y,t)$ is the surface elevation, V , V_x , $V_y(x,y,t)$ are the wind speed and components in x and y directions, $p, q(x,y,t)$ are the flux densities in x and y directions ($\text{m}^3(\text{s.m})^{-1}$), (vh, uh) , (v, u) are the depth-averaged velocities in x and y directions, and τ_{xx} , τ_{xy} , τ_{yy} are the components of effective shear stress.

MIKE 21 HD uses the Alternating Direction Implicit (ADI) technique to integrate the equations for mass and momentum conservation in the space-time domain. The equation matrices that result for each individual grid line along each direction are resolved by double sweep (DS) algorithm. The raw bathymetry used to produce the mesh had been previously digitized using the nautical chart and sounding sheets. Moreover,

triangular grids were applied in the model using different scales to match the coastal areas. The resolution of the grids became higher from inshore to offshore, particularly in the Tiaozini area. The grid length was less than 300m in the center of the study area and gradually increased towards the open ocean. The mesh contained 837,655 nodes. The input data for wind were acquired from the IFREMER website with a resolution of $0.5^\circ \times 0.5^\circ$. The resistance was set by the Manning coefficient which was calculated from the water depth, using the formula $M=1/(0.015+0.01/\text{abs}(\text{depth}))$ ¹¹. Eddy viscosity was calculated by using Smagorinsky formula¹⁵. The ocean boundary conditions were specified water level data obtained from the tidal model of the Eastern China Sea¹⁰. The model was run with a time lapse of 60s, which according to the Courant-Friedrichs-Lewy criterion was sufficiently small to ensure numerical stability. From October 13, 2012 to December 30, 2012, the tide levels variations in the RSR area was simulated using MIKE 21 HD. The calculated results were validated by the measured data from six tide-gauge stations. The model verification diagram showed that the calculated values agreed with the measured water level (Fig.3), thus indicating that the model can be used to simulate the hydrodynamic environment in this region.

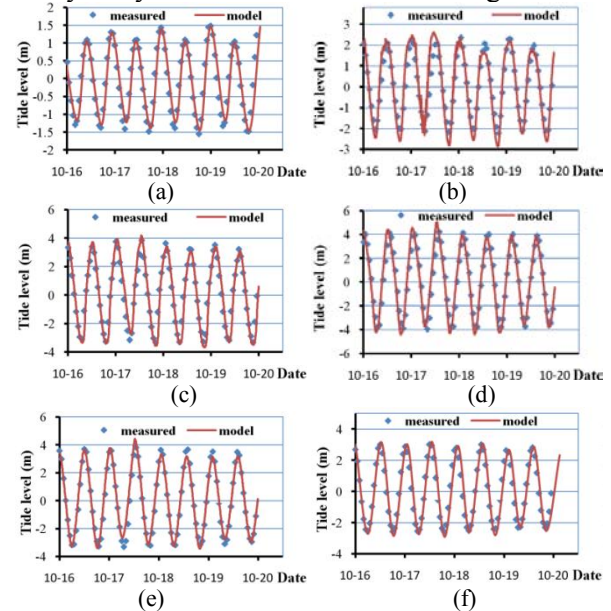


Fig.3 — Verification of water level calculated by hydrodynamic model: (a) SY station, (b) DF station, (c) DDG station, (d) XTYG station, (e) YK station, (f) LS station.

Results

This study demonstrates the characteristics of tidal range in the RSR area from three aspects: point, line, and polygon. From the point aspect,

