Sediment distributions and transport patterns in the Pearl River Estuary and its adjacent coastal ocean

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Abstract. Coastal sediment is important for the development of river deltas and for carrying both nutrients and pollutants into estuaries and coasts. Totally 265 surficial sediments collected from the Pearl River Estuary and its adjacent coastal ocean were analyzed by using Gao-Collins method to study the sediment transport path and deposition center. The Pearl River Estuary was an area of sandy mud sediment and showed some muddy patches. There were 5 distinguishable sediment convergence centers, which represent 3 types of sediment transport patterns and hydrodynamic environments. The net sediment transport pathways in the estuary and shelf sea were mainly in the offshore and landward direction, respectively. The analyzed results indicated that the main part of muddy sediment was confined to the mouth of the estuary due to the combined effects of the expansion and salinity intrusion.

Keywords: Pearl River Estuary; surficial sediment type; grain size trend analysis; sediment convergence center.

1. Introduction

Understanding the transport and deposition of surficial sediment is crucial to predicting its impacts on artificial reef, offshore wind power, offshore bridges and tunnels. The information of sediment transport and burial can be recorded by sediment grain size distribution, which is of great significance for revealing regional sedimentation dynamic characteristics, sediment transport processes and sedimentary environment evolution [1]. McLaren and Bowles proposed a one-dimensional sediment grain size trend model, which can use two grain size trends to determine the net sediment transport direction [2]. Based on this one-dimensional model, Gao and Collins proposed a two-dimensional sediment grain size trend analysis model [3, 4]. This model first determines the type of particle size, then quantitatively analyzes the grain size parameter relationship of each adjacent sediment and converts it into sediment net transport direction. Gao-Collins grain size trend analysis has been widely applied in estuaries [5, 6], bays [3], continental shelf [7], and other sedimentary environments.

As the largest river in the northern continental margin of the South China Sea, the Pearl River transports nearly 90 Mt of suspended sediments to the South China Sea every year, which has an important impact on the sediment composition in the northern South China Sea [8]. Numerous studies have been conducted on surficial sediment of Pearl River Estuary regarding its the transport trend and deposition. Based on collected surficial sediments from the Lingdingyang Bay in December 2016 (dry season) and August 2017 (flood season) to analyze their grain size parameters, two major mud depo-centers in the northeastern and southwestern parts of the bay were revealed [6]. The Coupled Ocean Atmosphere Wave Sediment Transport modeling system was used to study the sediment transport in the Pearl River Estuary [9]. The results showed that the seaward sediment transport was dominated by river run off in the upper estuary and by tidal forcing in the lower channels, while winds and tides controlled the sediment transport in the lower shoals.

Accordingly, in this study, we present an analysis of surficial sediments in the in the Pearl River Estuary and its adjacent coastal ocean collected in 2022 to expound the spatial variations in grain size, sediment type, and sediment transport patterns. Gao-Collins grain-size trend analysis was applied to investigate the sediment dispersal and trapping patterns. Therefore, the objective of this research is to understand the feature of the surficial sediment distribution, elucidate the sediment transport patterns by grain size trend analysis, thereby providing important information for the management of the Pearl River Estuary and its adjacent coastal ocean.

2. Materials and Methods

2.1 Field Observations

Field cruise was conducted using R/V Haijian 303 from 19 June to 3 September 2022 in the Pearl River Estuary and adjacent northern South China Sea (Fig. 1). The sampling stations with a sampling interval of ~1-5 km spanned from the Lingdingyang to the Huangmaohai and reached offshore to ~60 m isobath. Surficial sediment samples at all total 265 sites (Fig. 1) were collected using a box corer (30×30×50 cm in length, width and height, respectively). Upper sediments within 10cm of the surficial sediment samples were saved at 4 ℃ to analysis the grain size in the laboratory. During the period of the voyage investigation, the Differential Global Positioning System (DGPS) technology was used to record the coordinates of the sampling stations.

