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## Abstract

The benthic, or bottom, boundary layer (BBL) is the region of the ocean adjacent to the ocean floor. The complex dynamic process of the BBL is closely related to seabed stability and geological hazards. In this study, the subaqueous Yellow River delta, where submarine landslide and erosion occur frequently, was chosen to conduct in situ observations. Hydrodynamic data, including wave and current parameters, and seawater turbidity, was observed using a tripod observation system. Besides, the excess pore water pressure was observed simultaneously below the seabed surface at depths of 30 and 60 cm. Data analysis showed that wave-induced shear stress can lead to the slight seabed erosion, while wave-induced pore water accumulation inside the seabed can greatly contribute to the severe seabed erosion.

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## Keywords

Benthic boundary layer • Sediment re-suspension • Seabed erosion • Sediment liquefaction • Pore water pressure

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## 21.1 Introduction

As is known for its extremely heavy sediment load, the Yellow River discharges more than hundreds of millions of tons of sediment into sea each year, and approximately 80–90 % of these sediment loads is deposited within the range of 30 km around the current estuary (Saito et al. 2001). However, the modern Yellow River delta is subject to much more serious erosion after the estuary has been abandoned than the other deltas in the world (Meng et al. 2012).

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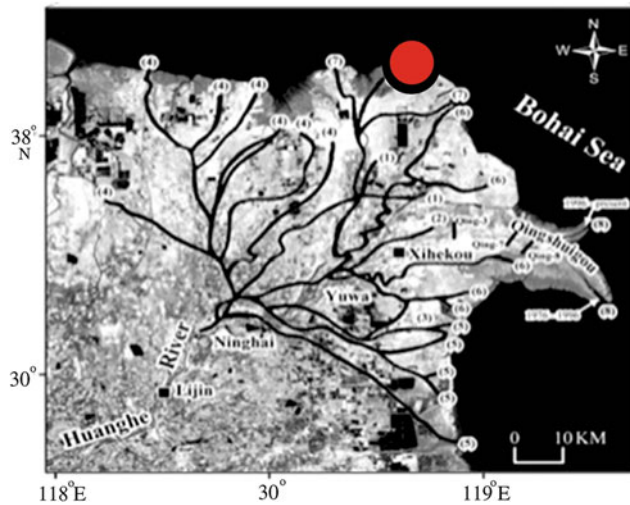
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Dynamic processes of the Benthic Boundary Layer (BBL) in the Subaqueous Yellow River delta can play a significant role in the mechanism of sediment erosion. Therefore, we conducted the in situ BBL observations to study the variation in suspended sediment concentration, seabed interface, and pore water pressure under different hydrodynamic conditions.

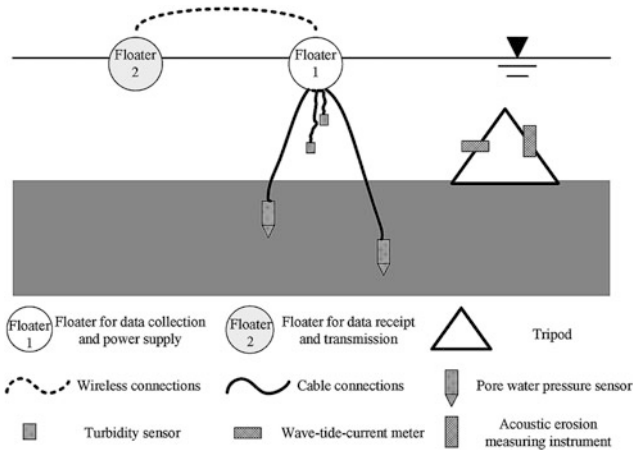
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## 21.2 Instrumentation and Experimental Sites

The shallow-water seabed we investigate in this study is situated in the northern subaqueous delta of the Yellow River forming during the period from 1964 to 1976 (Fig. 21.1). The tidal cycle for the test site is irregularly semidiurnal, with a mean tidal range varying from 0.7 to 1.7 m, and an extreme of 2.17 m. The maximum tidal flow rate is above 120 cm/s. The average wave height is less than 0.5 m, and the largest is 3.3 m. Under extreme conditions, the wave height can reach 5.8 m (Chu et al. 2006). The water



**Fig. 21.1** Location of the study site



**Fig. 21.2** The in situ observation system

depth at the experimental site ranges from 0.2 m to 2.6 m during the in situ observation period.