the largest tidal range of 9.39 m was observed in XTYG station. On October 17, 2012, the measured tidal level was 5.07m (local mean sea level) at 13:03, and -4.32m at 19:11(Fig.4). Therefore, the tidal range was 9.39m, larger than the currently used tidal range of 9.28m observed in Xiaoyangkou near XTYG station in the 1980's. The observed data is significant and reliable because of the following reasons: First, the observation platform is stable. The support platforms of outdoor equipment of DF and Yangkou stations are set up in the trestle of the pre-existing port. And also, in XTYG and DDG stations, the platform consist of a Column Steel Tower fixed using 3-6 grouped wire cables. The underwater part of the wire cable is 13-15m in length. Second, each monitored data is the average of consecutive values obtained in 5 minutes. Third, according to the weather forecast in October 17, 2012, the yellow sea state was good and calm under the control of the subtropical high. Besides, Chen had given the characteristics of wave in this sea area¹⁶. The result from Chen showed that the wave height was 1-1.2m and the period was only 5s (Table 3). However, the observation of tide level in each station was the mean value of continuous observation in 5 minutes which was far longer than 5s. So, the influence of wave could be eliminated.

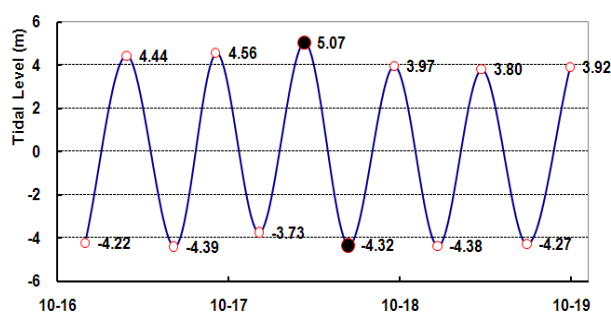


Fig.4—Tide curve of XTYG station

Table 3—Wave characteristics of Yellow Sea¹⁶

Season	Wave height/m	Period/s
Spring	<1.0	3~4.5
Summer	<1.2	4~5.5
Autumn	1~1.2	5~5.5
Winter	1.4	5~6
Mean	1.1-1.2	4.3~5.4

Using the water level data during the whole year of 2012, we counted the annual average tidal range in different tide conditions (spring tide, neap

tide) as shown in Fig.5. Among the six stations, XTYG had the largest annual mean tidal range of 5.3m. During the spring tide, the tidal range could reach 8m. During the neap tide, the tidal range was 4.1m. The station observing the second largest tidal range was DDG in the north of Tiaozini. On moving towards north and south, the tidal range gradually reduced. Moreover, the tidal range in the north was smaller than in the south.

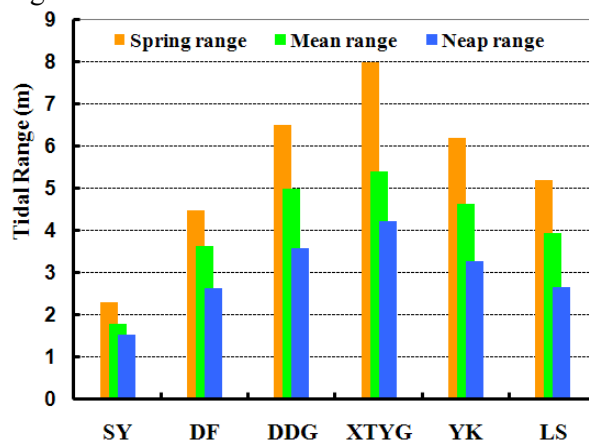


Fig.5—Annual average tidal range

From the line aspect, tide level curves obtained from six stations along the coast showed the morphological characteristics of skipping known as 'rope skipping effect'. Fig.6 showed this special characteristic of the tidal level along the coast. Four water-level curves: high water spring, low water spring, high water neap, and low water neap were drawn along six stations. During the period of high water, the tide level of the central area (XTYG station) was higher than the northern and southern flanks. In contrast, during the period of low water, the central tidal level was lower than the flanks. Because of the continuous ebb and flow of tides, the tide level curves presented a rope skipping shape. This was one of the main features of the coast in RSR.