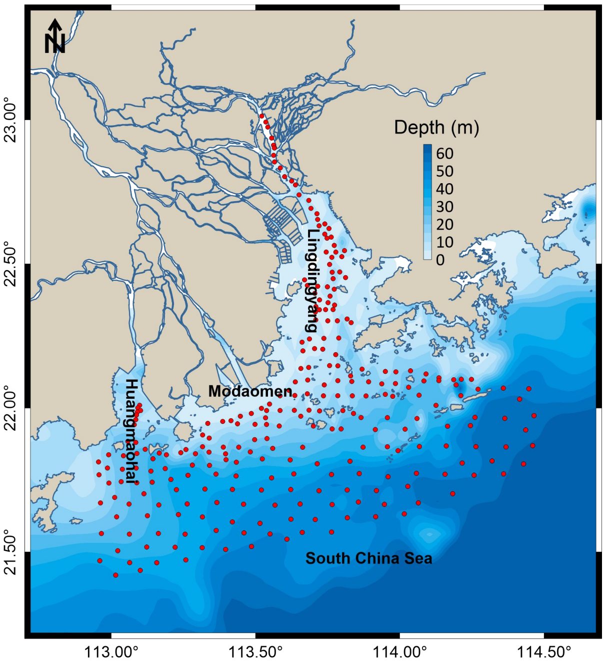

Fig. 1 Surface sediment samping sites (red circles) in the Pearl River Estuary and its adjacent coastal ocean during 2022.

2.2 Grain Size Analyses

Grain size of the surficial sediment was measured using a Mastersizer 3000 laser diffraction particle size analyzer (Malvern Panalytical, Malvern, UK) with a measurement range of 0.01-3500 μm and a resolution of 0.01 Φ [10]. The samples from all 265 stations were oven-dried for seven days, and carefully homogenized to make them representative. These samples were treated with 30% hydrogen peroxide for 24 h to remove organic matter. Subsequently, the powder was treated by soaking in the right amount of hydrochloric acid at a concentration of 3 mol L^{-1} for 24 h, and repeated this step to fully remove the bioclastics. The samples were washed with distilled water, and added the dispersants of hexametaphosphate at a concentration of 3 mol L^{-1} for dispersion. Finally, the soaked samples were poured into the groove chamber of Mastersizer for measuring the distribution of the grain size.

The grain size characteristics of surficial sediments are the important indicators that reflect the sediment dynamics and the sedimentary environment. Folk-Word Graphical-Method was used to calculate the grain size parameters including mean grain size, sorting coefficient, and skewness coefficient [11]. After determining the sediment samples in the three classes of particle size: mud sand, and gravel, sediment types were present according to the Folk's classification diagram.

2.3 Grain Size Trend

According to the mean grain size, sorting coefficient, and skewness coefficient of the surficial sediment, two adjacent sampling stations can be compared to define the direction of net transport of sediment in the grain-size trend vector images [3, 4]. There are two trends that appear more frequently within the eight grain size trends in in the net transport direction of the sediments. Eight particle size trends can be defined between two adjacent sampling points, but there are two trends that appear more frequently in the net transport direction of sediments. In the transport direction, one is that the sorting becomes better, the grain size becomes finer and more negative skewness, and the other is that the sorting becomes better, the particle size becomes coarser and more positive skewness. The grain size parameters of each samples are compared with the grain size parameters within the characteristic distance range to determine the grain size trend vector. In this study, the maximum sampling interval is used as the characteristic distance range. The grain size trend vector on the plane can be obtained to sum all the unit vectors of each sampling station, and the calculation formula is as follows,

$$\vec{R}(x,y) = \sum_1^n \vec{r}(x,y)_i \tag{1}$$

where $\vec{R}(x,y)$ is the combined vector of the sampling station, $\vec{r}(x,y)_i$ is the i'th unit vector, and n is the number of unit vectors.

The trend vector obtained from formula (1) is averaged with the trend vectors of adjacent stations to eliminate noise and better reflect the net transport pattern of sediments, and the formula is as follows,

$$\overrightarrow{R_{av}}(x,y) = \frac{1}{k+1}\left[\vec{R}(x,y) + \sum_1^k \vec{R_j}\right] \tag{2}$$

where $\overrightarrow{R_{av}}(x,y)$ is the average transport trend vector, $\vec{R_j}$ is the grain size trend vector of adjacent stations, and k is the number of adjacent stations. The resulting composite vector pattern is the direction of net transport of the surficial sediment.

