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Spatial variability and representation of seabed sediment grain sizes: An example from the Zhoushan-Jinshanwei transect, Hangzhou Bay, China

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Abstract **Grain size analysis was undertaken for the 2-cm interval sub-samples of eight short cores collected along the Zhoushan-Jinshanwei transect in Hangzhou Bay, using a Malvern Mastersizer 2000 laser particle size analyzer. The result indicates that there are different vertical distribution patterns of mean grain size for the short cores. In the study area, the thickness of the seabed moving layer on an annual temporal scale is much larger than that of the deposited layer, i.e. the sedimentary environment is highly dynamic. As a result, the vertical distributions of mean grain size within the short cores represent different types of sedimentary records formed in the same environment, rather than signals of long-term environmental evolution. The seabed sediment consists mainly of silts in the study area, and the vertically-averaged value of mean grain size has a tendency of convergence when the thickness over which the mean value is derived increases. Such patterns indicate that the grain size composition of the deposit is controlled mainly by the source of material supply; nevertheless, to some degree hydraulic sorting is effective, which has resulted in the differences in distribution patterns along the transect between the grain size values of the surficial sediment and the vertically-averaged values. For long-term sediment transport modeling for an environment associated with strong tidal action and silty sediment, it may be more appropriate to use the vertically-averaged grain size than the value for the surficial sediment, as the model input.**

Keywords: grain size analysis of short cores, vertical distribution of grain size, seabed mobility, Hangzhou Bay.

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One of the characteristics of a sedimentary environment with strong tidal currents and fine-grained sediments is intense and frequent changes in erosion-accretion patterns on the seabed. For example, in Hangzhou Bay, which is a typical macrotidal estuary with fine-grained sediment supplied by the Changjiang River[1], the seabed is highly mobile, with the thickness of the bottom moving layer being of the order of 1 m on an annual temporal scale[2,3], and the sediments are constantly subjected to the processes of entrainment, settling, accumulation and resuspension. Hence, a problem arises with regard to the seabed with high mobility and active hydrodynamic sorting processes: Can the grain size characteristics of the surficial sediment represent those of the entire moving layer? An evaluation of the representation of grain size data is important to the determination of seabed mobility, material transport and accumulation rate in estuaries with strong tidal influences, because the grain size data form a basis for the mapping of seabed sediment distributions and serve as the input for sediment transport modeling. The purpose of the present contribution is to undertake a preliminary research in a solution to this problem, on the basis of the grain size analysis of a number of short cores collected from Hangzhou Bay.

1 Study area

Hangzhou Bay is located in northern Zhejiang Province, eastern China; it is the outer part of the Qiantang River estuary, adjacent to the East China Sea (Fig. 1). The Zhoushan Archipelago is located in the southeast of the embayment.

During the early Holocene, Hangzhou Bay was connected with the Taihu Lake and the coastal waters around the Shanghai-Jiaxing region, as a part of a large coastal bay. After the middle Holocene, this region was silted up gradually. Around 6000 aBP, the Qiantang River estuary, including Hangzhou Bay, began to take its shape. Henceforth, with the accretion of the southern bank of the Changjiang Delta, the shoreline retreating of the northern bank of Hangzhou Bay, and the accretion along the southern shoreline of the embayment, Hangzhou Bay was developed into a trumpet shaped estuary, similar to its present form, at 3000—4000 aBP[1].

Strong tidal influences characterize the hydrodynamic environment of Hangzhou Bay. The tides in the middle and in the north are regularly semi-diurnal, whilst the tides in the south are irregularly semi-diurnal. Mean tidal range at the outer part is 2—3 m, and it exceeds 4 m near Jinshanwei[1,4]. The tidal currents here are mainly rectilinear, with a maximum tidal current speed being above 2 m • s^{-1} near the bay mouth, and more than 4 m • s^{-1} in the bay head areas. The study area is influenced frequently by storms, especially typhoons in the summer season and cold outbreaks in the winter season.

In response to the shallow water depths, strong tidal currents (which means a high carrying capacity for suspended sediment), and a large fine-grained sediment supply from the Changjiang River, the suspended sediment concentration (SSC) in Hangzhou Bay is high during the entire tidal cycle. According to *in situ* measurements, the SSC near the water surface tends to exceed 1 kg • m^{-3}, and near the bottom it can reach 5 kg • m^{-3}. The highest SSC recorded in the past is 51.1 kg • m^{-3}[5], in response to a tidal current speed of 4.48 m • s^{-1}.

