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Patterns of Sediment Transport Pathways on a Headland Bay Beach—Nanwan Beach, South China: A Case Study

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ABSTRACT



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Embayed beaches bounded by headlands, headland bay beaches, are a common feature along the coast of southern China. The patterns of sediment transport pathways in these beaches are important for understanding changes in beach and nearshore geomorphology that are a response to different wave energy conditions. Nanwan Beach in southern China is characterized by a large seasonal variation of incident waves. In this study, sediment samples and a series of beach profiles from Nanwan Beach are examined to determine spatial changes in sediment transport pathways. Empirical orthogonal function analysis of the profile data indicates that the variation of sediment transport occurs in two distinct modes. The first mode is related to seasonal changes in cross-shore sediment transport with associated alongshore sediment transport. The trend of sediment transport is seaward in winter and landward in summer. The second mode is onshore-offshore sediment exchange, which occurs in the intertidal zone in summer and in the swash zone in winter. Moreover, grain size trend analysis of sediment samples suggests that sediment transport in the nearshore zone is predominantly in the northwesterly direction because of southeast incidence waves in winter, with Nanwan Bay opening to the south. The sediment transport pathways are to the north in summer from the influence of typhoons.

ADDITIONAL INDEX WORDS: *Sediment transport, grain size trends, EOF analysis, Nanwan Beach.*

INTRODUCTION

Headland bay beaches are bounded by rocky outcrops or rocky headlands (Moreno and Kraus, 1999). They are widely distributed around the world and are also known as zeta curved bays, half-heart-shaped bays (Silvester, 1960), crenulate-shaped bays (Finkelstein, 1982; Silvester and Ho, 1972), and embayed beaches (Ranasinghe *et al.*, 2004). Because the projecting headlands can protect these beaches from wave attack, they have often been used as harbors and for recreation. Thus, stability of these beaches is important to coastal engineering and development of local economies. Extensive research has been focused on these beaches as exemplified by (1) geomorphologic studies (*e.g.*, Dai and Li, 2004; Klein and Menezes, 2001; Moreno and Kraus, 1999; Short, 2002), (2) analysis of configuration of the shoreline (Dai, Li, and Zhang, 2004; Klein, Adriani, and Menezes, 2002; Leblond, 1979; Silvester and Ho, 1972), (3) discussions of beach states (Wright *et al.*, 1979), and (4) sedimentologic studies (Ranasinghe *et al.*, 2004; Short, 1999; Wright *et al.*, 1979). This research has improved the knowledge of sediment transport in headland bay beaches. However, up to now, most of these beaches studied rarely focus on the identification of sediment transport pathways in different energy environments, which is important for understanding the morphodynamics of beaches.

Headland bay beaches are common in southern China (Dai and Li, 2004; Dai, Li, and Zhang, 2004), extending over 20% of this coastal region. At least 100 headland bay beaches distributed throughout southern China are dominated by rocky headlands at the mouths of deeply incised valleys and estuary bays. These rocky headlands consist mainly of granite, which bound the sediment movement in the limited headland bays. Because of the seasonal changes in wave climate and occasional typhoons in southern China, it is difficult to identify pathways of sediment transport on these beaches. This information on sediment transport is necessary for the development of harbor engineering and tourism. Although some research on geomorphologic modes and shoreline changes of these beaches has been carried out (Dai, Li, and Zhang, 2004; Dai *et al.*, 2007; Li, 1986), there are only a few reports about changes of sediment transport along the large tropical coast of South China. Therefore, Nanwan Beach, located on the central coast of southern China and chosen as a typical headland bay beach in this study, was investigated (1) to analyze seasonal accretion and erosion of the beach, (2) to determine the sediment transport pathways in response to seasonal wave climate, and (3) to examine the effects of typhoon action on sediment movement.

REGIONAL SETTING

Nanwan Beach in southern China is an unconsolidated, quartz sandy beach that is tied between bedrock headlands at

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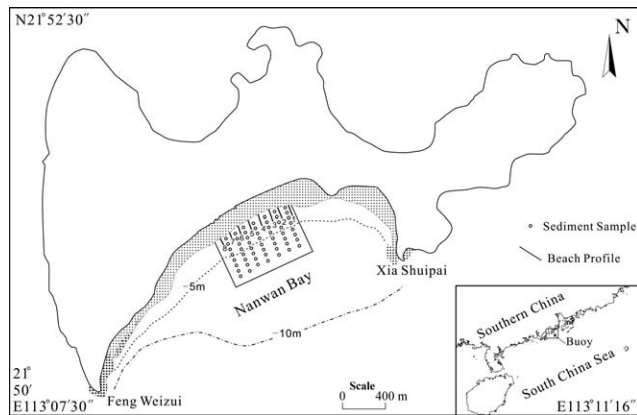


Figure 1. Study area and stations for surface sediment sampling in summer.