3. Results and Discussion

3.1 Surficial Sediment Types

According to the Folk's classification diagram, the 265 sediment samples in the study area were divided into 7 categories, namely mud, sandy mud, slightly gravelly mud, muddy sand, slightly gravelly muddy sand, sand and gravelly muddy sand (Fig. 2). Sandy mud was the most widely distributed type of the surficial sediments, mainly concentrated in the Pearl River estuary and offshore areas outside the estuary, covering more than 50% of the survey area. The mud was mainly distributed in the offshore area outside the Pearl River Estuary, especially in the northeast of the study area, where the distribution area was relatively large. In addition, there were also discontinuous small-scale exposures within the Pearl River Estuary and near the shore on the west side of the Pearl River Estuary. The slightly gravelly mud and muddy sand were patchy distributed in Humen, Neilingding island, Wanshan islands and outside the Pearl River Estuary. In the offshore area outside the estuary, three types of sediments with the smallest distribution area were roughly distributed in a ring, and they were slightly gravelly muddy sand, sand and gravelly muddy sand from outside to inside.

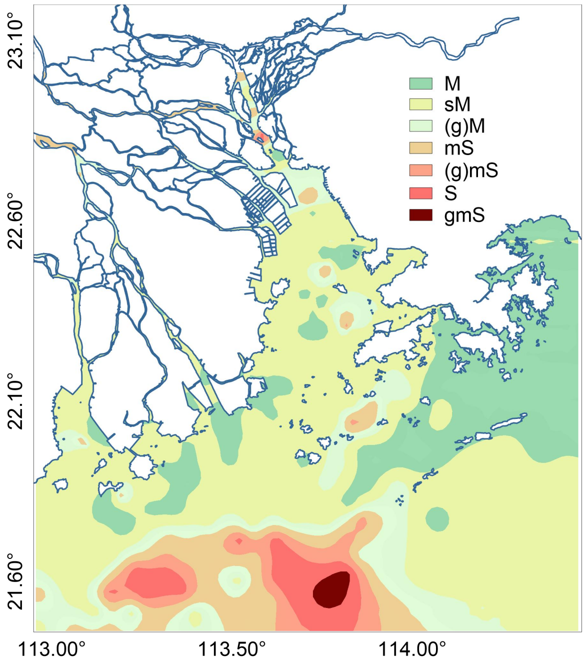

Fig. 2 Spatial distribution map of the Mud (M), sandy mud (sM), slightly gravelly mud ((g)M), muddy sand (mS), slightly gravelly muddy sand ((g)mS), sand (S) and gravelly muddy sand (gmS) in the Pearl River Estuary and its adjacent coastal ocean.

3.2 Grain Size Parameters of the Surficial Sediment

The range of mean grain size was 0.74-7.08 Φ in the study area, with an average value of 5.74 Φ. From the perspective of the spatial distribution of the mean grain size, the sediments in the south of the survey area affected by coastal currents were relatively coarse, with the value of Φ below 3 (Fig. 3a). However, the sediments in the east and west of the survey area and the Pearl River Estuary were relatively fine, with the value of Φ from 4 to 7 (Fig. 3a). The distribution trend of sediment grain size was similar to that of sediment types, the average particle size of the surface sediment was relatively larger in the muddy sediment area, on the contrary, the average grain size was relatively smaller in the sand sediment area (Fig. 2). In the upper estuary, the distribution of mean grain size was similar to the results of previous studies. The average grain size represents the concentration tendency of the grain size distribution, which can directly reflect the particle size, and thus indirectly reflect the average kinetic energy of the sediment transport.

The sorting coefficient reflects the uniformity of sediment particle size, and its main influencing factors are hydrodynamic conditions and material sources. It is often used as an environmental indicator, and various sedimentary environments can be better distinguished by using the sorting coefficient. The distribution characteristics of the sorting coefficient show that most of the regional sediments in the survey area are poorly sorted (Fig. 3b). The sorting coefficient ranged from 1.92 to 2.64, the average value was 1.88, which indicated that the sorting ability was generally poor. However, in the southern part of the study area, appeared some homogeneous sand stations with better sorting (Si<1) .It indicated that the hydrodynamic force in this area was obvious and the action period was relatively long.

