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Classifying the sedimentary environments of the Xincun Lagoon, Hainan Island, by system cluster and principal component analyses

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Abstract

An understanding of the sedimentary environment in relation to its controlling factors is of great importance in coastal geomorphology, ecology, tourism and aquaculture studies. We attempt to deal with this issue, using a case study from the Xincun Lagoon, Hainan Island in southern China. For the study, surficial sediment samples were collected, together with hydrodynamic and bathymetric surveys, during August 2013. Numerical simulation was carried out to obtain high-spatial resolution tidal current data. The sediment samples were analyzed to derive mean grain size, sorting coefficient, skewness and kurtosis, together with the sand, silt and clay contents. The modern sedimentary environments were classified using system cluster and principal component analyses. Grain size analysis reveals that the sediments are characterized by extremely slightly sandy silty mud (ESSSM) and slightly silty sand (SSS), which are distributed in the central lagoon and near-shore shallow water areas, respectively. Mean grain size varies from 0 to 8.0Φ, with an average of 4.6Φ. The silt content is the highest, i.e., 52% on average, with the average contents of sand and clay being 43% and 5%, respectively. There exists a significant correlation between mean size and water depth, suggesting that the surficial sediments become finer with increasing water depth. Cluster analyses reveals two groups of samples. The first group is characterized by mean grain size of more than 5.5Φ, whilst the second group has mean grain size of below 3.5Φ. Further, these groups also have different correlations between mean grain size and the other grain size parameters. In terms of the tidal current, the average values of the root mean square velocity (RMSV) are 7.5 cm/s and 6.9 cm/s on springs and neaps, respectively. For the RMSVs that are higher than 4 cm/s, a significant positive correlation is found between the content of the 63–125 μm fraction and the RMSV, suggesting that the RMSV determines the variability of the very fine sand fraction. Based on system cluster and principal component analyses (PCA), the modern sedimentary environments are classified into three types according to the grain size parameters, RMSVs and water depth data. The results suggest the importance of grain size parameters and high-spatial resolution hydrodynamic data in differentiating the coastal sedimentary environments.

Key words: surficial sediment, grain size, lagoon sedimentary environment, statistical analysis, numerical simulation, Hainan Island

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1 Introduction

Grain size characteristics of seabed sediment reflects transport, deposition and re-distribution processes. Any grain size distribution curve is controlled by four dominating factors, i.e., sediment provenance, transport distance, hydrodynamics and seabed topography (Gao et al., 1994; Flemming, 2007; Gao, 2009). Attempts have been made to determine sediment provenance (Yang et al., 2003; Lim et al., 2006; Zhou et al., 2009), hydrodynamic conditions (Jiang and Gao, 2002; Peng et al., 2004; Liu et al., 2007), sediment transport trends (Gao and Collins, 1992; Gao, 1996; Cheng and Gao, 2000; Cheng et al., 2004) and sedimentary environments (Visher, 1969; Sun et al., 2003; Wang et al., 2009), using information on spatial changes of grain size parameters. An in-depth understanding of modern sedimentary environments is of great importance in geomorphology, ecosystem and aquaculture of coastal areas. Generally, sediment provenance, hydrodynamic conditions, topography and human activates influence the behavior of modern sedimentary environments in coastal oceans (Li and Chen, 2003; Fang, 2008); thus, the environments can be classified based on these conditions (Wang et al., 2009; Xu et al., 2012; Li et al., 2014). However, such studies have two limitations: (1) the classification schemes were mainly depended on grain size parameters alone (e.g., Li and Chen, 2003; Chen et al., 2014), while the same grain size pattern may be related to different hydrodynamic settings; and (2) for the majority of these studies, the sedimentary environment was defined without high-spatial resolution hydrodynamic data (e.g., Molinaroli et al., 2007; Xu et al., 2012).

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The Xincun Lagoon represents a tidal inlet-lagoon system. Previously, studies have been focused on the hydrodynamic conditions (Gong et al., 2007, 2008a, b), the evolution and stability of the tidal inlet (Gong et al., 2004; Gong and Wang, 2006; Zhou and Wu, 2008), water quality (Li et al., 2010) and biological feature (Sun, 1991; Li and Huang, 2012; Wang et al., 2012). In this study, grain size distribution patterns in relation to the modern sedimentary environment in the Xincun Lagoon, Hainan Island in southern China, will be investigated. The specific objectives are to: (1) describe the grain size distribution and sediment types in the lagoon environment; (2) investigate the hydrodynamic conditions by *in situ* measurements and numerical simulations; and (3) classify sedimentary environments using PCA and system cluster analyses incorporating grain size, bathymetric and high-spatial resolution hydrodynamic data.