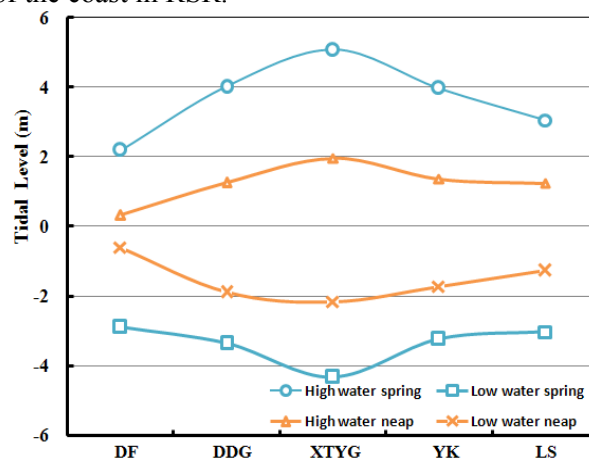


Fig.6—Rope skipping effect

The (2D) hydrodynamic model was able to provide the characteristics of tidal range from a polygon aspect. During the typical spring and neap tides, the model calculated the spring and neap ranges in the entire area, thus providing the distribution maps (Fig.7 (a) and (b)). Furthermore, the mean tidal range map of eight months was acquired by the statistical analysis of water levels calculated from the model in the entire area (Fig.7 (c)). The distribution maps of tidal range showed that the isoclines of tidal range presented fan-shaped with Tiaozini as the vertex. From the fan vertex to the border i.e., from inshore to offshore, the tidal range reduced gradually. The large tidal range up to 8 m in spring tide occurred in the Tiaozini area. The maximum tidal range was observed in the south of Tiaozini, near XTYG station. This matched with the maximum tidal range of 9.39m observed in XTYG.

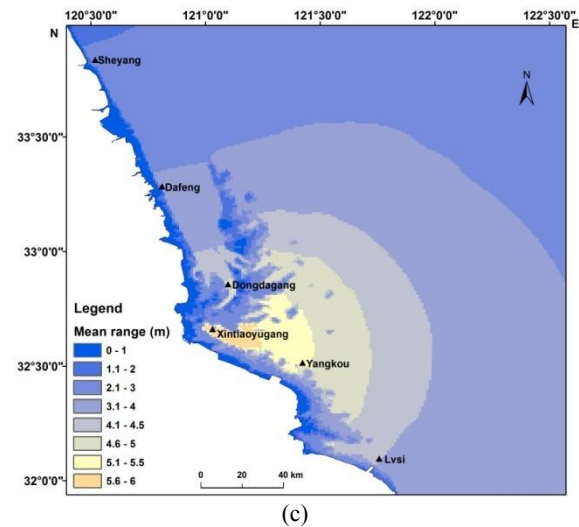
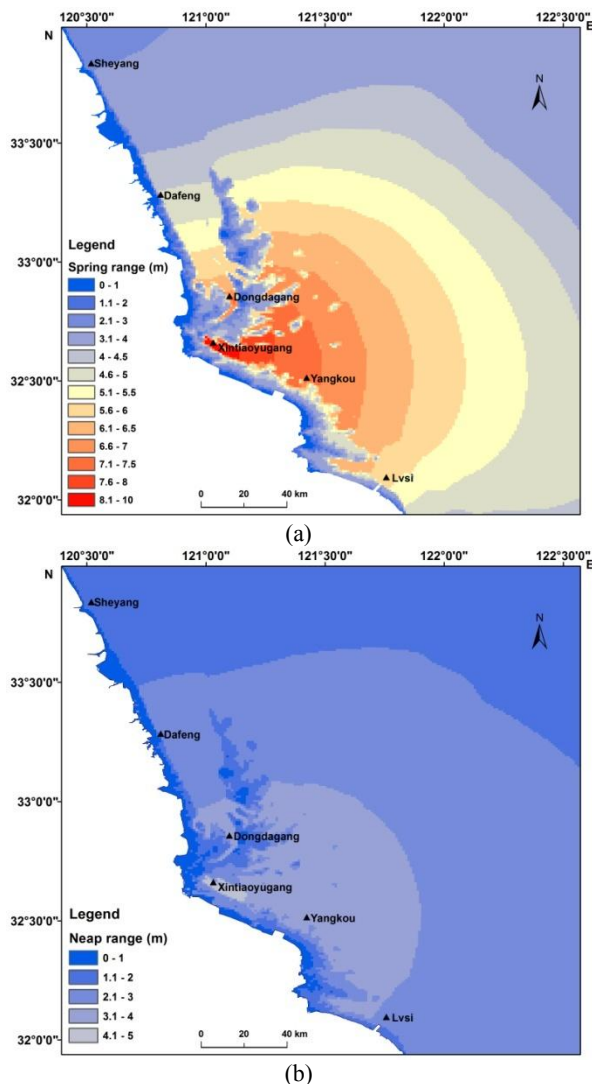


