

The observations of seabed sediment erosion and resuspension processes in the Jiaozhou Bay in China

LIU Xiaolei^{1, 2}, ZHU Chaoqi^{1, 3}, ZHENG Jiewen², GUO Lei⁴, YIN Ping⁴, JIA Yonggang^{1, 2*}

¹ Shandong Provincial Key Laboratory of Marine Environment and Geological Engineering, Ocean University of China, Qingdao 266100, China

² Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, China

³ Key Laboratory of Marine Environmental and Ecology, Ministry of Education, Ocean University of China, Qingdao 266100, China

⁴ Qingdao Institute of Marine Geology, Chinese Geology Science, Qingdao 266071, China

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Abstract

In estuarine and coastal areas, the seabed is in a constant process of dynamic change under marine conditions. Seabed sediment erosion and resuspension are important processes that safely control the geological environment. Field tripod observations conducted in the Jiaozhou Bay in China are reported, to investigate the effects of hydrodynamic conditions on the erosion and resuspension processes of the seabed. The observational results show that the maximum shear stress created by tidal currents can reach 0.35 N/m², which is higher than the wave-induced shear stress during fair weather conditions. A seabed erosion frequently occurs during the flood tide, whereas a seabed deposition occurs during ebb tide. Waves can produce a bottom shear stress approximately equivalent to that induced by currents when the local wind reaches Force 4 with a speed of 5 m/s. When the wind reaches 7 m/s and the significant wave height reaches 26 cm, waves play a more significant role than currents in the dynamic processes of the seabed sediment resuspension and lead to a high value of turbidity that is approximately two to eight times higher than that in fair weather. These analyses clearly illustrate that periodic current-induced sediment erosion and resuspension are dominant in fair weather, whereas episodic high waves are responsible for significant sediment resuspension. Additional work is needed to establish a more thorough understanding of the mechanisms of sediment dynamics in the Jiaozhou Bay.

Key words: seabed sediment, erosion, resuspension, tripod, Jiaozhou Bay

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1 Introduction

In the shallow coastal waters and deep sea, both anthropogenic and natural processes can regulate sediment erosion and resuspension processes and then influence the chemical, biological and physical characteristics of marine environments (Birja et al., 2015; Churchill, 1989; Ferré et al., 2008; Martín et al., 2014). Moreover, anthropogenic activities have effects on the sediment erosion and resuspension processes in the vicinity of the sources while the natural process generally operates on a larger scale (Sabol et al., 2005). In the shallow coastal waters, both waves and currents play a fundamental role in the physical and biological functioning of coastal systems. The interaction between the hydrodynamic conditions near the seabed and the seabed sediment controls and affects the sediment erosion and resuspension processes and also contributes to the variation of the geological environment for marine engineering facilities (Sumer et al., 1999). In general, wave- and current-induced bottom stresses act as key factors in assessing the sediment resuspension behaviour (Grant and Madsen, 1979; Jing and Ridd, 1996). Recent successful modelling of coupled waves and currents has provided valu-

able insight in characterizing the sediment dynamic processes in shallow waters (e.g., Dalyander et al., 2013). However, the processes of sediment erosion and resuspension are more complicated and there is no suitable model that can be applied in any seawater environment when considering the differences in specific shorelines, topography, bed forms, sediment types, and other unforeseen factors (Green and Coco, 2014).

It is well known in the scientific world that China's coastal seas are characterized by high turbidity, particularly in the estuarine areas of large rivers that carry several billion tons of sediment into the sea annually (Milliman and Syvitski, 1992; Ren, 2015). However, recent evidence shows that the sedimentary dynamic system is also complicated in the estuarine areas of small and medium-sized rivers (Liu et al., 2008b). The semienclosed mouth of the Jiaozhou Bay in the western Yellow Sea is an estuarine area characterized by a low sediment supply and a weak hydrodynamic environment that has attracted attention in sedimentology since the 1980s. On the basis of analyses of drilled sediment samples, earlier studies have confirmed that the distribution of sediment particles was related to sediment sources and