2 The study area

The field observations were carried out in the Xincun Lagoon (Fig. 1). The area is associated with a tropical environmental setting, with a water temperature of 25.8–30.0°C and a salinity value of 30.64–34.44 (Yang and Yang, 2009; Wang et al., 2012). Seagrass communities are densely and continuously distributed along the southern coastline of the lagoon, including four species, i.e., *Enhalus acoroides*, *Thalassia hemperichii*, *Cymodocea rotundata* and *Halodule uninervis* (Yang and Yang, 2009). In addition, a large area (more than 0.05 km^2) of pearl and fish aquaculture is present in the lagoon, with an annual fishery production of 1 105 t (Yang and Yang, 2009).

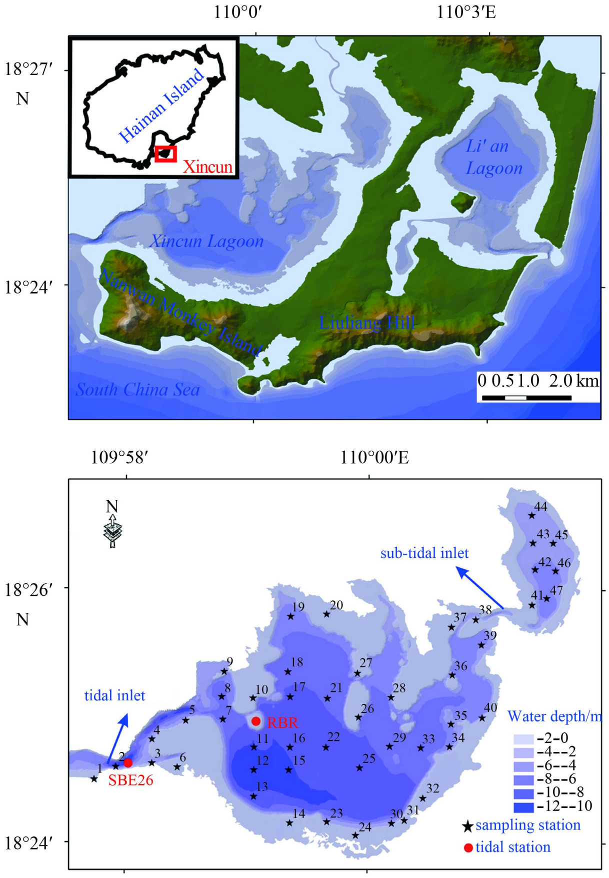

Fig. 1. Location of sampling stations of surficial sediments and tidal gauge stations in the Xincun Lagoon.

From the viewpoint of geomorphology, the Xincun embayment is a semi-closed lagoon system with a narrow tidal inlet connected with the open sea. The entrance channel is 0.3–0.4 km wide, with an averaged water depth of 5 m. In addition, the flood and ebb deltas are well developed (Gong et al., 2004; Gong and Wang, 2006). The Xincun Lagoon is actually made up of two sub-lagoons which are connected by a channel within the embayment (Fig. 1) (Gong et al., 2007). The lagoon is approximately 6 km in width in the east-west direction and 4 km in the south-north direction, covering an area 22.5 km^2, 4.2 m deep on average (Gong et al., 2007, 2008a). At the entrance, the eastern side is confined by rocky strata associated with the Nanwan Monkey Island, whilst the western side is characterized by sandy deposits, where the Xincun fishing port is situated (Gong et al., 2007).

There are only two streams entering the lagoon with small freshwater discharges (Gong et al., 2008a; Yang and Yang, 2009). Tidal current is the main dynamic forcing in the lagoon, with relatively weak wave action (Gong et al., 2004, 2007). The tides are irregularly diurnal, with an average tidal range of 0.93 m, reaching up to 1.63 m during the normal spring tides; the tidal current exhibits a time-velocity asymmetry pattern, with a flood duration of 13 h 20 min, which is longer than the ebb duration (11 h 20 min), and with a stronger ebb current (with a maximum of 0.86 m/s) than the flood current (0.84 m/s) at the entrance (Gong et al., 2004). However, the current velocity over the inner part of the lagoon is much weaker, i.e., generally below 0.1 m/s (Gong et al., 2008a). Wind waves are mainly from the southeast and the south, with an average wave height of 0.7 m and a mean wave period of 4.0 s, as measured at an adjacent offshore station (Gong et al., 2004, 2008b). In addition, the Xincun Lagoon is frequently affected by typhoons, on average twice a year (Yang and Yang, 2009).

3 Methods

3.1 *Field work and grain size analysis in the laboratory*

Surficial sediment samples (each with a mass of 0.5–1 kg, sampling depth of around 5 cm) were collected at 47 stations using a grab sampler, during August 21–22, 2013 (Fig. 1). In the meantime, the sampling locations and corresponding water depth were recorded by a handheld GPS and an YSI 6920 instrument (water quality monitoring system), respectively. As shown in Fig. 1, the sampling stations were not evenly distributed due to the obstacles caused by the large-scale aquaculture in the lagoon. Furthermore, tidal water level was measured at the entrance and an inner part of the lagoon using a Wave and Tide Recorder (SBE26, Sea-Bird Electronics) and a Conductivity–Temperature–Depth profiler (XR620 RBR CTD) during the entire month of August 2013, respectively (Fig. 1).