Fig.7—Tidal range distribution map in (a) spring tide, (b) neap tide, (c) mean tide

Discussion

What's the reason for such a large tidal range in RSR? Tidal flow movement, broadly speaking, is determined by the tidal wave system. It belongs to semi-diurnal tide in the RSR area and is controlled by two tidal wave systems: the first one is the propagating tidal wave from the East China Sea and the second one is the rotational tidal wave system from the Southern Yellow Sea. The incoming wave from the north at the beginning travels towards the south and gradually turns to the shore of Jianggang (Tiaozini tidal flat), where it meets the wave from the south. Two tidal wave peak lines converge and forms a standing tidal wave in the RSR area. The standing tidal wave moves gradually towards the shore of Tiaozini area because of the friction of the seafloor. Hence, it is known as the movable standing tidal wave, resulting in the existence of the large tidal range in the entire RSR area and the largest tidal range in Tiaozini area. Fig.8 showed the change of co-phase lines of M_2 component in Southern Yellow sea when the two waves meet.

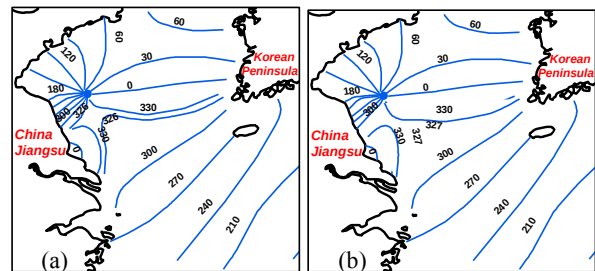


Fig.8—Co-phase lines of M_2 component⁶: (a) Two waves meet before, (b) Two waves meet after

Tidal range is the vertical difference in height between the consecutive high and low tides. Besides, the D-value of the maximum and the

minimum tidal level in the same place (XTYG station) is always very important. So in this paper, we counted the maximum and the minimum value of tidal level and calculated the D-value between the maximum and minimum (Table 4). The result showed that the D-value of tidal level range could reach 9.62m which also was a special important figure in the research on RSR sea area.

Table 4—Statistical table of tidal level in XTYG station

Date	Time	Max (m)	Min (m)	D-value (m)	Time interval
10-17, 2012	13:03	5.07	—	—	—
10-17, 2012	19:11	—	-4.32	9.39	adjacent
10-16, 2012	18:40	—	-4.39	9.46	1 day
11-14, 2012	18:48	—	-4.55	9.62	27 day

Conclusion

Based on the water levels data of six tide-gauge stations, a 2D numerical model was applied to calculate the tidal range covering from the neap tide to spring tide in the RSR in the Southern Yellow Sea. The result shows that the tidal range presents a fan-shaped distribution with Tiaozini area as the central vertex where the largest tidal range appeared. The maximum tidal range of 9.39m was observed in XTYG station in the south of Tiaozini. It represents the largest tidal range record of this sea area. Besides, the D-value between the maximum and minimum tidal level was 9.62m in XTYG station. The “movable standing tidal wave system” is the main hydrodynamic factor resulting in the large tidal range.