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*Corresponding author, E-mail: yonggang@ouc.edu.cn

local hydrodynamic conditions (Wang et al., 1982; Zheng and Shen, 1986). A sedimentation rate is 0.64–1.74 cm/a, based on the sediment cores isotope determination and sediment balance principle (Li et al., 2003; Liu et al., 2008a). Wang and Gao (2007) investigated the transport tendencies of sediment in the Jiaozhou Bay through particle analysis, turbidity measurements and historical data analysis and noted that a significant relationship existed between the temporal and spatial distributions of suspended sediment concentrations and hydrodynamic conditions, terrestrial runoff, and weather conditions. A tidal current can be considered the primary sedimentary dynamic force contributing to the formation of deltas inside the Jiaozhou Bay (Dong et al., 2006). Yuan et al. (2008) deployed a suite of optical and acoustic instruments in this area to study sediment dynamics over two semidiurnal tidal cycles and proposed that a tidal-induced bottom shear stress was a primary stirring factor. There is common understanding that interactions between hydrodynamic forces and the seabed sediments in the Jiaozhou Bay may be a dominant mechanism for removing sediments from coastal deposits and delivering them across the bay mouth (Wang and Gao, 2013). However, it remains unclear how these hydrodynamic forces impact the bottom boundary layer in different environments. This dynamic mechanism must be further studied through comprehensive *in situ* observations.

The studies on the sediment transport off China's coast have been typically performed with data from moorings and a numerical simulation (Du et al., 2010; Jia et al., 2014a; Kong et al., 2011), which provide a good view of processes in a water column (Yang et al., 2007, 2008) but require assumptions to be made about processes occurring in the bottom boundary layer. Recently, some observation instruments were used in study on the sediment erosion and resuspension processes. Perez et al. (2010) described a new *in situ* observation platform to measure shear stress and erosion rate constant of underwater sediments. Some observation instruments were even utilized in deep water to study a deepwater sediment transport, such as turbidity currents (Talling et al., 2015; Xu et al., 2014; Zhang et al., 2014; Zhao et al., 2015). We also developed an underwater *in situ* tripod to study the bottom boundary layer and deployed it in the Baisha Bay (Zhu et al., 2017a) and the Huanghe River subaqueous delta (Zhu et al., 2017b, c). This time an *in situ* bottom-instrumented tripod was deployed in the Jiaozhou Bay to collect data. The synchronous observational results of the hydrodynamic conditions, the turbidity, and a sea floor interface allow us to analyse the sediment dynamic processes in different sea conditions and discuss the mechanisms of the sediment erosion and suspension from the bottom. The findings in this paper may also provide a guidance to fisheries production and marine engineering construction.

2 Study site

The Jiaozhou Bay is located on the shore of the Yellow Sea on the southeast coast of the Shandong Peninsula with a narrow (3 km) inlet. It is a typical semienclosed bay in the shape of a trumpet, with a width of 15 km from east to west and 18 km from north to south. The average water depth is 7 m and the maximum water depth is 64 m (Zhao et al., 2002). The study site is located in the southwest part of the bay (36°7'36"N, 120°10'36"E). The dominant wave direction is consistent with the wind. Inside the bay, the sea states are generally characterized as calm-rippled or smooth-rippled, and few states exceed moderate. Tides in the bay are regular semidiurnal tides with a maximum tidal range of 4.75 m and a mesotidal range of 2.80 m (State Oceanographic Ad-

ministration, 1993). The flood current is greater than the ebb current, and the flood time is less than the ebb time. The bed sediments in the bay and the Yellow Sea are dominated by silt and clay (mineral content being greater than 90%), although deposits toward the bay mouth become coarser due to the entrainment of tidal currents. The existing borehole data show there are five sediment layers in the sequence of mucky soil, silty clay, medium to coarse sand, silty clay and coarse to gravel sand (Bai, 2005). Given that the upper layer has a direct interact with the sea water, the mucky soil is the most important part for us to understand the erosion and resuspension processes of the seabed. The geotechnical test results for the upper layer showed a high void ratio of 1.07–2.57 and high water content of 26.3%–83.2%. On the basis of a grain-sized data set of *in situ* bottom grab samples analysed in the laboratory, a significant portion of silt is revealed and the seabed sediment can be classified into medium silt ($d_{50}=0.026$ mm) on the Wentworth scale (Lane, 1947).