The steps of grain size analysis are summarized as follows. First, surficial sediment samples of each station needed to be sufficiently mixed. Second, moderate amount of samples were dispersed by adding 0.05 mol/L $(NaPO_3)_6$ solution (10–20 mL) and by ultrasonic treatment for 15 seconds before measurement. Third, a laser Malvern Mastersizer 2000 granulometer (range 0.02–2 000 μm with a duplicate measurement error less than 3%) was utilized for grain size analysis (Obscuration ranges from 10%–20%). Finally, the grain size parameters (mean grain size, sorting, skewness, kurtosis and percentage of sand, silt and clay) were calculated from the distribution curves, using moment statistics (McManus, 1988; Liu et al., 2013). In addition, sediments were classified and named using the textural classification of gravel-free muddy sediments on ternary diagrams proposed by

Flemming (2000).

3.2 *Hydrodynamic parameters*

Using the boundary conditions defined by the tidal water level measurements, the short-term flow and water level of the Xincun Lagoon induced by tidal action were simulated using the Delft3D, which is popularly applied to coastal simulation system in the world (Roelvink and van Banning, 1994). The influence of wind waves on the hydrodynamic conditions was not considered here because the waves are weak inside the Xincun Lagoon, under normal weather conditions. Elsewhere, the model has been validated for the simulation of hydrodynamic and morphodynamic, over various timescales (including several days to decades, even hundreds of years), within different coastal environments such as coastal embayments, estuaries, and intertidal flats (Xing et al., 2012; Xie et al., 2012; Yu et al., 2012a, b ; Qian et al., 2014; Ni et al., 2014). In the present study, the model was verified using the measured tidal water level. As shown in Fig. 2, the Delft3D simulated water level is consistent with the measurements.

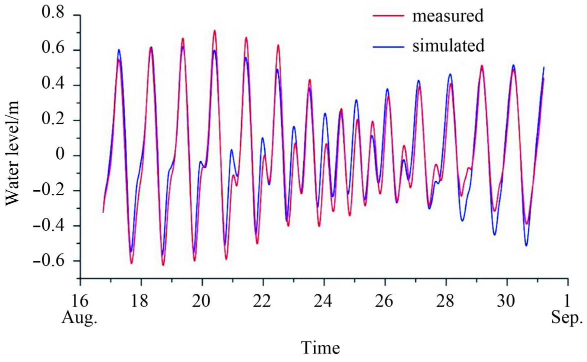

Fig. 2. Measured and simulated water level in the Xincun Lagoon.

To investigate the hydrodynamic conditions of the Xincun Lagoon and its implications on grain size distribution, the root mean square velocity (RMSV) of each sampling station was computed from the model results. The RMSV was calculated using the following formula (Molinaroli et al., 2007):

$$RMSV(x,y)=\sqrt{\overline{vel^2\,(x,y)}}, \tag{1}$$

where $vel(x, y)$ is the depth-averaged velocity at point (x, y), with the over bar indicating an averaging operation. Furthermore, the computation of RMSV makes it possible to identify areas characterized by similar grain size which are more heavily influenced by hydrodynamic intensity or sediment provenance.

The RMSV provides a suitable estimate of hydrodynamic intensity in the Xincun Lagoon. On the other hand, the erosion process within the bottom boundary layer is generally controlled by bed shear stress (BSS), which is (Molinaroli et al., 2009):

$$BSS=\rho\cdot C_{\rm d}\cdot RMSV^2, \tag{2}$$

where ρ is the sea water density and $C_{\rm d}$ is the bottom drag coefficient. However, RMSV determined the variability of BSS, which can be properly used as a parameter to characterize the variability of average hydrodynamic intensity within the entire lagoon (Molinaroli et al., 2007, 2009).

3.3 *System cluster analyses and PCA*

System cluster analyses can extract key information using the similarity or distance of parameters, which contains the important information on all of the grain size parameters. Generally, there are two different clustering algorithms, i.e., hierarchical and K-mean cluster analyses (Yu and He, 2003; Adame et al., 2012). Furthermore, the principal component analyses (PCA) technique was used to determine the relative importance of the grain size parameters (Meglen, 1992; Beaugrand, 2004), which has been applied to many areas of marine research, e.g., the relationship between sediment grain size and beach profile (Medina et al., 1994), suspended sediment transport (McManus and Prandle, 1997) and estuary morphological changes (Dai et al., 2013). Generally, the accumulative contribution of the first k principal components accounted for over 85% of the total variability, maintaining most of information of original data. In the present study, both system cluster analyses and PCA were applied to the treatment of the dataset, using the Classify toolbox in SPSS 19.0.

