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Geo-morphological changes of the Wanpingkou tidal system arising from the building of a sailing boat station in Rizhao of China

Shuhua Bian · Yuanzhi Zhang · Aiping Feng · Long Chiu · Sangyun Wu · Zejian Hu

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Abstract This paper examines a small tidal system in Wanpingkou, Rizhao of China. The tidal system was originally maintained by a balance of the natural interaction between tidal currents and waves. But this tidal system was diminishing by reclamation processes since the 1980s, especially in 2003 when a sailing boat station was built in the study area. To investigate the stability and development mechanism of the tidal system, its feasibility was evaluated before the sailing boat station was built. The erosion and deposition in and out of the tidal system was analyzed, forecasted and compared with the data from field monitoring. The results show that the tidal system would remain relatively stable, although its adjacent shoreline might change somewhat after the newly built sailing boat station. This change would also affect the coastal water and wetland environment in the study area. Further field monitoring in the area is still necessary.

Keywords Tidal inlet · Monitoring · Jetties · Erosion · Deposition

S. Bian · A. Feng · S. Wu · Z. Hu
First Institute of Oceanography,
State Oceanography Administration (SOA),
Box 98, 266061 Qingdao, China

Y. Zhang (✉) · L. Chiu
Institute of Space and Earth Information Science,
The Chinese University of Hong Kong,
Shatin, NT, Hong Kong
e-mail: yuanzhizhang@cuhk.edu.hk

Introduction

Tidal inlet is a special type of geo-morphology systems in the coastal region, which is of interest to geo-morphologists and engineers. In a lagoon the water area is usually protected by barriers and connects to the open sea only through a narrow gate. This makes it an excellent region for marine organism breeding, recreation, and reclamation. Human's impact on this fragile geological environment has caused some adverse effects such as gate migration, water pollution, and ecological and environmental deterioration (Zhang et al. 1995, 1999; Feng 1998; Tian and Li 2006). These impacts also lead to the recognition of the need to investigate its origin and development, in order to exploit the sustainability and preserve its valuable resources (Ji 1998; Szuwalski and Morang 2001).

The Wanpingkou tidal inlet is located in the south beach along the Shijiu port in the Rizhao coastal area of Shandong Province (Fig. 1). The original area of the tidal flat in the lagoon is about 5.00 km^2 with a water area of about 1.00 km^2. The gate width of the tidal inlet is about several tens of meters. Originally, the tidal inlet has been stable. However, because of human's reclamation, most of its area became aquatic ponds and salt pans, and the lagoon area has been diminishing since the 1980s. When the Rizhao government planned to build a sailing boat station in 2002, the lagoon area was only 1/10 of its original size with a gate width of less than 10.00 m.