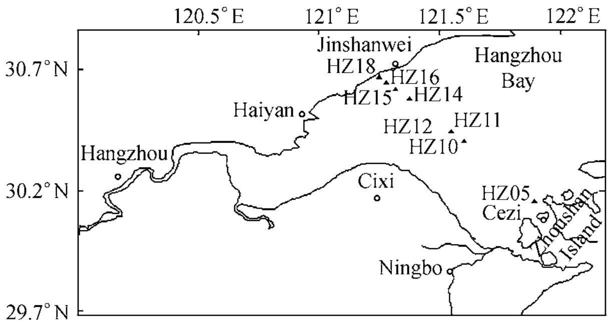

Fig. 1. Location of the study area and the short core sampling sites.

A number of rivers including Qiangtang, Caoejiang and Yongjiang Rivers discharge into the Hangzhou Bay. The Qiantang River contributes a part of the sediment sources to Hangzhou Bay, but the major supply is from the Changjiang River in the north[1,6].

The average water depth in Hangzhou Bay is 8.5 m. In the west of the bay there is a shallow, sand-dominated deposition area (i.e. a sand sheet)[7,8], and to the east of the sand sheet there is a tidal ridge system where the water depth varies. The seabed of eastern Hangzhou Bay is covered with fine-grained sediments[3,9,10], with a flat bed morphology. Deep channels are present near the northern shoreline of Hangzhou Bay[11,12], wide tidal flats are formed on the southern coast, and there are a number of islands in the southeast part (where there are water channels linking with the open sea waters) of the embayment[3,10].

2 Materials and method

In December 2001, eight short cores were collected along the Zhoushan-Jinshanwei transect in Hangzhou Bay (Fig. 1); the surrounding areas of the transect are characterized by strong tidal currents and plume frontal processes and, as a result, sediment movement is active[6,13]. In total, 643 sub-samples were taken from the short cores in 2 cm intervals, for grain size analysis with a Malvern 2000 laser particle size analyzer. The measurement range of the instrument is 0.02—2000 μm, and the relative error for repeated measurements is within 3%. The procedures for the pretreatment of the samples include: (i) The sample was mixed thoroughly and placed into a beaker with a serial number; (ii) 0.5 mol/L sodium hexametaphosphate ($NaPO_3$) solution was added to let the sample disperse for 24 h; and (iii) The sample was subjected to ultrasonic oscillation for 1 min immediately before the instrumental measurement.

The steps of the laser particle size analyzer operation are as follows: (i) Clean water was injected into the measuring chamber to let the instrument adjust the light level and determine the background value automatically; (ii) The prepared sample was added into the chamber and mixed with stirring, ultrasonic dispersion and water circulation to form the suspension for the measurement; (iii) Computer-controlled signals were sent to the instrument to start the measurement and the data were recorded; (iv) Real time display of the grain size distribution curve was realized using the built-in software; and (v) The system was rinsed for 2—3 times for subsequent analysis.

It is worth pointing out that, for use of the Malvern 2000, the concentration of the suspension should not be too high, and the sample should be fully dispersed. Otherwise, the error of measurement can be large. For instance, if the concentration is unacceptably high, then there will be a false peak at the fine part of the grain size distribution curve; likewise, if bubbles or flocculated particles are present in the suspension, or the instrumental laser beam is unstable, then there will be a false peak at the coarse part of the curve. In order to avoid such errors, the concentration of the suspension should be adjusted according to the standard, the instrument tested carefully and, when necessary, the measurement should be repeated.

Finally, the formulae introduced by McManus[14] were used to calculate the grain-size parameters (i.e. mean grain size, sorting coefficient and skewness).