4 Results and discussion

4.1 *Grain size parameters*

The surficial sediments of the lagoon are dominated by silt and sand fractions, being 52% and 43% on average (Figs 3a, b and c). The mean grain size (Mz) values range from 0 to 8.0Φ, with an average of 4.6Φ (Fig. 3d). A positive correlation between Mz and water depth (R=0.47, two-tailed test, α=0.01) was recorded (Fig. 4a), indicating that the surficial sediment becomes finer with increasing water depth. The values of sorting coefficient (σ) are between 0.6 and 3.2, with an average value of 1.7. In addition, the sediments of the central and southern parts of the lagoon have relatively high degree of sorting, whilst those of the northern and northeastern parts have poor sorting (Fig. 3e). Furthermore, the distributions pattern of skewness (Sk) and kurtosis (Ku) had the similar trends to the Mz patterns (Figs 3f and g). The average values of Sk and Ku were 0.9 and 4.4, respectively.

The variability of mean grain size within the lagoon according to K-Mean cluster analyses is characterized by two groups. The first group (consisting of 24 sampling stations) had a mean size of >5.5Φ with an average value of 6.8Φ, belonging to fine silt (silt content 86.7% on average), whilst the second group (23 sampling stations) had a size of <3.5Φ with an average value of 2.2Φ, falling into the fine sand category (sand content 82.0% on average). Further, there are two different relationships between mean grain size and the other parameters (i.e., σ, Sk and Ku), as shown in Figs 4b, c and d. For the first group, there is a significant negative (R=0.88, p=0.01) correlation between Mz and σ but a positive (R=0.68, p=0.01) correlation with Sk. Generally, Ku decreased slightly or remained unchanged (averaged value of 3) with the increase in mean grain size. In the second group, positive correlation was found between Mz and σ (R=0.70, p=0.01), whilst the negative correlations were present between Mz and Sk or Ku. Such differences indicate differences in the sedimentary environment, due to varied sediment provenance and hydrodynamic conditions.

4.2 *Hydrodynamic parameters*

The hydrodynamic parameters (i.e., RMSVs) for different stations during the spring tide (from 0:00, August 19 to 6:00, August 20, 2013) and neap tide (from 14:00, August 24 to 6:00, August 25, 2013) were derived on the basis of the model results (Fig. 5). The RMSV distribution trends of spring and neap tides were similar,