Acknowledgements

This work is financially supported by the National Key Technologies Research and Development Program of China (Grant no.2012BAB03B00), National Natural Science Foundation of China, (Grant no.51179067), and Natural Science Foundation of Jiangsu Province, (Grant no.BK2012414) and Graduate Student Research and Innovation Project of Jiangsu General Higher Learning Institution, No.CXLX12_0256. The authors thank Dr. Xufan, Mao Zhibin, and Sun Yulong who participated in the field work for the establishment of the tide-gauge stations and Xia Juan, Pan Jin who participated in the water level data analysis in the laboratory.

References

- 1 Ren, M.E., *Comprehensive Investigation of the Coastal Zone and Tidal Land Resources of Jiangsu Province*, (Ocean Press, Beijing) 1986, pp. 25-28. (In Chinese).
- 2 Wang, Y., *Radiative sandy ridge field on continental shelf of the Yellow Sea*, (China Environmental Science Press, Beijing) 2002, pp. 31-33. (In Chinese).
- 3 Zhang, C.K., *The basic status of marine environment and resources in Jiangsu province*, (Ocean Press, Beijing) 2013, pp. 91-93. (In Chinese).
- 4 Zhang, C.K., *Jiangsu offshore investigation and assessment report*, (Science Press) 2013, pp. 441-443. (In Chinese).
- 5 Liu, Z.X., Huang, Y.C., Zhang, Q.N., Tidal current ridges in the southwestern Yellow Sea. *Journal of Sedimentary Petrology*, 59 (1989): 432-437.
- 6 Zhang, D.S., Zhang J.L., M₂ tidal wave in the Yellow Sea Radiate Region. *Journal of Hohai University: Natural Sciences*, 24(5) (1996): 35-40.
- 7 Zhu, Y.R., Chang, R.F., Explanation of the origin of radiant sand ridges in the southern Yellow Sea with numerical simulation results of tidal currents. *Journal of the Ocean University of Qingdao*, 27 (2) (1997): 218-224.
- 8 Yan, Y.X., Zhu, Y.L., Xue, H.C., Hydromechanics for the formation and development of radial sandbanks (I) —Plane characteristics of tidal flow. *Science in China (Ser. D)*, 42(1) (1999): 13-21.
- 9 Zhang, C.K., Zhang, D.S., Zhang, J.L., et al., Tidal current-induced formation-storm-induced change-tidal current-induced recovery-Interpretation of depositional dynamics of formation and evolution of radial sand ridges on the Yellow Sea seafloor. *Science in China (Ser. D)*, 42(1) (1999): 1-12.
- 10 Tao, J.F., Zhang, C.K., Numerical simulation of water environment for radial sandy ridge area of the Yellow Sea, *Journal of Hohai University: Natural Sciences*, 33(4) (2005): 472-475. (In Chinese with English abstract)
- 11 Xing F., Wang Y.P., Wang H.V., Tidal hydrodynamics and fine-grained sediment transport on the radial sand ridge system in the southern Yellow Sea. *Marine Geology*, 291(2011): 192-210.
- 12 Wu, D.A., Yan, Y.X., Ma, L.Y., Tong, Z.F., Calculation and analysis of possible maximum tidal difference in Jiangsu radial sand ridges sea area. *Journal of Dalian Maritime University*, 34(4) (2008):75-78. (In Chinese with English abstract)
- 13 I.R. Warren, H.K. Bach. MIKE 21: a modeling system for estuaries, coastal waters and seas. *Environmental Software*, 7(4) (1992): 229-240.
- 14 Danish Hydraulic Institute, *User Guide and Reference Manual of MIKE 21 Hydrodynamic Modules*. Release2.7 (2005): pp.12.
- 15 SMAGORINSKY J, General circulation experiments with the primitive equations I: the basic experiment. *Monthly Weather Review*, 91(3) (1963): 99-164.
- 16 Chen Hongxia, Hua Feng, Yuan Liye, Seasonal Characteristics and Temporal Variations of Ocean Wave in the Chinese Offshore Waters and Adjacent Sea Areas. *ADVANCES IN MARINE SCIENCE*, 24(4) (2006): 407-415.(In Chinese with English abstract)