Xia Shuipai Point and Feng Weizui. Nanwan Bay is open to the south (Figure 1). The beach is 4 km in length and has an arc-shaped appearance in plan form. Longshore distribution of morphodynamic states of this beach is linked with the nearshore water circulation pattern, and beach states, ranging from fully dissipative to fully reflective, can be observed on the beach, as described by Wright *et al.* (1979; Dai and Li, 2008). Moreover, alongshore multibar patterns are a common feature at the central of the beach, and terrace shoals occur on the eastern rockwall section of the beach (Dai *et al.*, 2007). Semidiurnal tides are dominant, ranging from 0.2 m (neap) to 2.1 m (spring). A previous study showed that the residual currents by tides in headland bay beaches of southern China are too weak to influence trends of sediment transport (Li, 1986). Figure 2 shows 1 year of observed wave data at the buoy, which is 40 km from the study site in the southeast direction (Figure 1). The wave data show seasonal variations with wave directions from S–SSW and S–SE in summer (*ca.* April–September) and winter (*ca.* October–March), respectively. The average significant wave height is 1.1 m, with a mean wave period of 5.5 seconds. In addition, waves with heights more than 4 m only occur during typhoon periods, with two or three typhoons influencing the studied area every year. The average wave heights are larger in winter than in summer. Thus, waves in March and July can be representative of wave climate in winter and summer, respectively, although two typhoons influenced this region in July.

MATERIALS AND METHODS

Data Sets and Processing

Daily surveys of beach profile along eight transects in the center section of the beach were performed from July 4 to August 6 in 2001 and from February 24 to March 28 in 2002 by using the stake and horizon method at the lowest water level of each day (Figure 1; Emery, 1961). The profiles were 50 m apart and covered a length of 350 m alongshore and had a width of about 200 m from the foot of the foredune to the maximum water depth of about 3 m, which is related to a common base

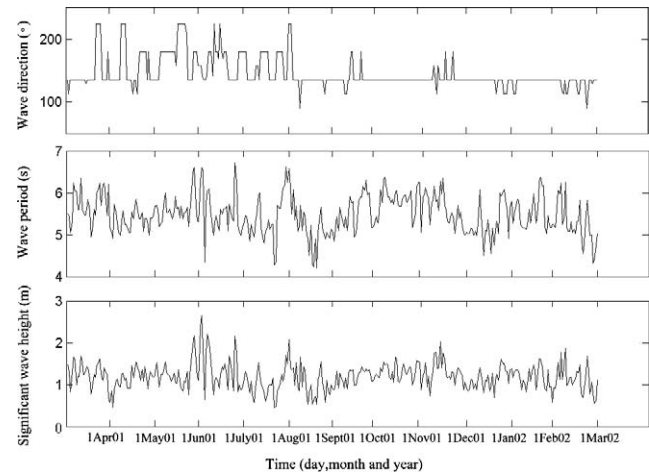


Figure 2. Records of wave parameters from April 2001 to March 2002 (Dai, Chen, and Du, 2008).

datum (Yellow Sea Datum of China). In addition, all the stakes of the beach were established again in winter at a location approximately 200 m west of the previous surveys because of local coastal engineering needs and several typhoon actions in this zone in the summer. Because the waves that occurred in March and July can be considered representative of the wave climate in summer and winter, respectively, the objective of this beach leveling in these typical months was mainly to examine the sediment transport over the subaerial beach in response to different wave climates.

The survey data for each profile were reduced to volumetric information of horizontal slices of 0.5 m thickness. The first layer and the last layer are 2 m and –0.5 m high, with relation to the Yellow Sea Datum, respectively. Volumes of seven datasets in the upper beach, midswash, lower swash, upper intertidal, midtidal, lower midtidal, and lower intertidal zones were determined. The horizontal slices approximately correspond to tidal and high-tide, swash process zones identified by Duncan (1964). The upper beach slice incorporates a dry or drying sand zone, which is influenced by swash action during occasional spring tides or by high seas (Clarke and Eliot, 1988). Swash inundation occurs more frequently in the upper beach zone, particularly under spring tide conditions. The lower intertidal zone is saturated under most conditions. Therefore, separation of the horizontal slices, according to the predominant processes operating at each level, assists data interpretation (Clarke and Eliot, 1988). Clearly, analysis of the time series for the seven beach segments is meaningful because it provides a detailed, three-dimensional account of cross-shore sediment movements. Moreover, the daily cross-shore location of the 0 m line and the beach volume from 0 m to the stable stake of unit width in each profile were calculated on the basis of the measured data so as to analyze alongshore sediment movement.

Sediment sampling was carried out in the study area on July 27, 2001, and on February 25, 2002. Sediment samples were collected every 50 m seaward from the low tidal line to

Table 1. The records of typhoons affecting the Nanwan beach (Dai *et al.*, 2007).