3 Methods

3.1 Instrumentation and deployment

The *in situ* observation was conducted between September and October 2012 using a bottom-supported tripod at the study site (Fig. 1). The bottom-supported tripod was made of steel with the length of 2 m and the height of 1 m and developed to monitor sediment dynamics near the bottom boundary layer. Three cables with equal length were raised up from a stable base in order to set and retain the tripod. As shown in Fig. 2, mounted instruments include two water gauges (TWR-2050, RBR Company, Canada), two current meters (AEM-HR, Alec Electronics Company, Japan), a turbidity meter (XR-420 CTD+Tu, RBR Company, Canada), and two autonomous altimeters (AA400, EofE Ultrasonics Company, Korea). The sampling frequency was 10 min for both the wave gauges and the turbidity meter, 5 min for the autonomous altimeters, and 30 min for the current meters. The detailed elevation and parameters of the instruments mounted on the tripod are summarized in Table 1. This sampling regime produced a good temporal and spatial resolution of the variations in waves, currents, turbidity, and seabed erosion and deposition processes throughout the entire observation period.

Prior to the *in situ* observations, the equipment was fixed on the tripod and divers entered the sea to survey the sea floor and ensure that the marine environment satisfied the practical requirements of each piece of equipment. A winch on the deck was used to sling the tripod and place it in the chosen location of the study area with the assistance of the divers. Once the tripod was set on the bottom of the sea, divers again submerged into the sea to examine the state of the *in situ* observation tripod; a mooring rope tied to a buoy was fastened to the tripod to warn passing ships and pinpoint the facility. After the observations were completed, divers reconnected the lifting hook of the tripod to the winch, recovered the tripod and placed it on the deck.

3.2 Calculation of shear stress

The wave forces exerted on the seabed can be classified into a vertical dynamic loading and a horizontal shear force (Jia et al., 2014c). Both linear wave theory and nonlinear wave theory can determine a wavelength and shear stresses (Gao et al., 2003; Jeng and Lin, 1997; Jeng, 2013; Ye et al., 2014). In this paper, the linear wave theory was used in terms of both accuracy and simplification.

The horizontal shear force (Sheng and Lick, 1979) can be calculated as follows:

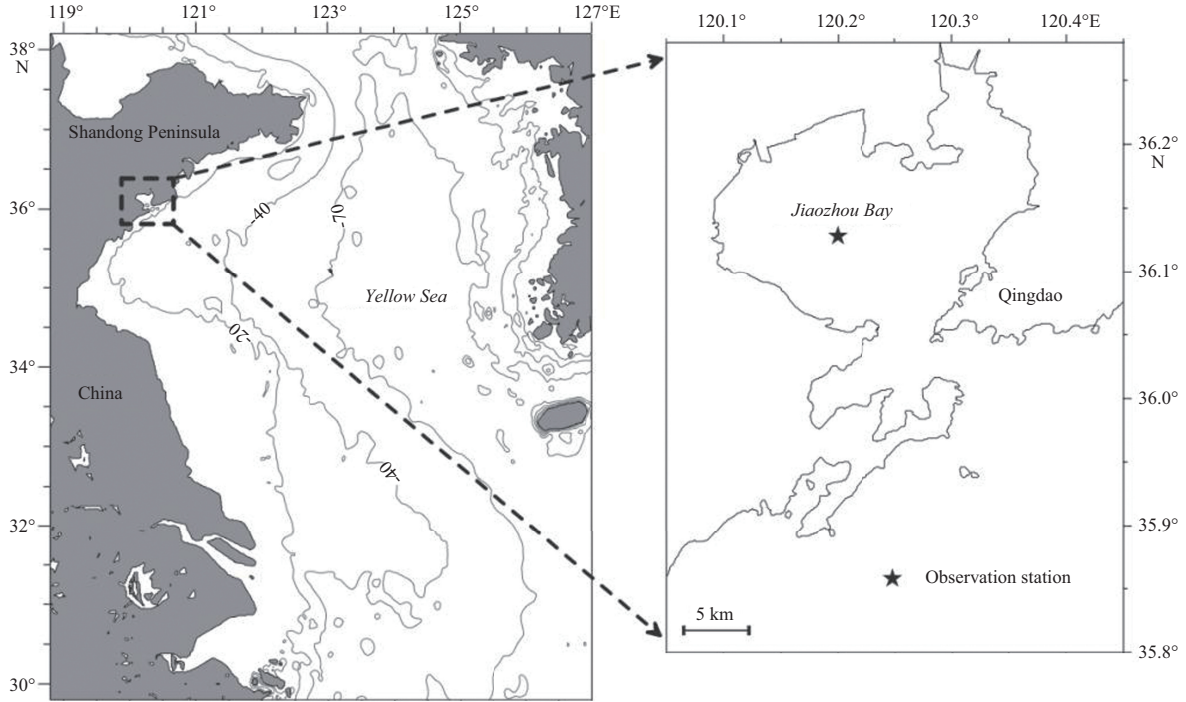


Fig. 1. The maps of the Jiaozhou Bay and the location of the observation station.