Over a 5 days period beginning on November 21, 2011 and ending on November 26, 2011 we deployed an array of hydrodynamic and sediment dynamic sensors on a tripod frame, including two turbidity sensors, two pore water pressure sensors, one sea gauge wave tide recorder, one kinemometer, and one acoustic erosion measuring instrument (Fig. 21.2).

## 21.3 Observational Results

### 21.3.1 Marine Hydrodynamics

In the observation region, the water depth ranged from 0.47 to 3.96 m, and the tidal range varied from 0.31 to 2.46 m, which was obviously influenced by north and northeast

winds in winter (Fig. 21.3a). Rough sea conditions were recorded on November 24 and 25, 2011, during which the maximum wave height can nearly reach 2.0 m (Fig. 21.3b); the maximum significant wave height was 1.62 m (Fig. 21.3c); the significant wave period ranged from 4 to 8 s (Fig. 21.3d); and the current velocity varied prevalently from 20 to 80 cm/s with the maximum value of 120 cm/s (Fig. 21.3e).

On November 22, another strong northeasterly wind struck this sea area, which was weaker than that mentioned above (Fig. 21.3). During this event, the maximum water depth was 2.71 m; the maximum wave height was 1.32 m; the significant wave height ranged from 0.6 to 0.9 m; the significant wave period ranged from 3 to 7.5 s; and the maximum current velocity varied from 5 to 45 cm/s, with the maximum of 84.2 cm/s.

Under the normal sea conditions, the tidal range was small, varying from 0.4 to 1.4 m. The maximum water depth reached no more than 2 m, and the minimum value was 0.47 m. The maximum wave height was 0.69 m, and the significant wave height was no more than 0.6 m, and the significant wave period ranged from 3 to 6 s. The current velocity was mostly less than 20 cm/s.

### 21.3.2 Suspended Sediment Concentration

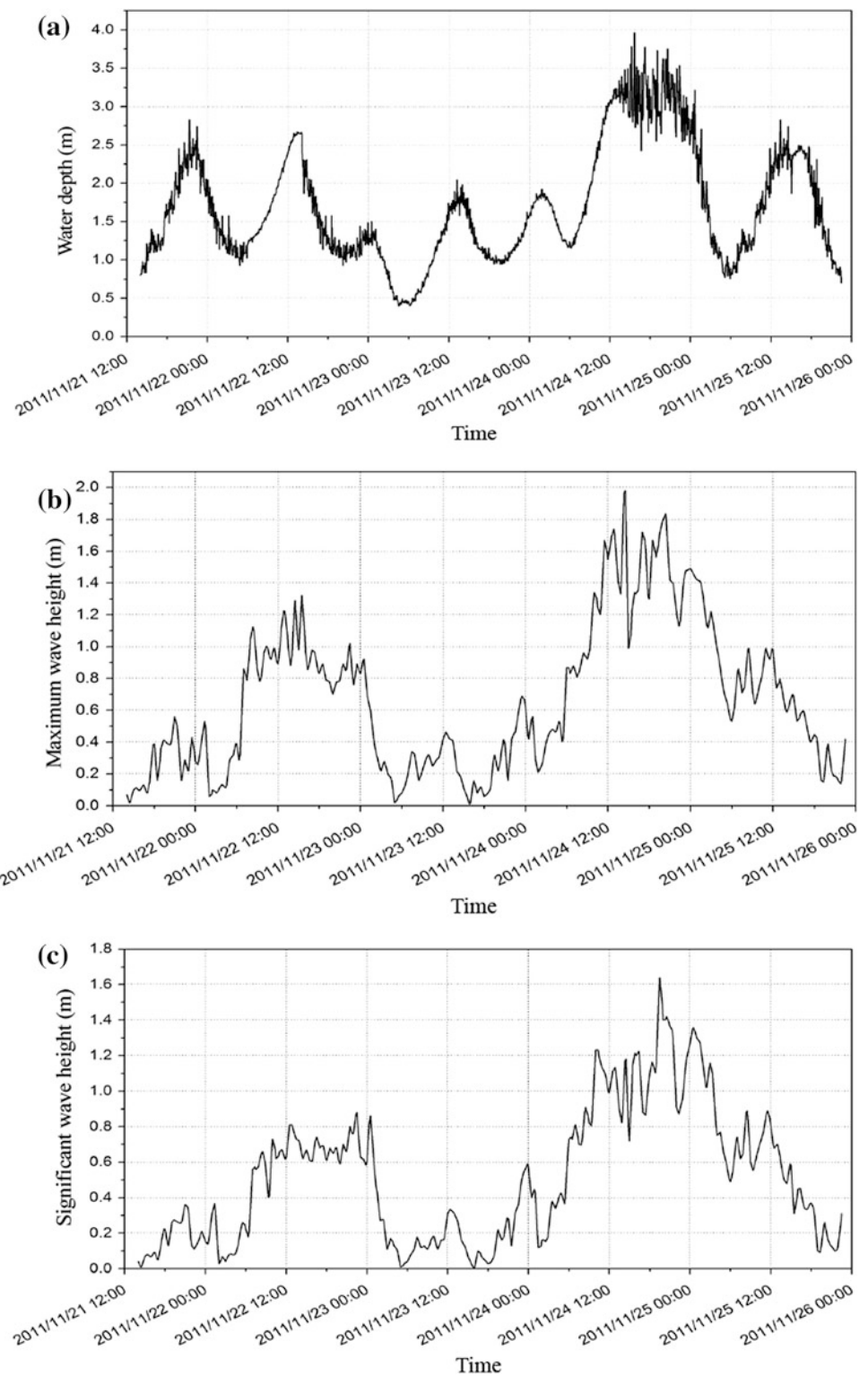
The seawater turbidity above the seabed was observed to indicate the variation of suspended sediment concentration under different hydrodynamic conditions. As is shown in Fig. 21.4, under the normal sea conditions, turbidity remained less than 200 FTU; while under the rough sea conditions on November 24 and 25, 2011, it reached 745 FTU; and under the other rough sea conditions on November 22, 2011, the maximum turbidity was 400 FTU.