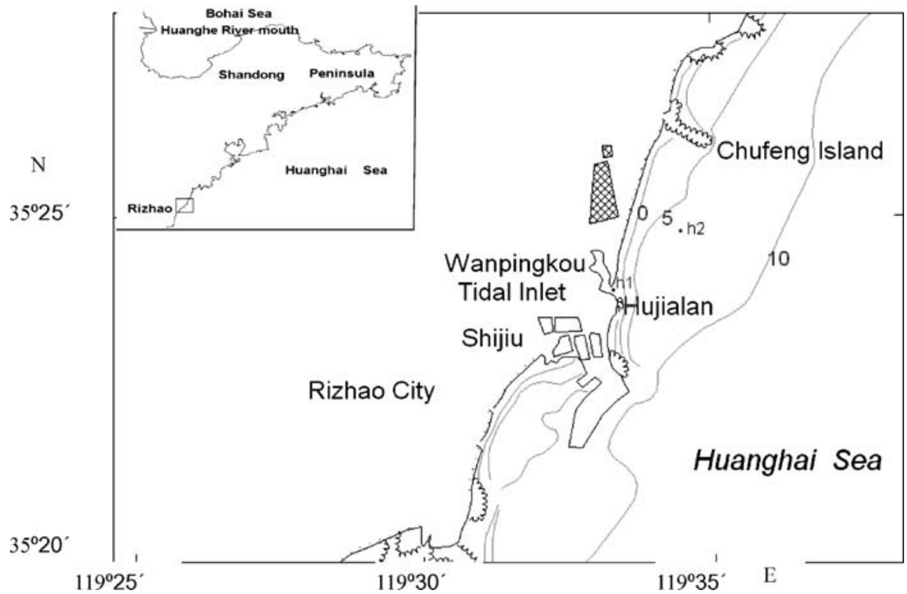

Fig. 1 The location of the Wanpingkou tidal inlet

According to the plan, the southern part of the lagoon would be exploited in the first stage of this project. An area of 1.56 km^2 would be dredged down to a depth of 2.00 m, while the gate located at the south would be widened to 100.00 m. With the newly built sailing boat station, the natural balance state of the tidal system would be broken. Meanwhile, geo-morphological changes might occur in the gates, the lagoon, and the barrier bars. In this study, we analyze the stability and development mechanism of the Wanpingkou tidal system, and propose some proper engineering measures to keep its natural balance after the building of a sailing boat station. We also forecast geo-morphological changes using mathematical equations, and compare the forecast results with the monitoring data.

Geo-morphological settings

The Wanpingkou tidal inlet was developed from a small set-off river mouth located at the south of the Shijiu-Baima beach. The beach is about 25.00 km long with the main sediments of coarse and middle sands. There are two or three rows of dunes bordering the beach at the land. A big river, Baima, enters the sea into the north of the beach, which brings abundant sand for the development of its geo-morphology in the coastal zone.

Waves recorded in 2002 indicated that the prevailing waves were from northeast (NE) and east (E) directions. The heights of about 87% waves were lower than 0.70 m, whereas about 0.7% of the waves were higher than 1.6 m. The normal waves were broken at a depth of about 2.00 m and made most sediment in motion (Chang 1986). Therefore, the net long-shore sediment transports are directed towards south with a rate of about 5.00–10.00$\times 10^4$ m^3/a, while the uni-transport rate directed to the north or the south is about 10.00–20.00$\times 10^4$ m^3/a (Cui 1986; You 1986).

The mean tidal range is about 3.00 m, which may form strong tidal currents at the gate area. According to our survey, the maximum current velocity is about 0.60–0.90 m/s towards the NE, which is much higher than that the offshore component. Usually, ebb currents dominate and show longer duration and higher maximum velocity than those of flood currents. They are clearly different from those offshore currents (Table 1). In addition, small tidal flats and tidal channels were developed inside and outside of the gate due to the current. The tidal channel outside the gate extends to the ENE direction, which is almost the same as the ebb current, with a depth of 0.00–1.50 m, a width of less than 10.00 m, and a length of about 100.00 m. Obviously, tidal channels and tidal flats in the Wanpingkou tidal system are small and not well-developed. Thus, many geo-morphological units in classic flood and ebb tidal deltas (Hayes 1975) are absent in the area because of the effect of strong wave actions.

Table 1 The maximum flood/ebb current in the Wanpingkou tidal inlet

Position	Stations	Depth (m)	Items	Surface		Bottom	
				Flood current	Ebb current	Flood current	Ebb current
Offshore	h1	1.00	Duration (h)	4.00	9.00	4.00	9.00
			Velocity (cm/s)	64.20	87.60	64.80	89.40
			Direction	SSW	NNE	SSW	NNE
Gate of the tidal inlet	h2	6.00	Duration (h)	6.00	6.00	5.00	7.00
			Velocity (cm/s)	37.50	21.10	39.30	15.80
			Direction	W	E	W	NEE

Stability analysis

The development of the Wanpingkou tidal inlet is mainly affected by both waves and tidal currents. Its stability is related to the ratio of the tidal prism (*P*) over the long-shore sediment transport rate (*M*) (Bruun et al. 1975). The units of P and M are m^3 and m^3/a (e.g., /a means annually), respectively. According to Bruun et al. (1975)

1. If P/M is more than 300, the tidal inlet is relatively stable and the sediment of the tidal inlet would not be considered to involve in the littoral sediment movement;
2. If P/M is less than 100, the tidal inlet is instable and the sediment of the tidal inlet would be considered to involve in the littoral sediment movement.