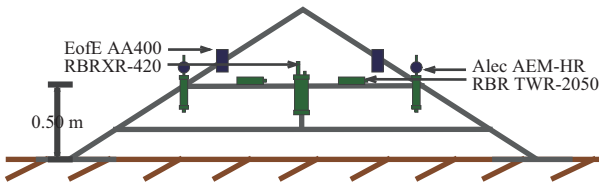


Fig. 2. Depiction of the observational set-up. Two water gauges (RBR TWR-2050), two current meters (Alec AEM-HR), a turbidity meter (RBR XR-420 CTD+Tu), and two autonomous altimeters (EofE AA400) were mounted on the tripod as depicted in the figure.

$$\tau_w = \rho f \mu^2 \cos^2(2\pi t/T), \quad (1)$$

where ρ is the bulk density of the sea water ($1.03 \times 10^3 \text{ kg/m}^3$); t is the time (s) variable; T is the significant wave period (s); f is the wave friction coefficient; and μ is the horizontal orbital velocity (cm/s) of the waves on the sea floor surface. The latter (Madsen, 1976) can be calculated as follows:

$$\mu = \pi H / [T \sin h(2\pi h/L)], \quad (2)$$

where H is the significant wave height (cm); h is the water depth (m); and L is the significant wave length (m) at elevation h . L and f (Jiang et al., 2000) can be obtained as follows:

$$L = (gT^2/2\pi) \tan h(2\pi h/L), \quad (3)$$

$$f = \exp[-6 + 5.2(A_\delta/K_s)^{-0.19}], \quad (4)$$

where A_δ is the near-bottom excursion amplitude, which can then be obtained by using $A_\delta = H/[2\sin h(2\pi h/L)]$; and K_s is the

bottom physical roughness (Nielsen et al., 2001), at 0.2 mm in this paper.

The current-induced shear stress (Sheng and Lick, 1979; Hawley, 2000) can be calculated as follows:

$$\tau_c = \rho \gamma^2, \quad (5)$$

$$\gamma = k\gamma_z / \ln(z/z_o), \quad (6)$$

where γ is the hydrodynamic coefficient; $k=0.4$, is the Karman constant; γ_z is the current velocity (cm/s) at the water depth z ($z=0.55 \text{ m}$ in this case); and z_o is the bottom physical roughness (Hawley, 2000), also at 0.2 mm in this paper.