3 Results of analysis and calculations

The vertical distributions of the grain-size parameters are shown in Fig. 2. In the 8 short cores, the sediment consists mainly of silt-sized material, with clay and sand being the secondary constituents. No gravel is present. Generally, the sediment of Core HZ05 is the coarsest, with the mean grain size being around 5Φ; the material of Core HZ18 is the finest, with the mean grain size ranging from 5.5Φ to 8Φ. The mean grain size of the other cores is mainly between 5.5Φ and 6.5Φ. Core HZ18 is located near a tidal flat where the sediment sequence is characterized by inter-layered silt and silty clay, causing the observed fluctuations in mean grain size. Among the 8 short cores, except for HZ18, the sorting coefficient is similar to each other, within the range of 1.2—1.5Φ. Within HZ18, the sorting coefficient of the silt layers is also within the above mentioned range, but the sorting of the silty clay layers is poorer, being around 2.5Φ. Most of the samples are positively skewed, which reflects the character of a tide-dominant sedimentary environment[15].

The vertical distributions of mean grain size for most of the short cores show a fluctuating pattern, with the range of fluctuations reaching 1—2Φ. Further, the distribution trends of the sediment mean grain size within the cores differ. For example, in the top 0.8 m (which is the length of the shortest of the cores), HZ05, HZ10, HZ14

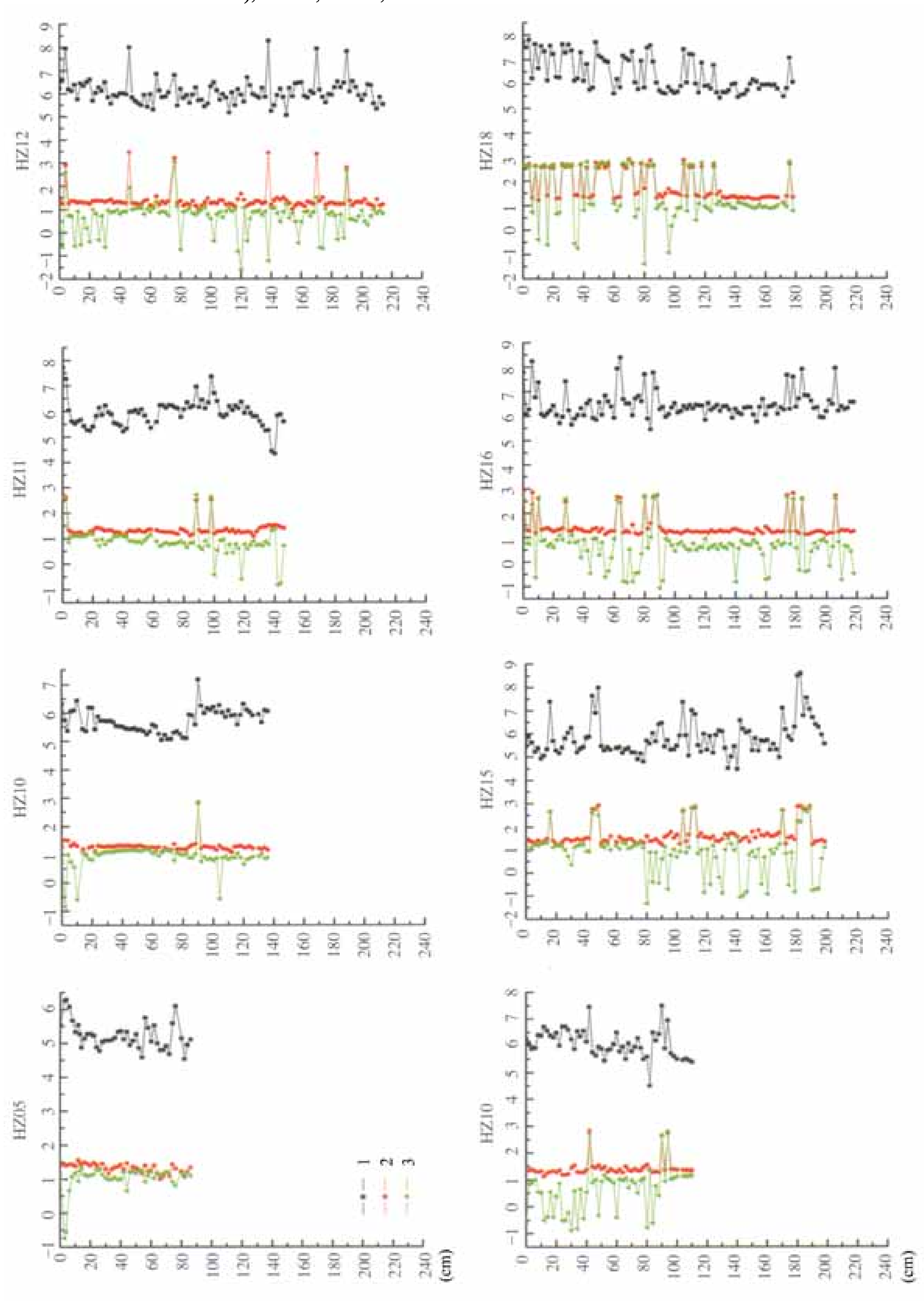

Fig. 2. Vertical distributions of the Hangzhou Bay sediment grain size parameters (i.e. mean grain size, sorting coefficient and skew-