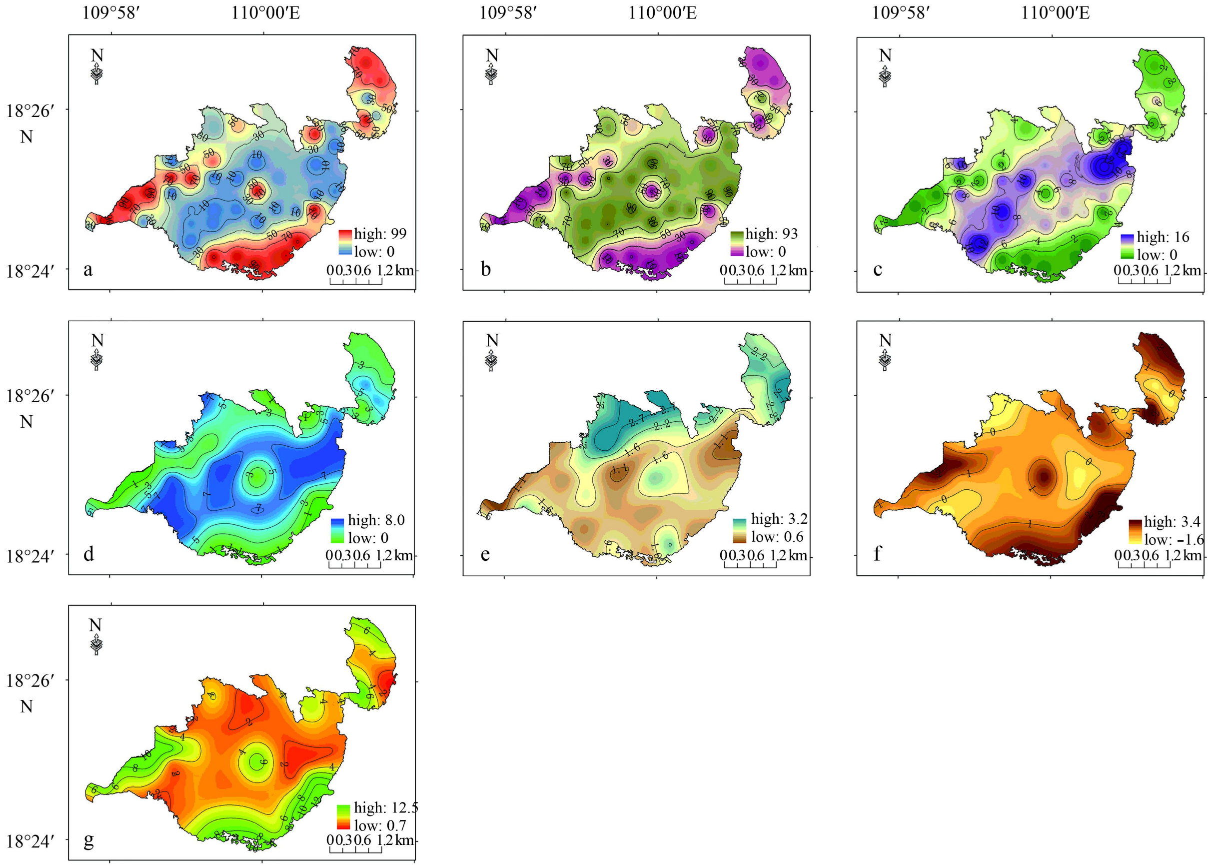

Fig. 3. Distribution of grain size parameters of surficial sediments: sand (%) (a), silt (%) (b), clay (%) (c), mean grain size (Φ) (d), sorting (e), skewness (f), and kurtosis (g).

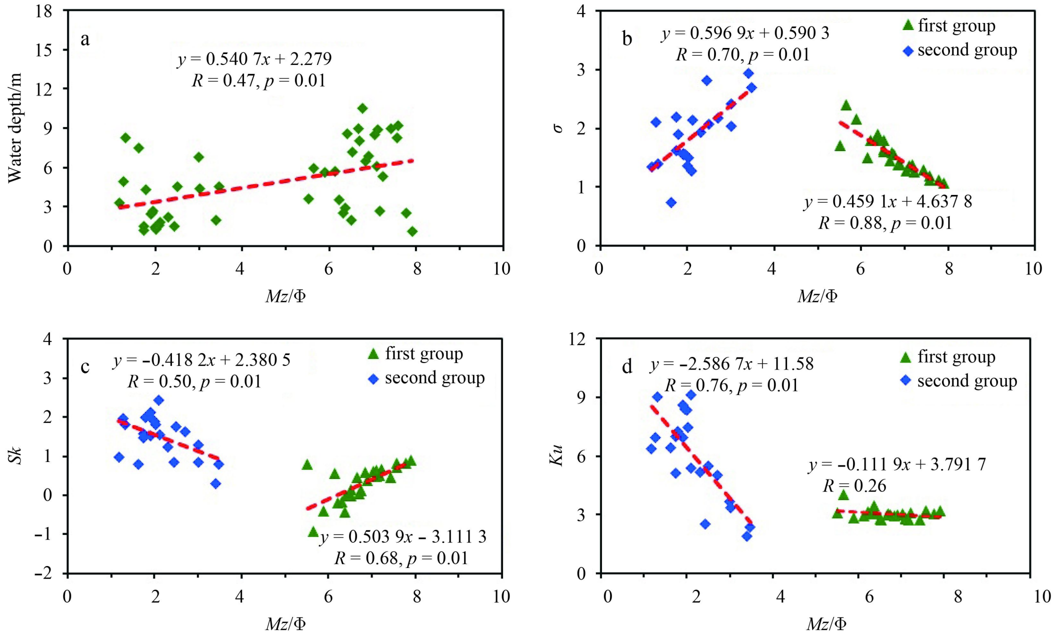

Fig. 4. The relationships between *Mz* and water depth (a), *σ* (b), *Sk* (c), and *Ku* (d).

and their values ranged from 0 to 85.9 cm/s and 0 to 83.9 cm/s, respectively. The average values of the RMSV during the spring and neap tides were 7.5 and 6.9 cm/s, with standard deviations of 15.3 to 14.9 cm/s, respectively, indicating a high-spatial heterogeneity of the Xincun Lagoon. The entrance channel is associated with the highest values of RMSV (86 cm/s). The hydrodynamic decreases from the entrance towards the inner regions of the lagoon. In the innermost regions of the lagoon, RMSV values reduced to 1 cm/s. In addition, the relatively high RMSVs are also recorded in the sub-tidal inlet. The average V_e/V_f (ebb RMSV/

flood RMSV) during the spring and neap tide was 0.7 and 1.2, respectively, implying that flood tidal currents prevail on the spring, whereas ebb currents prevail on the neap.