4 Results

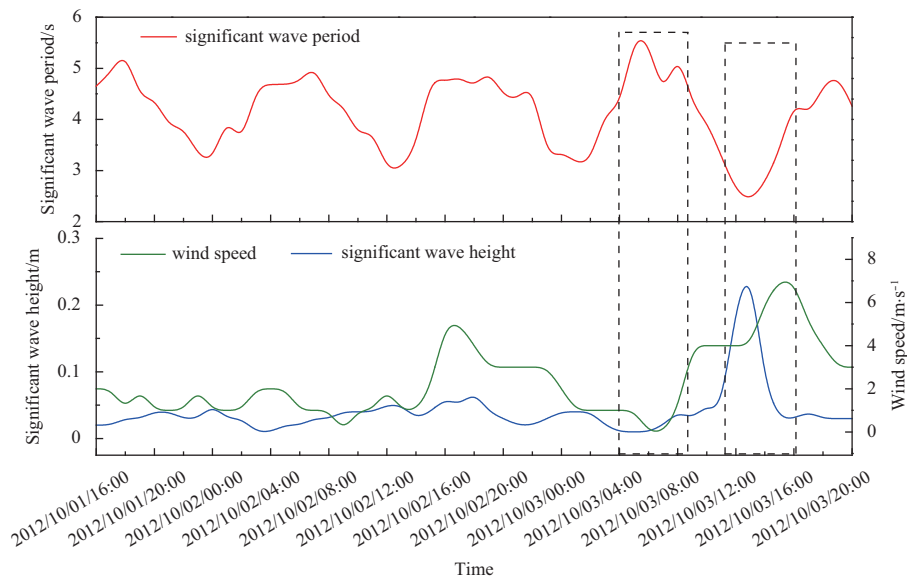
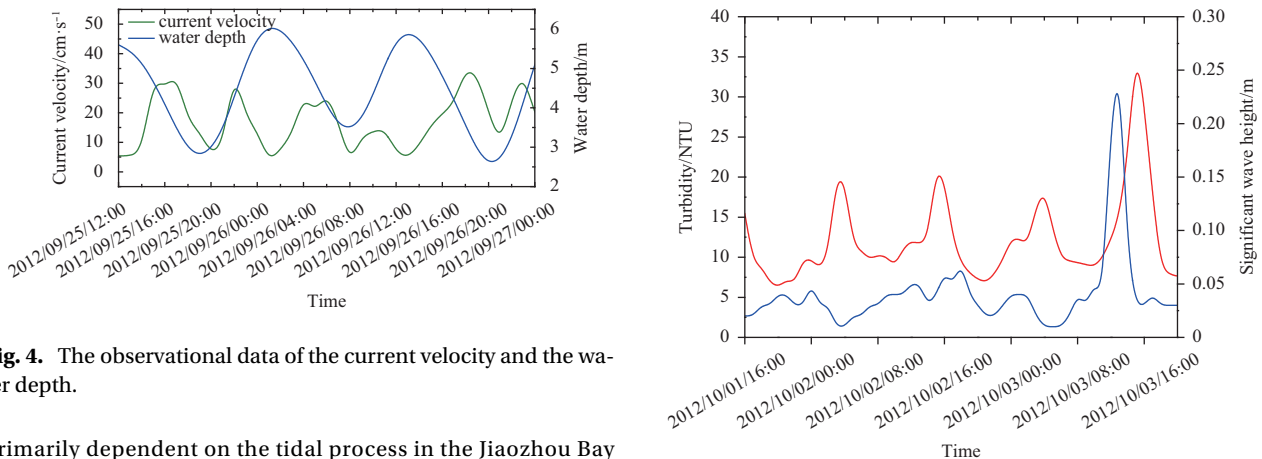
4.1 Hydrodynamic results

The evolutions of the wave period, wave height, and wind speed over the observation period are depicted in Fig. 3. A significant meteorological event occurred on October 3, 2012 and the wind speed increased to a maximum of 7 m/s at 13:00. The significant wave period was longer when the wind speed was relatively low, with values ranging from 2.5 to 5.6 s over the entire period; there was more congruence between the wind speed and the wave height (Talke and Stacey, 2008). The significant wave height increased from a minimum of 0.01 m during the meteorological event to a maximum of 0.26 m (Fig. 3).

Two days of current data were collected at the study site from 25 to 27 September, 2012 (Fig. 4). It should be noted that no current velocities were reported for the later days (Fig. 3) because the quality of the current meter data was insufficient. The variations in the current velocities during the two periods were approximately the same as the symmetrical time of the astronomical tide when considering that the current conditions were

Table 1. Observational instruments mounted on the tripod and their parameters and distance in meters above bed.

Instrument	Type	Elevation/m	Precision	Sampling interval/min
Water gauge	RBR TWR-2050	0.50	5 mm	10
Current meter	Alec AEM-HR	0.55	1 cm/s	10
Turbidity meter	RBRXR-420 CTD+Tu	0.55	2%	30
Altimeter	EofE AA400	0.55	1.0 mm	5

**Fig. 3.** The observational data of the significant wave period, the significant wave height, and the wind speed.**Fig. 4.** The observational data of the current velocity and the water depth.

primarily dependent on the tidal process in the Jiaozhou Bay (Yuan et al., 2008). The observational results show that the current velocity presents a periodical variation with the tidal process, with the maximum velocity appearing 1.5–2.0 h before the highest tide. The maximum current velocity reached 36 cm/s and the minimum velocity was 3 cm/s (Fig. 4).

Figure 5 shows the observational results of the turbidity and significant wave height from 1 to 3 October, 2012. There are four peak values of turbidity. The last peak value of the turbidity is near 35 NTU and it is significantly greater than other previous peak values. Further, the significant wave height increases sharply during the last peak value of turbidity in despite of a phase difference. However the three previous peak values of the turbidity do not change with the significant wave height. Therefore we can conclude that only episodic high waves were responsible for significant increases in the turbidity and the sediment resuspension.

Fig. 5. The observational data of the turbidity and the significant wave height.