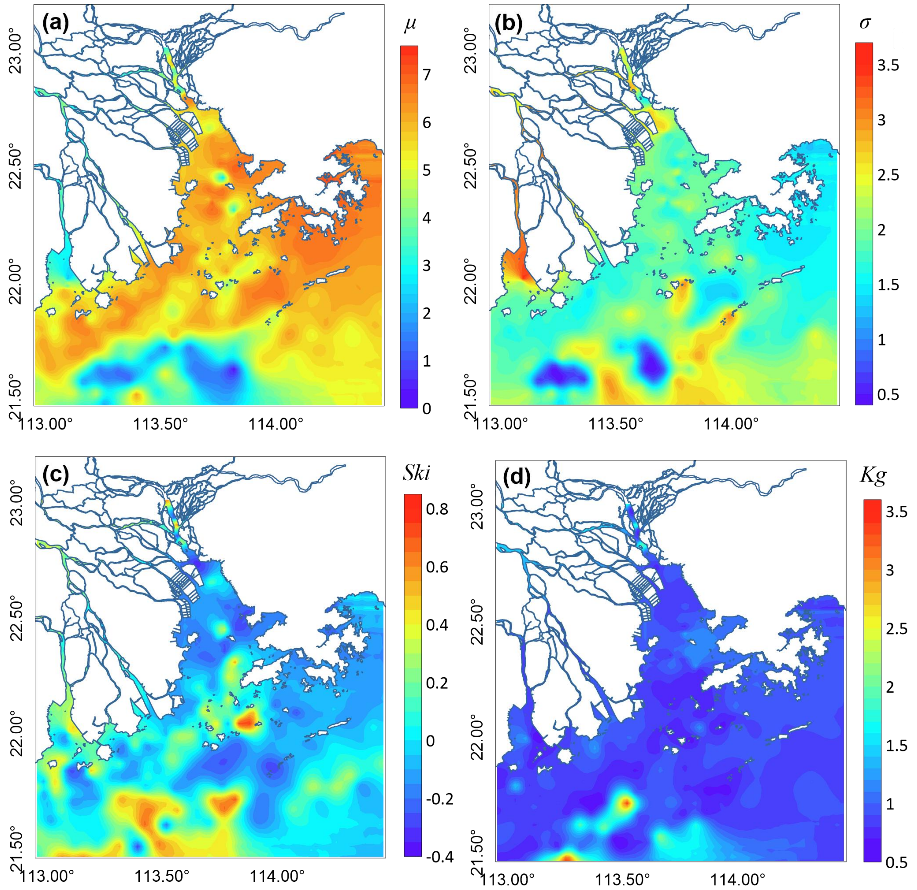

Fig. 3 The distributions of the (a)mean sizes (μ), (b) sorting coefficient (σ), (c) skewness (*Ski*) and (d) kurtosis (*Kg*) of the surficial sediments in the Pearl River Estuary and adjacent the Northern South China Sea.

Figure 3c showed that both positive and negative skewness were distributed in the study area, the variation range of skewness was -0.35-0.77, and the average value was 0.04. In the region affected by the southern coastal current, the positive skewness was dominant, and in the vicinity of the Pearl River channel and the Dangan Islands, the negative skewness was dominant. There was a negative correlation between the skewness and the average particle size (Fig. 3a). The larger the grain size value of Φ, the finer the sediment particles, and the smaller the skewness value.Skewness identifies the symmetry of the sediment distribution, and indicates where the relative position of the mean and the median values. If the sediment is negative skewness, the grain size of the sediment is concentrated in the coarse-grained part; on the contrary, the grain size of the sediment is mainly concentrated in the fine-grained part. Sediment skewness characteristics reflect the degree of energy variation during the deposition process and the degree of sensitivity to the response to the deposition environment, which plays a certain role in understanding the factor of sediments.

The kurtosis value of the survey area varies from 1.53 to 4.07, with an average of 2.40 (Fig. 3d). The grain size frequency curve of the station with mud type was roughly broad kurtosis, and the grain size frequency curve of the station with sand type was roughly narrow kurtosis. Within the Pearl River Estuary kurtosis was small, it indicated that the degree of sediment modification was ordinary, which was caused by the mixed hydrodynamic environment of the river runoff and tidal currents. While the value of kurtosis was relatively high outside the estuary, and this area was dominated by tidal currents. This indicated that the degree of sediment modification was relatively high.

3.3 Surficial Sediments Transport Pattern

Grain size trends of surficial sediments during the 2022 flood season were analyzed using the Gao-Collins model (Fig. 4). The sediment source in the Pearl River Estuary is multi-source, and it is also affected by various forces and factors such as runoff, tidal current, coastal current and topography. Generally speaking, there were five main sediment convergence centers, one of which was located within the Lingdingyang estuary, and the rest were located near the mouth of the estuary. Region I was located in the west of Neilingding Island, where the runoff during the flood period meets the high-saline salt water from the shelf sea. The salt water wedge was frequently active, which was favorable for the deposition of sediments from river runoff and shelf sea. This result is basically consistent with the net sediment transport trend of Lingdingyang surface sediments using the grain size data of surface sediment samples collected in Lingdingyang in the summer of 2017 [6].