The average RMSV values for the first and second groups are 2.8 and 8.5 cm/s, respectively, suggesting that sedimentological and hydrodynamic conditions for the two groups are quite different. For the first group, there are low correlation coefficient between the very fine sand fraction (63–125 μm) and RMSV, due to the majority of RMSVs being below 4 cm/s which may cannot mobilized the very sand fraction. For the second group, significant relationships are found between the very fine sand fraction and RMSV (R=0.89–0.90) during spring and neap tides (Fig. 6), especially when the RMSV exceeds 4 cm/s. These results suggest that RMSV determines the variability of very fine sand fraction in the lagoon if the RMSV is above 4 cm/s.

4.3 *Sediment classification*

The surficial sediments of the Xincun Lagoon consist mainly of five types: extremely slightly sandy silty mud (ESSSM), very silty and slightly sandy mud (VSSSM), slightly silty sand (SSS), very silty sand (VSS) and sand (S) on the basis of sand/silt/clay ratios proposed by Flemming (2000). Furthermore, the surficial sediments are dominated by ESSSM (19 sites) and SSS (15 sites), which were distributed in the central lagoon and near-shore shallow water areas, respectively. Grain size and hydrodynamic parameters of the five types are listed in Table 1. In addition, av-

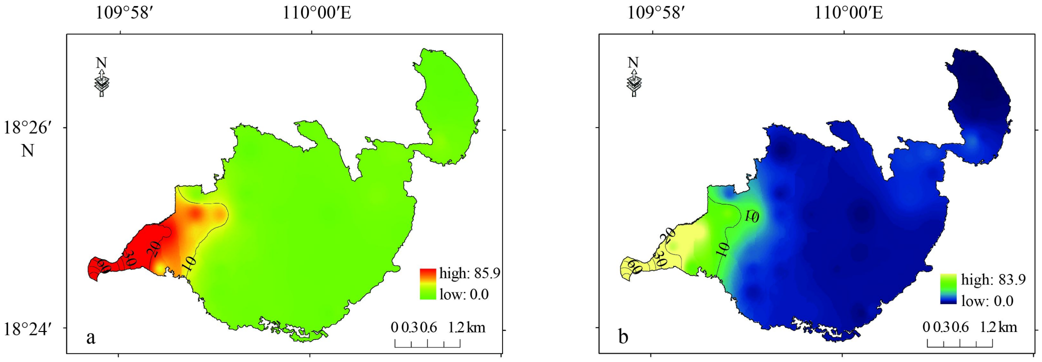

Fig. 5. Distribution of RMSV (cm/s) for spring tide (a) and neap tide (b).

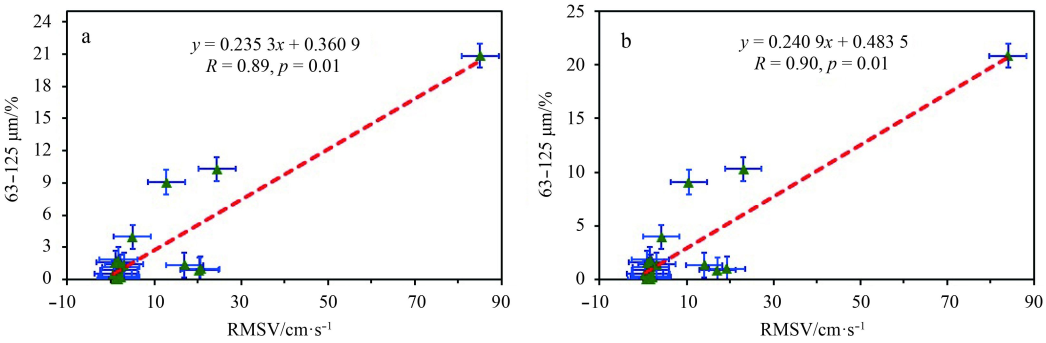

Fig. 6. The relationships between very fine fraction (63–125 μm) and hydrodynamic parameter (RMSV) with standard errors during spring tide (a) and neap tide (b).

Table 1. Grain size parameters and hydrodynamic parameters of surface sediments

Sediment type	Depth/m	RMSV/cm·s^{-1}		Clay/%	Silt/%	Sand/%	Mz/Φ	σ	Sk	Ku
ESSSM	6.2	2.9	Mean	7.1	86.0	6.9	6.5	1.6	0.2	3.0
			Min	4.3	74.4	0.0	5.5	1.3	–0.9	2.7
			Max	9.9	92.2	21.3	7.2	2.4	0.8	4.0
VSSSM	5.5	2.6	Mean	13.0	87.0	0.0	7.6	1.2	0.7	3.0
			Min	10.7	84.3	0.0	7.2	1.1	0.4	2.7
			Max	15.7	89.3	0.0	7.9	1.4	0.9	3.2
SSS	2.6	3.8	Mean	0.6	11.2	88.2	2.1	1.8	1.7	6.6
			Min	0.0	7.5	74.6	1.3	1.4	1.3	3.4
			Max	2.0	23.4	91.9	3.0	2.4	2.4	9.1
VSS	3.7	7.1	Mean	1.9	31.1	67.0	3.1	2.6	0.7	2.6
			Min	0.8	24.3	55.3	2.4	2.0	0.3	1.9
			Max	2.9	41.5	74.3	3.5	2.9	0.9	3.7
S	6.4	31.1	Mean	0.0	2.7	97.3	1.4	1.2	1.2	7.3
			Min	0.0	1.2	94.6	1.2	0.7	0.8	6.4
			Max	0.0	4.5	98.8	1.6	1.4	1.8	9.0

eraged frequency curves of grain size distribution of the five types are presented in Fig. 7.