4.2 Sediment dynamic results

The observational data of the turbidity, altitude, and water depth collected by the RBRXR-420 CTD+Tu and the EofE AA400 are presented in Fig. 6. The distance, measured by EofE AA400 from its sensor to the seabed, can reflect a seabed altitude variation. The time-series curves show that four obvious increases in the water turbidity occurred during the observation period, three of which were closely related to the periodical tidal process. The turbidity gradually increased to its highest value during the flood tide process and then decreased to a normal value (7–10 NTU). The altitude also presented a similar variation trend to the turbidity, indicating that the seabed sediment experienced a pro-

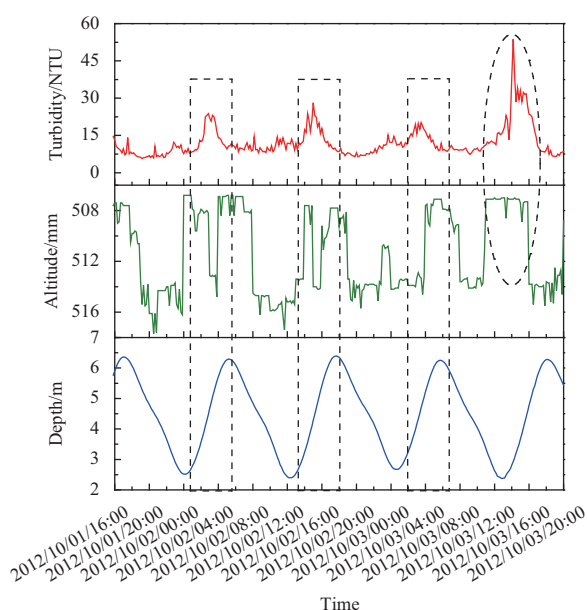


Fig. 6. The observational data of the turbidity, the altitude, and the depth.

cess of resuspension and redeposition during the flood tide. The fourth increase in the turbidity was likely induced by a meteorological event occurring on October 3, 2012. The turbidity value reached approximately 53 NTU, which suggests a clear deposition-like phenomenon because the relative distance between the surface of the sea floor and the autonomous altimeter decreased to a low level. A possible explanation is that the seabed sediment is softened by the cyclic wave loading in the windy sea conditions (e.g., Davidson-Arnott and Langham, 2000). Variations in the strength of local seabed sediment would lead to the sediment erosion and the variation of tripod location (Lambrechts et al., 2010; Kirca, 2013), thus producing the observed behaviour.

5 Discussion

It has been shown that both waves and currents are important to sediment resuspension in shallow coastal waters (Jing and Ridd, 1996; Warrick, 2013), although they make different contributions in different sea conditions (Green et al., 1997; Desguée et al., 2011). By providing the calculated bottom shear stresses based on the observational data, the results of this study offer some insight into the mechanism for sediment resuspension in the semienclosed Jiaozhou Bay. The time series of the bottom shear stresses induced by both currents and waves are shown in Fig. 7. The periodic maximum current-induced bottom shear stress is 0.35 N/m^2 (Fig. 7a), which is considerably greater than the wave-induced bottom shear stress ($0.01\text{--}0.11 \text{ N/m}^2$) during fair weather conditions (i.e., Period I; Fig. 6b). This suggests that the tidally induced sediment resuspension is dominant on a small scale in fair weather when the tidal currents are responsible for the driving forces; this is consistent with another observation study from Yang et al. (2004). However, the effects of waves on the sediment resuspension should be magnified during windy weather because wave parameters are assumed to be proportional to the wind speeds (Chang, 1991). In comparing the observational hydrodynamic conditions with the calculated bottom shear stresses under waves and currents (see Figs 3 and 7), it is estimated that waves can produce a roughly equivalent bottom shear stress to that induced by currents when the local wind

reaches Force 4 with a speed of 5 m/s . It is thus apparent that waves play a dominant role in the process of the sediment resuspension in this area for weather conditions with a wind speed more than 5 m/s . We noted that there were rough sea conditions during the observation (i.e., Period II, Fig. 7b) when the wind reached 7 m/s and the significant wave height reached 26 cm , leading to an abrupt increase in the bottom shear stress. The high value (up to 53 NTU) of the water turbidity measured by the turbidity meter, approximately two to eight times higher than that in fair weather, indicated that significant sediment resuspension occurred due to the wave-sediment interaction.