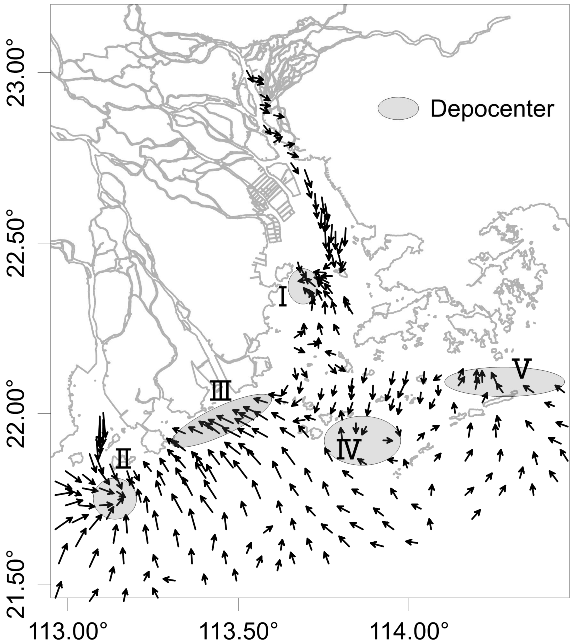

Fig. 4 Net surficial sediments transport patterns during summary 2022 as revealed by the Gao-Collins grain-size trend analysis. The black arrows mean the net surficial sediments transport vectors. Major depocenters are in grey.

Four sediment convergence centers near the mouth of the Pearl River estuary were located at the mouth of the Huangmaohai estuary, the mouth of the Modaomen estuary, the southwest of the Wanshan Islands, and the north of the Dangan Islands, respectively (Fig. 4). These four sediment convergence centers were basically consistent with the distribution of muddy sediment types (Fig. 2). This indicated that the sedimentary center was mainly composed of fine-grained sediments. The sediments in region II and region III were mainly affected by the sediment from the Pearl River, and deposited in the western part of the Pearl River Estuary under the action of Coriolis force. Region IV and region V are located on the east side of the Pearl River estuary. Under the influence of the southwest monsoon in summer, the diluted water the Pearl River expands eastward [12]. Simultaneously this area was located in the overlapping area of the Pearl River estuary plume front and the bottom salinity front [13]. Thus, the sediment carried by diluted wate and shelf salinity water may be deposited on the east side, and then formed the sediment convergence centers.

The mud depo-center in the Lingdingyang bay, which is characterized by high values of grain-size end member and increased contributions of terrestrial organic carbon in the flood season [6]. In the adjacent coastal waters of the Pearl River Estuary, the grain size trend results are mainly in the landward direction, which is quite consistent with the long-term bottom residual current [14].

A long-term morphodynamic model based on TELEMAC numerical modeling system was applied to the Modaomen, results showmorphology is adjusted through silting in the flood [15]. Given the rich organic carbon of the sediment , the surfical sediment strongly impacts the adjacent coastal ocean through, for instance, hypoxia [16]. Therefore, understanding the dynamic characteristics of the surficial sediments transport is a first step to resolving geomorphic evolution, environmental issues.

4. Summary

There are 7 types of surface sediments in the Pearl River Estuary and the northern shelf area adjacent to the South China Sea. There were three muddy sediment types, mud, sandy mud, slightly gravelly mud, and four sandy sediment types, muddy sand, slightly gravelly muddy sand, sand and gravelly muddy sand. The sandy mud was the most widely distributed, and the distribution areas of other types were small and patchy. The sandy sediments were roughly distributed in a ring shape, with the mean grain size becoming larger and the sorting becoming better from outside to inside.

Five convergence centers in the Pearl River Estuary were obtained through grain size trend analysis, and the locations of the convergence centers were basically consistent with the types of muddy sediment. Combining the source and hydrodynamic characteristics of the estuary area, the sedimentary dynamic environment of the Pearl River estuary can be well revealed. Sediments from the Pearl River Estuary were mainly deposited near the mouth of the estuary by the interaction of river plume expansion and salt intrusion of shelf sea. The dynamic deposition processes can be further studied by source analysis, end-member analysis, and numerical simulation.

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