This implies that the tidal inlet is more stable under a bigger tidal prism and smaller wave energy. Otherwise, it deposits more easily under the stronger littoral drift (Wang 2004). In the Wanpingkou tidal inlet, the original mean tidal prism is about 1.80×10^7 m^3 and the sediment transport rate is about 5.00–10.00×10^4 m^3/a. So the *P*/*M* is varying from 180–360. This means that the tidal inlet is marginally stable. After the reclamation, the tidal prism would be decreased, while the sediment transport rate along-shore would be increased. As a result, the tidal inlet becomes less stable. The littoral drift entered the tidal inlet and caused the water area of the lagoon to be diminished and the gate to be narrower. However, with the newly being built sailing boat station, the water area of the lagoon will be enlarged again by dredging down to 2.00 m. To make sure that the sailing boats enter or go out safely, the gate will be widened to 100.00 m. Such a width would probably lead to an unstable tidal system.

The cross-sectional area (*A*) at the gate and the tidal prism (*P*) of a natural tidal inlet can be expressed as (O'brien 1931; Jarrett 1976; Kraus 1998; Carr de Betts and Mehta 2001)

$$A = CP^n \tag{1}$$

where *C* and *n* are the coefficients. According to Zhang and Li (1994), *C* is 0.085 and *n* is 1.02 for the tidal inlets along Bohai Sea and Yellow Sea. The gate of the Wanpingkou tidal inlet will be 22.40 m wide after the sailing boat station is built, which is obtained from the above-mentioned relationship. This width would result in the littoral drift entering the tidal inlet (Table 2). Therefore, a special structure should be made to trap the alongshore transported sediments out of the tidal system to protect it from littoral deposition and to ensure that the proper operation of the sailing boat station.

Monitoring and modeling of geo-morphological changes

The feasible structures for the sailing boat station

To keep the alongshore sediments out of the tidal inlet, jetties should be built at both sides of the gate. The jetties should extend east to a depth of 2.00 m, corresponding to the depth of active sediment movement and the depth to be dredged down. Since the sediments are transported more to the south than to the north, the north jetty should be longer than the south one, with the end turning towards the south to

Table 2 The computed width of the gate of the sailing boat station

P (km^3)	*A* (km^2)	*h* (Depth, m)	*B* (Width, m)
1.50×10^{-3}	1.12×10^{-4}	3.00	22.40

protect the water area of the sailing boat from strong wave actions (Fig. 2). The length of the south jetty should be about 200.00 m, whereas the north one should be about 500.00 m.

Geo-morphological changes of the sailing boat station

Erosion and deposition in the water area of the gate

After the jetties are built, the sediment transported alongshore will be kept out of the tidal inlet. The deposition will be only caused by the settlement of suspension in the water area of the lagoon and at the gate. Using the Eysink and Vermas equation, the deposition rate caused by suspension in a recession water area (Sun 1989) can be written as

$$T_s = P \times C_m \times \frac{W_e}{Ad} \tag{2}$$

where T_s is the deposition rate (m/a) annually;

C_m is the mean suspension content in the flood water (kg/m^3) and taken here as 0.021;
W_e is the volume of the exchanged water in a tidal circle (m^3);
A refers to the area of the recession water area (m^2);
d is the dry volume weight of sand (kg/m^3) and
P is the settlement rate and approximated here as 99% based on experience.