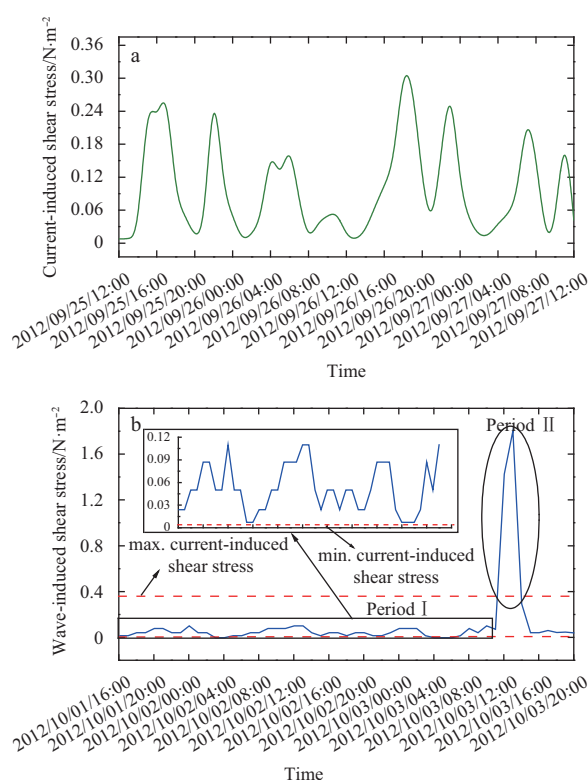


Fig. 7. The time series of the bottom shear stress induced by currents (a) and waves (b) calculated by the observational data.

Seabed liquefaction is another important process in the wave-sediment interaction that causes a considerable change in seabed properties in the short term, owing to the vertical cyclic loading and corresponding accumulation of the pore water pressure (Jia et al., 2011; Liu et al., 2013, 2017; Ye and Wang, 2016). Further seabed liquefaction can induce submarine landslides on the ocean floor and pose a great threat to submarine structures (Huang et al., 2015; Jeng, 2011; Jia et al., 2016). It should be noted that during the high turbidity of windy weather there is a clear sign of seabed “deposition” in the altitude data, as seen in Fig. 6. We thus speculate that the bottom-supported tripod subsides due to the wave-induced seabed liquefaction. The strength of the seabed can be reduced when the pore water pressure accumulates inside the sediment under wave cyclic loadings (Zheng et al., 2013). The seabed sediment can be quickly liquefied from its surface downwards when the seabed is exposed to higher waves (Tzang, 1998). Further study also demonstrates that wind waves can considerably increase the bed erosion during the liquefaction process (Lambrechts et al., 2010) and significantly contribute to the sediment resuspension amount through the vertical

transportation of particles (Tzang et al., 2009; Jia et al., 2014b; Zhang et al., 2017). It is thus apparent that neglecting the effects of the vertical cyclic loading actions of waves in the resuspension calculation can lead to the underestimation of sediment resuspension (Qin et al., 2004). Unfortunately, specific instrumentations for the sediment liquefaction were not included in our observations, and further investigations will be needed to gain a more thorough understanding of the sediment resuspension in the Jiaozhou Bay.

6 Conclusions

An *in situ* bottom-instrumented tripod was set in the Jiaozhou Bay to synchronously observe the hydrodynamic conditions, turbidity, and sea floor interface in real time. The combined analysis of the observational results demonstrates the sediment dynamic processes in different sea conditions and displayed the mechanisms of the sediment erosion and suspension from the bottom in the semienclosed Jiaozhou Bay. The following conclusions can be drawn from the studies.

(1) The calculated bottom shear stress is sensitive to the periodic tidal currents and the local wind speeds at the study site. The current-induced sediment erosion and resuspension are dominant in fair weather, and the sediment resuspension induced by the tidal currents is low.

(2) The high waves in windy weather led to an abrupt increase in the bottom shear stress, and episodic high waves are responsible for significant increases in the amount of the sediment resuspension. A significant sediment resuspension results from wave-sediment interactions in windy weather, approximately two to eight times higher than that in fair weather.

(3) The seabed sediment can become liquefied and lose its strength under the action of wave-induced vertical cyclic loading, particularly in stormy sea conditions, and thus easily become eroded and resuspended from the bottom. Neglecting the effect of the vertical cyclic loading actions of waves in the calculation of the sediment resuspension can lead to an underestimation of the sediment resuspension.

Without integrating specific observations for sediment liquefaction, further investigations will be needed to establish a more thorough understanding of the sediment resuspension in the Jiaozhou Bay in China and other places.

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