The grain size distribution curves of the ESSSM (Fig. 7) are unimodal, with an averaged RMSV of 2.9 cm/s, indicating weak hydrodynamics and single sediment provenance. Similar curves are found in the sediments of the VSSSM. The averaged grain size curves of the SSS present a bimodal feature, and the associated average value of RMSV is 3.8 cm/s (Fig. 7 and Table 1). Similar curves are found in VSS areas, with an averaged RMSV of 7.1 cm/s. These results are indicative of weak hydrodynamics and multi sources of sediment supply. For the S type, the grain size distribution curves are indicative of single sediment provenance and relatively strong hydrodynamics, with an averaged RMSV of 31.1 cm/s.

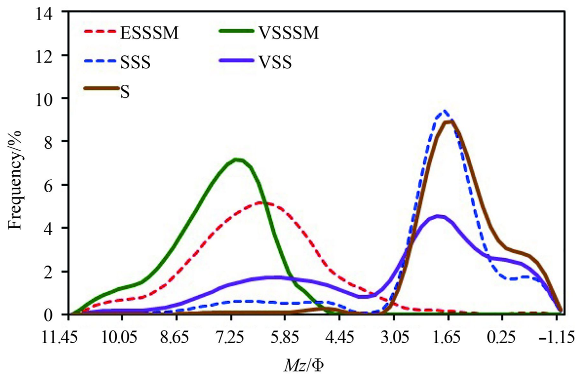

Fig. 7. Average grain size distribution curves of the ESSSM, VSSSM, SSS, VSS and S types.

Table 2. The clustering stages and results among grain-size parameters

Clustering stage	Parameter	Correlation coefficient
1	*Mz*, silt content	0.984
2	*Mz*, clay content	0.931
3	*Sk*, *Ku*	0.809
4	*Sk*, sand content	0.795
5	*σ*, *Sk*	0.407
6	*Mz*, *σ*	–0.153

The results outlined above show that the sediment type is closely related to the water depth by comparing sediment distribution pattern with the lagoon bathymetry. The ESSSM and VSSSM types are distributed basically in the central part of the lagoon, with an average water depth of >~6 m. The silt particles tend to accumulate in the central area of the lagoon; the weaker hydrodynamic is favorable for the settling of the silt particles (Wang et al., 2000). In contrast, the SSS, S and VSS types are mainly distributed in the near-shore area with an average water depth of <~3 m. The fine-grained particles were taken away and the coarser particles were left *in situ* due to relative strong hydrodynamic and multi sources of sediment supply. Therefore, the distribution patterns of the various sediment types represent a comprehensive result of water depth, hydrodynamic sorting and sediment provenance.

4.4 *Sedimentary environment classification*

The criteria for classifying modern sedimentary environments may be established using the information on grain size, hydrodynamics and water depth (Wang et al., 2009; Li et al., 2014). In the present study, hierarchical cluster analyses and PCA were performed to identify the proper grain size parameters. First, the grain size parameters (i.e., *Mz*, *σ*, *Sk*, *Ku*, and clay, silt and sand contents) are defined as clustering standard variables, and then the grain size parameters can be identified by searching the degree of relevance step by step. The detailed information concerning with the clustering procedures and results (Table 2) indicates that there exist three groups, i.e., Group 1 (*Mz*, silt and clay content), Group 2 (*Sk*, *Ku* and sand content), and Group 3 (*σ*), according to the correlation coefficients among grain size parameters. Second, the relative importance of grain size parameters for each group is determined using PCA. Finally, the Bartlett test of sphericity is used to test the validity of the PCA treatment, and the result suggests that the grain size parameters of the three groups are suitable. Subsequently, the factor loading of each parameter is estimated by the eigenvalues and eigenvectors, and the result indicates that *Mz*, *Ku* and *σ* were the dominating parameter for Groups 1, 2 and 3, respectively. Jiang (1995) and Li and Chen (2003) demonstrated that *Mz* generally represents the interaction between averaged hydrodynamic intensity and sediment source, *σ* is sensitive to the interaction between topography and flow field, and *Ku* represents the degree of concentration of grain size distribution, which relates to the sediment sources and hydrodynamic intensity. Therefore, high-resolution hydrodynamic and water depth data in combination with the proper grain size parameters were used to classify sedimentary environments using cluster analyses. The cluster results suggest that sedimentary environments can be well classified, i.e., in the study area, three types can be identified (Fig. 8). Thus, PCA and system cluster analyses represent an effective method to classify modern sedimentary environments.