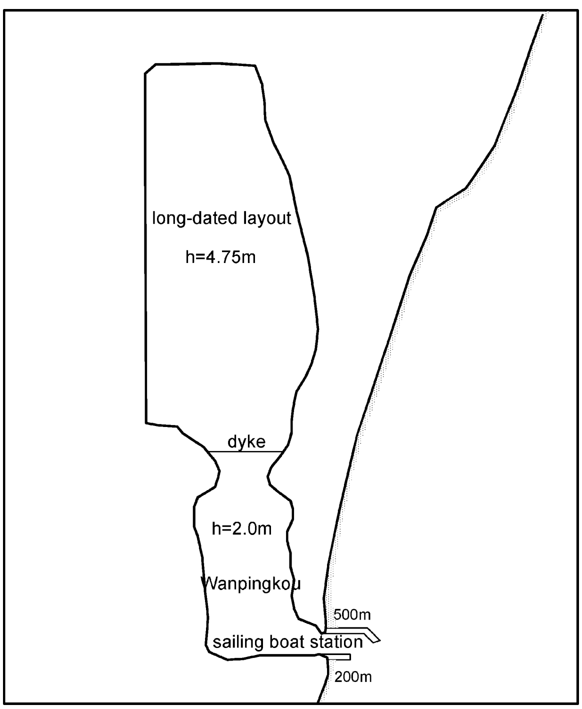

Fig. 2 The plan of the jetties of the sailing boat station

According to the computation, the deposition rate in the lagoon and at the gate is about 0.02–0.03 m/a after the water area is dredged. This implies that the water depth of the tidal inlet could be maintained well.

The shoreline changes

Rapid changes will occur on the shoreline adjacent to the tidal inlet because of the cut-off of the littoral drift after the jetties are built. The one-line model of GENESIS is developed for simulating the movement of the shoreline produced by the differences in alongshore sand transports at the open coast. The model can be used to forecast the shoreline changes that are caused by such diverse factors as irregular bottom bathymetry, wave diffraction, boundary conditions, line sources and sinks of sand, and constraint on the transport produced by seawalls, groins and jetties (Mark et al. 1991). We applied the GENESIS model to simulate the shoreline movement nearby the Wanpingkou tidal inlet after the jetties were built.

Data modeling

The GENESIS model

An equation governing shoreline change in the one-line model can be expressed as

$$\frac{\partial y}{\partial t} + \frac{1}{D}\frac{\partial Q}{\partial x} = 0 \tag{3}$$

In the equation, a right-handed Cartesian coordinate system is used in which the *y*-axis points offshore and the *x*-axis is oriented parallel to the trend of the coast. Q is the alongshore sand transport rate, D is the closure depth for the alongshore sand transport, which is 7.00 m in the Wanpingkou coast, and t is the time span. Q can be expressed as

$$Q = \left(HC_g\right)_b\left(\alpha_1 \sin\alpha_b - \alpha_2 \cos\alpha_b \frac{\partial H_b}{\partial x}\right) \tag{4}$$

where H is the significant wave height in deep water, C_g is the wave group speed given by the linear wave theory, subscript b donates wave breaking conditions,

Table 3 Simulated results of the north jetty in the Wanpingkou sailing boat station

Distance alongshore (m)		250	500	750	1,000	1,250	1,500	1,750 (The jetty)
Shoreline change (m)	1 year	−0.60	3.20	0.30	2.90	1.50	3.00	3.00
	2 years	−0.70	3.50	0.30	4.90	3.30	5.30	7.00
	3 years	−0.80	3.50	0.30	5.00	3.50	5.60	8.50

α_b is the angle of breaking waves to the local shoreline, α_1 and α_2 are non-dimensional parameters, which are given by

$$\alpha_1 = \frac{k_1}{16(R-1)(1-p)} \tag{5}$$

$$\alpha_2 = \frac{k_2}{8(R-1)(1-p)\tan\beta} \tag{6}$$

where k_1 and k_2 are empirical coefficients, as a calibration parameter taken to be 0.25 and 0.78, respectively, $R = {}^{\rho_s}/_{\rho}$, p=0.40 is the porosity of sand on the bed, tan β is the average of profile slopes.

Application of the model

The coastal line of the model is 2.00 km long, and begins at the north and ends at the south of the north jetty. Since it is close to the cape of Shijiuzui and its beach is very short, we did not simulate the shoreline change in the south of the jetty with the model.

In the model, the x-axis is oriented to the south and the y-axis directs to the east. Wave data in the deep water were collected from the Shijiu Wave Observation Station (SWOS) in 2002. The water depth and the original shoreline were read from the sea chart. The shoreline is divided into grids 100.00 m long for the model.

Data simulation

Based on the computed results of the model, the shoreline of about 1.30 km long north to the jetty would move seaward if the north jetty was built. The shoreline close to the jetty would undergo a significant change, and would also move seaward less farther from south to north than always from the jetty. But the shoreline located in 1.50 km far from the jetty would move landward a little bit.