ness). 1, Mean; 2, sorting; 3, skewness.

and HZ18 show a fining-upward trend, whilst the trend of HZ11 is coarsening-upwards; the remainder have no apparent fining- or coarsening-upward trend.

Averaging the sediment mean grain size in different thicknesses (0.1, 0.2, 0.3 m, etc.) for each of the cores generates an interesting result (Fig. 3). The vertically-averaged value has a tendency of convergence with the increase of the thickness over which the averaging calculations were carried out. Such a pattern indicates that the spatial difference of the sediment, using the vertically-averaged values, is not as large as shown by the surficial materials.

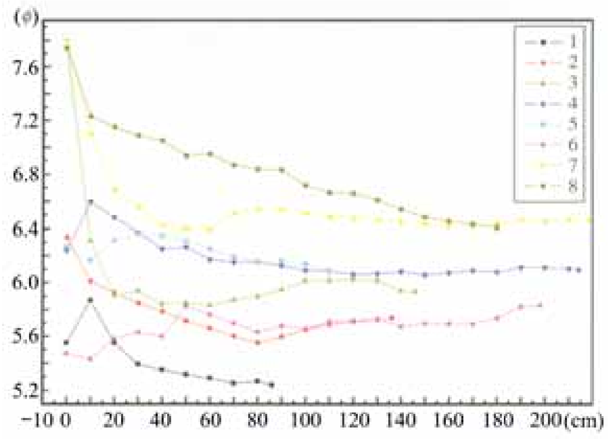

Fig. 3. Relationship between the vertically-averaged mean grain size and the thickness over which the average value is derived. 1, HZ05; 2, HZ10; 3, HZ11; 4, HZ12; 5, HZ14; 6, HZ15; 7, HZ16; 8, HZ18.

Figure 4 shows the mean grain size distributions along the transect. It is noticeable that the transect distribution of the values for surficial sediment (0—2 cm) is different from those derived by vertical averaging. The average values of the top 0.8 m samples are similar to those for the entire cores, with the latter having a trend of becoming finer from the southeast towards the northwest along the transect (with the exception of Core HZ15, which is close to a scour channel in northern Hangzhou Bay[12,16] and the sediment grain size is relatively coarse[3]; furthermore, HZ18, which is located in the tidal flat environment, shows a fining-upward trend over the full range of the of 1.8 m core). Generally, the surficial sediment size is smaller than the vertically-averaged values.

4 Discussion

The analytical results indicate that there are different vertical distribution patterns in terms of mean grain size for the short cores, with significant fluctuations. Although the thickness of the moving layer along the Zhoushan-Jinshanwei transect varies, the seabed mobility is high at all the sampling sites. Observations indicate that the moving layer can reach an order of 10^0 m in thickness, on an annual temporal scale, but the accumulation rate is

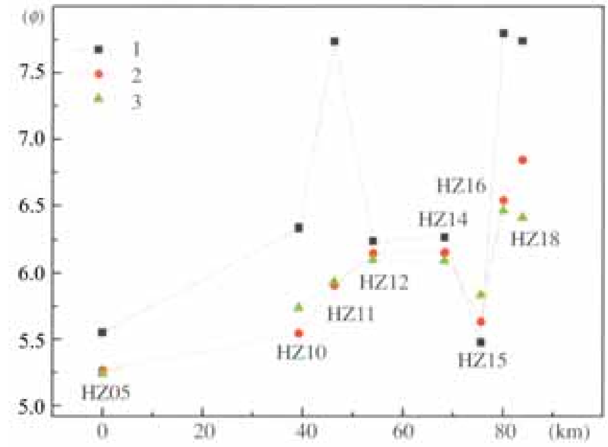

Fig. 4. Transect distributions of the mean grain sizes averaged over the surficial layer (0—0.02 m), top 0.8 m layer and the entire core. 1, Averaging over 0—2 cm section; 2, averaging over 0—80 cm section; 3, averaging over entire core.

only of the order of 10^{-2} m • a^{-1} on the 10^2 a temporal scale[2,3]. Thus, the sediment must be subjected to the processes of resuspension and settling many times before permanent deposition. Namely, the vertical distributions of mean grain size within 1—2 m thickness of sediment represent different types of sedimentary records in the same environment, rather than indicators of the regional environmental evolution.