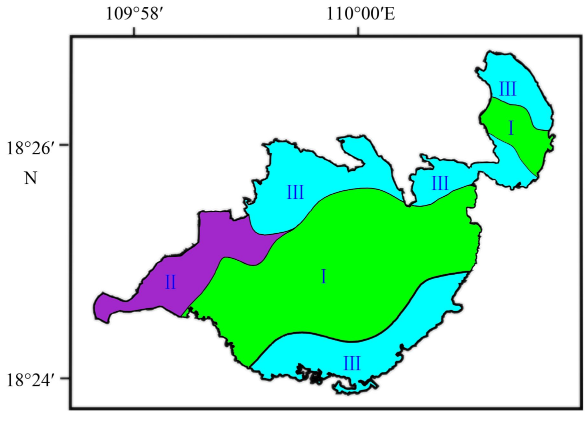

Fig. 8. Sedimentary environments in the Xincun Lagoon.

Type I is mainly distributed in the central part of the lagoon (Fig. 8), which dominates by the silt fraction, consisting of ESSSM and VSSSM. The water depth of this area is deeper than other two types, with an averaged value of 6.0 m. In addition, the hydrodynamic is weak, with an average RMSV of 2.0 cm/s. These conditions are favorable for the fine grained particles (derived from the open sea, through the entrance channel to enter the lagoon) to settling on to the bottom. As for Type II, primarily distributed in the vicinity of the entrance towards the lagoon (Fig. 8), consisting of S, SSS and ESSSM, with a water depth of 4.8 m. The bottom sediment is dominated by sand (i.e., the percentages of sand, silt and clay being 64.9, 31.9 and 2.5%, respectively). The coarse grained particles accumulating in this environment are related to transport from the adjacent beaches. With a relatively strong hydrodynamic activity (i.e., an average RMSV of 27.9 cm/s), the currents in this environment are able to erode the bed and redistribute the coarse grained particles. Type III has the coarsest sedimentary material among the three types, consisting mainly of SSS and VSS. However, the hydrodynamic intensity is weak (RMSV 2.1 cm/s). Therefore, the characteristics of this type are mainly controlled by sediment source rather than the tidal hydraulics. This type is distributed in the near-shore areas of the lagoon (Fig. 8), with a water depth of 2.0 m; the sediment is probably derived from terrestrial weathering processes.

Among the three types, Types I and II have significant differences in both hydrodynamic and sediment characteristics. As for Types I and III, although they have similar hydrodynamic conditions, their sediment characteristics are significantly different. Likewise, Types II and III have similar sediment characteristics, yet the hydrodynamic conditions are quite different. These contrasts indicate the importance of proper grain size parameters and high resolution hydrodynamic data in distinguishing modern sedimentary environments. In the present study, we attempted to classify the environments taking into account the hydrodynamic, sediment source, and bathymetric conditions. Further work is needed to consider the influence of human activities (e.g., pearl and fish aquaculture) and extreme events (e.g., storm surges due to typhoons) on the sedimentary environment.

5 Conclusions

(1) The surficial sediments of the Xincun Lagoon consist mainly of five types, i.e., ESSSM, VSSSM, SSS, VSS, and S. The dominant types include ESSSM and SSS, which are found in the central lagoon and near-shore shallow water areas, respectively.

(2) The mean grain size varies from 0 to 8.0Φ, with an average value of 4.6Φ. A significant correlation is found between mean grain size and water depth, i.e., the surficial sediment becomes finer with increasing water depth. There are two groups of seabed sediments on the basis of cluster analyses: the first group is characterized by Mz>5.5Φ, with an average value of 6.8Φ, whereas the second group Mz<3.5Φ, with an average value of 2.2Φ.

(3) The RMSV distribution patterns represent the averaged tidal hydrodynamic conditions of the lagoon. The average RMSV values were 7.5 and 6.9 cm/s during spring and neap tides, with standard deviations of 15.3 and 14.9 cm/s, respectively. The average V_e/V_f ratio indicates that flood tidal currents prevail on the spring, whereas ebb currents prevail on the neap. A significant correlation exists between 63–125 μm fraction and RMSV, for the sites where the RMSVs are higher than 4 cm/s. These results explain the variability of very fine sand fraction in the lagoon.

(4) System cluster analyses and PCA were used to identify the grain size parameters that can be used to distinguish the sedimentary environments. Three types of the environments have been identified using the information on grain size parameters, high-spatial resolution RMSVs and water depth data. Further studies are needed to take into account the impact of human activities and extreme events on sedimentary environments.

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