The rate of the shoreline change reduces slowly and gradually. Maximum change occurs in the first year at a rate of 0.30–3.20 m/a. This rate decreases to 0.10–2.30 m/a in the second year. According to the simulation, the shoreline will be relatively stable and then keep its balance after 3 years after the jetty is built (Table 3 and Fig. 3).

Field monitoring

No major storm occurred within the first 2 years after the sailing boat station was built in Wanpingkou. The office of the sailing boat station monitored the topography in and out of the tidal system. It was found that the littoral drift had been caught by the jetties. The depth in the water area of the lagoon and at the gate was almost same as before. The beach adjacent to the jetties was depositing at a rate which is very similar to the model simulation slightly larger than the data simulation. The shoreline north to the jetty moved seaward 15.00 m in the first year, and then decreased to 5.00 m in the second year. Clearly, these results are higher than our simulation. The main reason probably is that there was no storm during the past 2 years. Therefore, a long-term monitoring is required in the area.

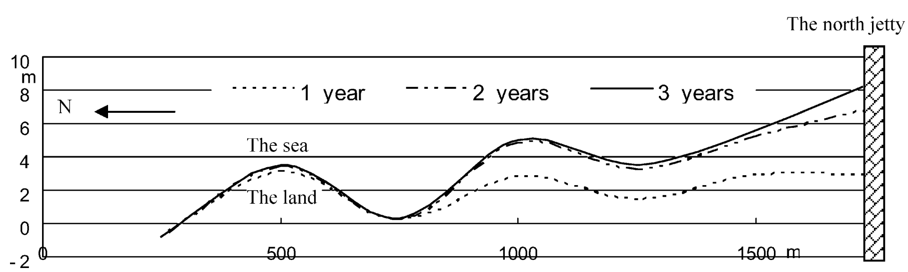

Fig. 3 Simulation results of the shoreline change with the building of the north jetty

The monitoring results also show the shoreline has changed in the south of the jetty. The shoreline close to the jetty moved seaward less than 10.00 m within the past 2 years. This is much smaller than that in the north of the jetty. But in the southern part near the Shijiu Cape, the shoreline was relatively far from the tidal inlet. As a result, it was eroded very little because there is the cut-off of the net littoral drift from the north to the south by the jetties.

Discussion and conclusions

The sailing boat station at Wanpingkou is a beneficial use of the small tidal system in the sandy coast. The disturbance due to human activities showed various impacts on the tidal system. Further investigations of the geo-hydrodynamic mechanism of the tidal system should be carried out and other projects should be developed in accord with the order of nature in the tidal system. In the sailing boat station, the jetties were built on both sides of the passage, taking into account the sediment movement under the tidal currents and waves. Since the littoral drift was blocked, it effectively protects, as expected, the water area from being enlarged and the tidal inlet from being widened. However, this probably has some adverse impacts when the shoreline changed adjacent to the jetties in the area. Since the sediment at the end of the north jetty possibly goes around of the jetty, it might be carried into the tidal system by storms. However it was neither observed nor forecasted by the monitoring data and modeling in the study. Therefore, non-structural alternatives and jetties should be adopted to reduce the shoreline change and to keep them pristine. Periodic monitoring of the beach adjacent to the jetties should be carried out. The sand caught by the north jetty should be dredged for the replenishment of the eroded beach at the south of the jetties. A long-term balance of the natural coastal zone shall be kept and a sustainable development can be achieved.

Our conclusions can be summarized as follows:

1. With the plan of a newly built sailing boat station, the lagoon’s water area was dredged, while the gate was widened in the Wanpingkou tidal system. Jetties were built at both sides of the gate in order to trap the alongshore transport sand out of the tidal inlet and to protect the tidal system from deposition;
2. The shoreline adjacent to the jetties moves seaward. Due to the truncation of the net sand transport, there is little erosion in areas away from the south jetty. But the deposited sand beside the north jetty may make a round at the end of the jetty, and probably arrive into the tidal system in storms;
3. Non-structural alternatives and the jetties should be made to maintain the shoreline so as to protect the sailing boat station;
4. The shoreline changes will also affect the coastal water and wetland environment in the region. Further field monitoring in the area is needed to maintain the balance condition of the tidal system and the sailing boat station for sustainable development.

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