According to the field seawater turbidity and sediment properties, it can be estimated that the suspended sediment concentration under rough sea conditions was ten times more than that under normal sea conditions, which is consistent with the field measurements conducted by Yang and Wang (1993).

### 21.3.3 Seabed Interface

Dynamic processes of seabed erosion and deposition both occurred during the in situ observation period (Fig. 21.5). In the normal sea conditions, sediment deposition predominated with the total deposition mass of 77.5 mm closely related to the sediment settling process. In the rough sea conditions, erosion predominated with the maximum erosion mass of 144.2 mm closely related to the sediment re-suspension.

**Fig. 21.3** Variations of marine hydrodynamic conditions.  
**a** average water depth;  
**b** maximum wave height;  
**c** significant wave height;  
**d** significant wave period;  
**e** bottom current velocity



#### 21.3.4 Pore Water Pressure

The pore water pressure inside the seabed nearly remained stable except under the rough sea conditions with the maximum accumulated excess pore water pressure of

3.9 kPa when significant erosion occurred and seawater turbidity increased obviously (Fig. 21.6). The seabed sediment can be liquefied when the excess pore pressure builds up progressively and become equal to the effective weight of the overburden during cyclic loading (van Kessel and

Fig. 21.3 continued

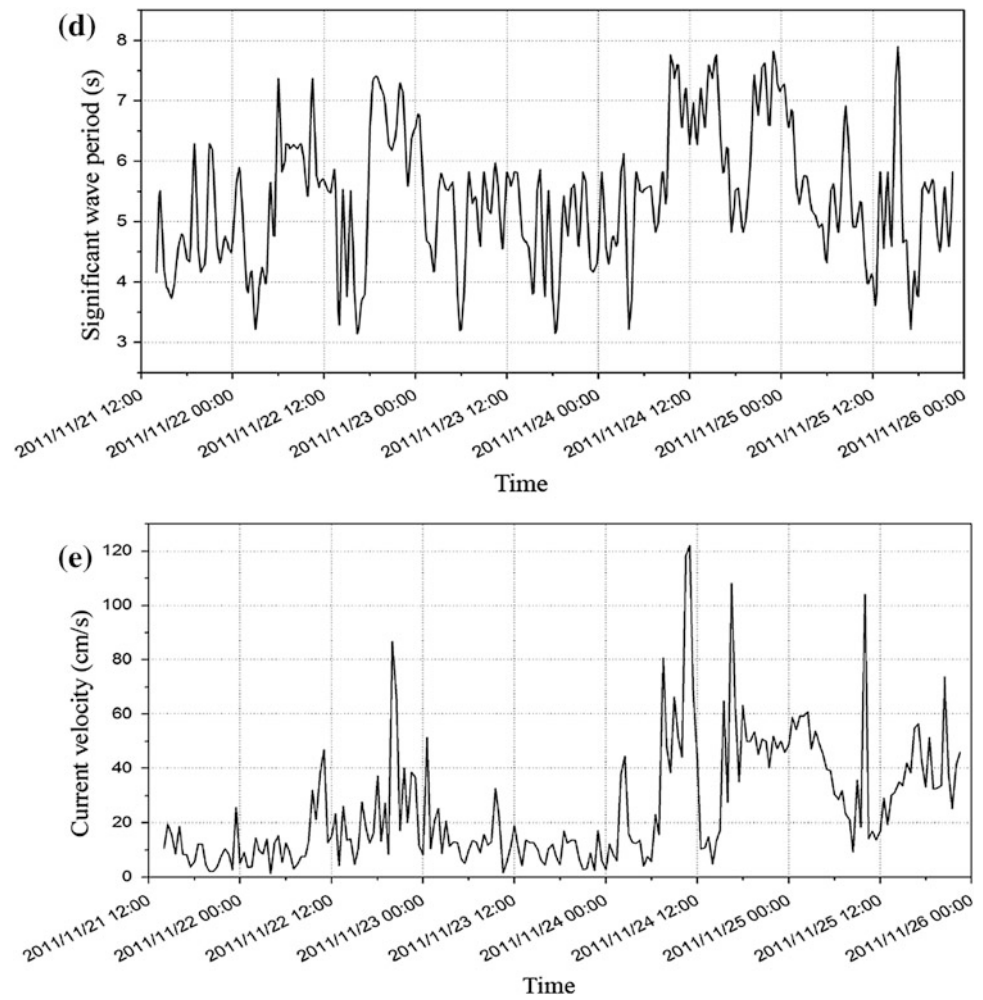
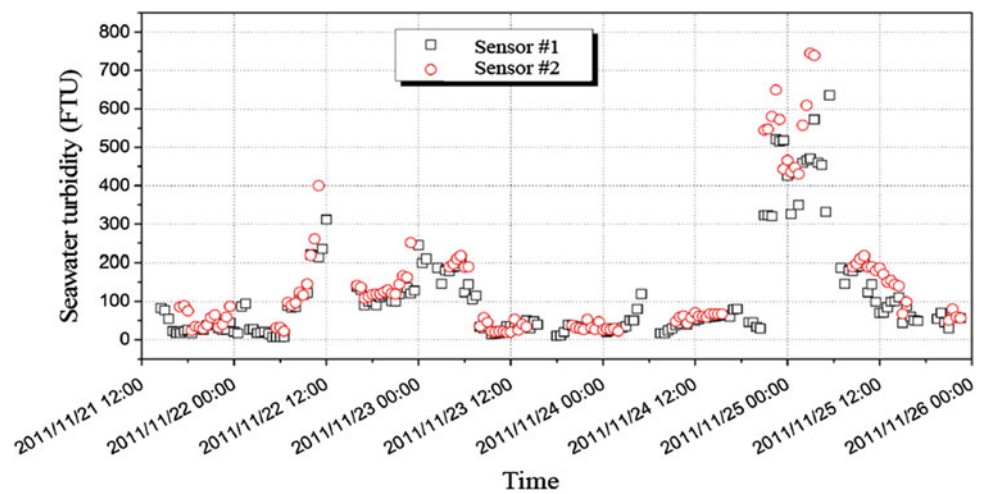


Fig. 21.4 Variation of seawater turbidity during the in situ observation

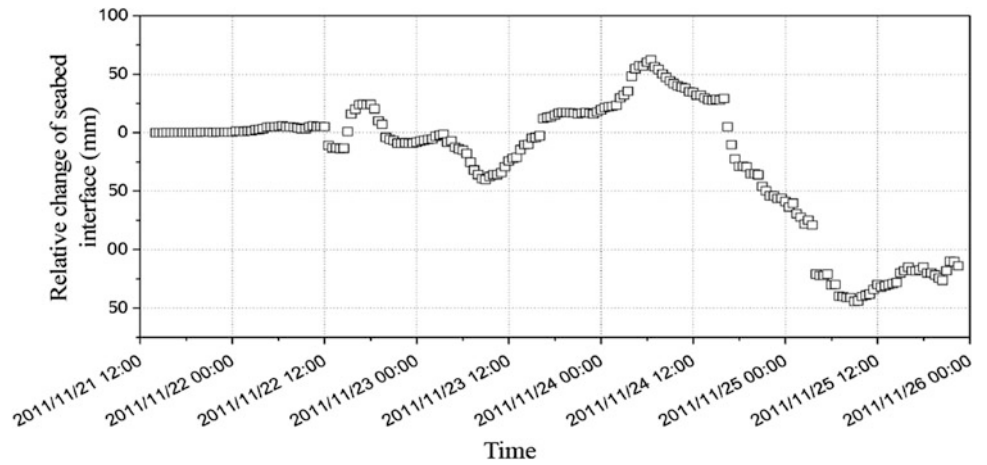


Kranenburg 1998; Jia et al. 2011). Therefore it can be assumed that wave-induced sediment liquefaction plays a significant role in sediment erosion and re-suspension under