The characteristics of grain size result from both the source of material supply and hydrodynamic conditions of the sedimentary environment[17]. The source determines the general size range of the material and the hydrodynamic conditions control the hydraulic sorting of the material. The materials accumulated in Hangzhou Bay are mainly derived from the Changjiang River[1,6] and, therefore, the complex hydrodynamic processes of the system[1,4] can only slightly modify the size characteristics inherited from the source. The convergence trend shown in Fig. 3 and the differences between the mean grain sizes of the surficial layer and vertically-averaged values are indicative of the source influence. On the other hand, the sediment is influenced also by hydraulic sorting, differential settling and mixing. These processes explain the different vertical distributions of mean grain size in the 8 short cores, in spite of the fact that the average compositions of the sediments are similar. For instance, in a deposition area, the sediment sequence may be fining-upwards as the hydrodynamic power weakens gradually; in an eroding area, the surficial sediment may be reworked by tidal currents to form a sedimentary sequence that is coarsening-upwards. The vertical sorting of the sediment may be intensified by storm surges and mixing of materials eroded from different sites.

It should be noted that the settling of the sediment is affected, at the same time, by a number of factors such as tidal currents and the suspended sediment concentration that act individually and/or in combination. Thus, the strong hydrodynamic power (provided by, e.g. storm surges) alone does not necessarily cause the formation of the sorting of sediment. For very low SSCs, of the order of 0.1—0.7 kg • m^{-3}, the aggregates or particles settle independently without much mutual interference; therefore, the settling velocity is independent of the concentration. However, if the concentration is higher than 5—10 kg • m^{-3}, then the settling velocity decreases with increase in the concentration; this has been referred to as hindered settling. At such high concentrations, the sediment suspension hinders the upward flux of water expelled by consolidation of the lower suspension[12,15]. Hence, it may be inferred that when a storm surge weakens, the high SSC (above 5 g • L^{-1}) will lead to hindered settling and abundant particles tend to settle together, causing rapid decrease in the SSC. Differential settling will not be effective until the SSC becomes below 0.7 g • L^{-1}. Therefore, during a single storm event, the effect of differential settling would be significant only in the top of the moving layer.

In a highly dynamic sedimentary environment where vertical sorting is effective, the mean grain size of the surficial sediment depends upon which layer is exposed on the surface of the bed. Thus, the transect distribution pattern of the surficial sediment mean grain size (Fig. 4) may merely represent the situation of the period when the samples were collected. The vertically-averaged values of mean grain size within the moving layer may be less influenced by vertical sorting; thus, it may be more appropriate to use such values to characterize the mean grain size of sampling sites (since the exact thickness of the moving layer is often not known, in our study the length of the total short core was used). The spatial distribution of mean grain size along the Zhoushan-Jinshanwei transect is changed after the mean grain size within the moving layer (i.e. the shore core) is averaged. The vertically-averaged mean grain size in the study area shows a trend of becoming finer from the southeast towards the northwest; this is consistent to some extent with the general pattern of grain size variations in Hangzhou Bay[18].

Sediment grain size is an important input parameter for sediment transport models. For long-term sediment transport modeling for an environment with strong tidal action and silty sediments, it may be more appropriate to use the vertically-averaged mean grain size, than the value determined from a surficial sediment sample. In the future, further investigations are required to define the thickness of the moving layer, and to determine the relationship between the spatial distribution of grain size and the sediment dynamic processes. On a small temporal scale, the sorting of sediment in the sequence itself becomes an important research topic; this study may provide crucial clues for the interrelationships among the formation of sediment sequence, the time-scale effect of accumulation rates and the preservation potential of sedimentary structures in shallow marine environments.

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