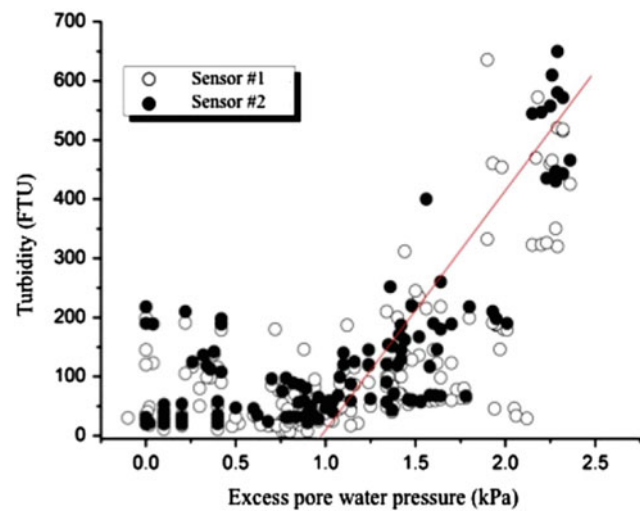
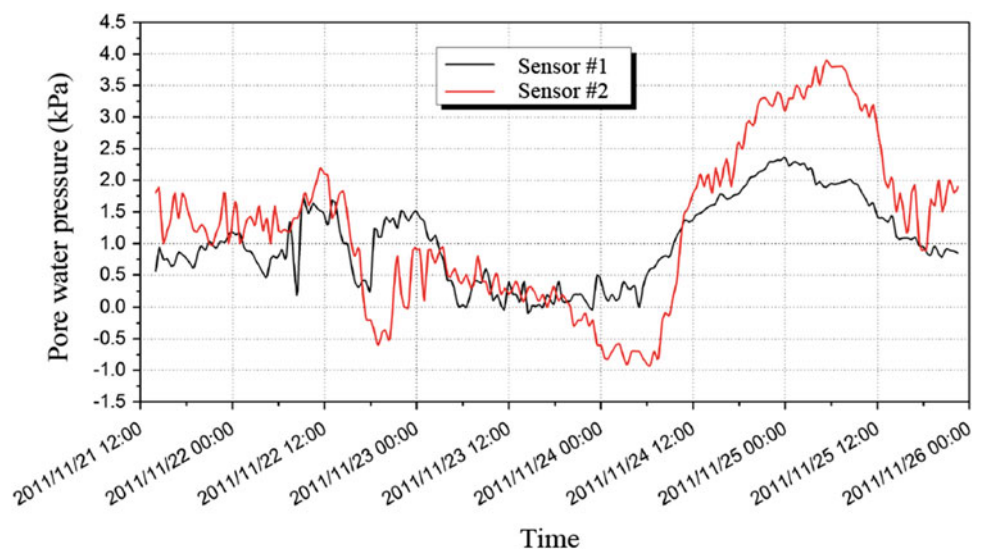
rough sea conditions. That is, sediment liquefaction in different degrees may lead to completely different erosion mass quantities.



**Fig. 21.5** Variation of seabed interface during in situ observation



**Fig. 21.6** Variation of pore water pressure during in situ observation



**Fig. 21.7** Scatter plot of water turbidity versus excess pore water pressure

### 21.4 Discussion

A good positive correlation existed between turbidity and excess pore water pressure caused by wave action in stormy sea conditions when the excess pore water pressure exceeds 1.0 kPa (Fig. 21.7). This indicated that the erosion mass increased with the increasing of sediment liquefaction degree. To better understand the mechanism of seabed erosion, the correlation between turbidity and bottom shear stress induced by waves and currents was also constructed, but no obvious relationship can be achieved for the rough sea conditions. Therefore, we can conclude that wave-induced sediment liquefaction is the primary factor affecting seabed erosion behavior during the significant sediment re-suspension event.

## 21.5 Conclusion

Overall, this study reveals the factors affecting the BBL dynamic processes in the Subaqueous Yellow River delta. Bed shear stresses under combined waves and currents exert a strong control on the routine events of seabed erosion and sediment re-suspension, which is consistent with previous studies. While sediment liquefaction generated by wave-induced accumulation of excess pore water pressure plays a critical role in seabed erosion and sediment re-suspension, especially under extreme events like storm or tsunami.

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