Typhoon Serial Number	Data Influenced	Greatest Wind Velocity (m/s)	Highest Wave (m)	Main Wind Direction	Main Wave Direction
200104	2001-07-5-07-7	11.3	2.8	SE-E	SE, S
200107	2001-07-22-07-24	7.58	2.2	SE-E	SE
Tropical depression	2001-07-25-07-27	13.3	2.9	SE-E	SE, S

approximately -7 m depth with the use of a grab sampler. The number of samples was 53 in winter and 56 in summer, with sample depths of about 5–10 cm. Sediment samples were taken in summer *ca.* 2–3 days after several typhoon events occurred in this region. These typhoons were mentioned in previous studies (Table 1; Dai *et al.*, 2007). The analysis of the sediment grain size was conducted by a sieving method with quarter-phi intervals (Liu and Zarillo, 1989). On the basis of the grain size classes of each sample, mean grain size, μ , sorting coefficient, σ , and skewness, sk , were calculated by the statistic moment method (Mcmanus, 1988). The aim of this sampling scheme was to analyze sediment transport in the submarine environment with different wave energy influences.

Sediment Transport over the Subaerial Beach—EOF Analysis

The advantage of empirical orthogonal function (EOF) analysis is that a set of intercorrelated variables can be decomposed into a set of statistically independent variables. Eigenanalysis separates the temporal and spatial dependence of the data, considering data as a linear combination of products of corresponding functions of time and space (Dai, Chen, and Du, 2008). Thus, several studies of sediment transport have used the EOF technique based on the changes of measured beach profiles (Aubrey, 1979; Clarke and Eliot, 1988; Haxel and Holman, 2004; Wijnberg and Terwindt, 1995). The variability of sediment transport along each profile can be quantified by a set of eigenvalues; each eigenvalue and its EOF define the importance of the eigenfunction. Moreover, the negative values of products of each function of time and space can represent sediment reduction along the beach profile, and corresponding positive values of those show sediment increase along the beach profile (Clarke and Eliot, 1988; Larson *et al.*, 1999; Wijnberg and Terwindt, 1995). Therefore, cross-shore sediment transport over the subaerial beach (over the lower intertidal level) in the present work is related to the removed average volumes of the seven slices of measured profiles involving EOF analysis.

Sediment Transport Pathway below Submarine Beach—Gao and Collins' Method

The grain size trends analysis method, which was proposed by Gao and Collins (1991, 1992, 1994), can indicate sediment transport pathways, as supported by hydraulic, geomorphologic, and sedimentologic evidence (Cheng, Gao, and Bokuniewicz, 2004; Van Lancker *et al.*, 2004). The theoretical principles of this method can be shown as follows: On the basis of the two dominant trends of sediment transport, wherein sediment is finer, better sorted, and more negatively skewed in the

downstream direction of transport (case 1) and coarser, better sorted, and more positively skewed in the downstream direction (case 2), respectively (McLaren and Bowles, 1985). With the use of slightly modified versions of the trends in cases 1 and 2, Gao and Collins (1991, 1992) improved the method to define a grid of trend vectors, which can then be smoothed and transformed into transport vectors by averaging the vectors of neighboring stations. A detailed explanation of the method can be found in Gao and Collins (1994).

In this study, the Gao and Collins' method was adopted for analyzing net transport pathways in the nearshore environment of the study area.

RESULTS AND DISCUSSION

Beach Width and Beach Volume

Each of the eight beach profiles have similar shape features but have different behaviors between summer and winter. The typical beach profile 8 (Figure 3a) shows obvious differences in the sandbar location in different seasons, in that the water depth of the sandbar was about 0 to *ca.* -2 m in summer and -1 to *ca.* -3 m depth in winter, respectively. The beach topography of each survey was created by kriging interpolation of the profile leveling data (Figure 3). From this it can be seen that the distances between the stable stake and the different elevation contours, 2, 1, 0, and -1 m isobaths, in summer were much larger than those in winter. In addition, assuming that the beach changes were determined by variations of beach width between 0 m and the stable stakes and the beach volume between 0 m and the stable stake with unit width, the beach width and beach volume can be obtained as shown in Figure 4. From Figure 4, the mean values of beach width and beach volume of each profile in summer are much larger than those in winter, which means that dominant cross-shore sediment transport occurred along the beach. However, the mean values of width and volume of the beach sections from profile 4 and profile 8 show gradually decreasing trends in summer and increasing trends in winter, respectively. These results suggest that a minor alongshore sediment transport direction is from west to east in summer and from east to west in winter.

In addition, although a coastal current flows westward along the west coast of southern China all year round, which is related to fresh water from Zhujiang River and the South China Sea Warm Current, the sediment transport of the studied area could not be influenced by this kind of current action. It was reported that the width of the Pearl River sediment plume transported by coastal currents is only around 10–20 km seaward (Ying, 1999). The present study area is located at the outer rim of the sediment plume, with weak current and low concentration of the suspended load (Ying,

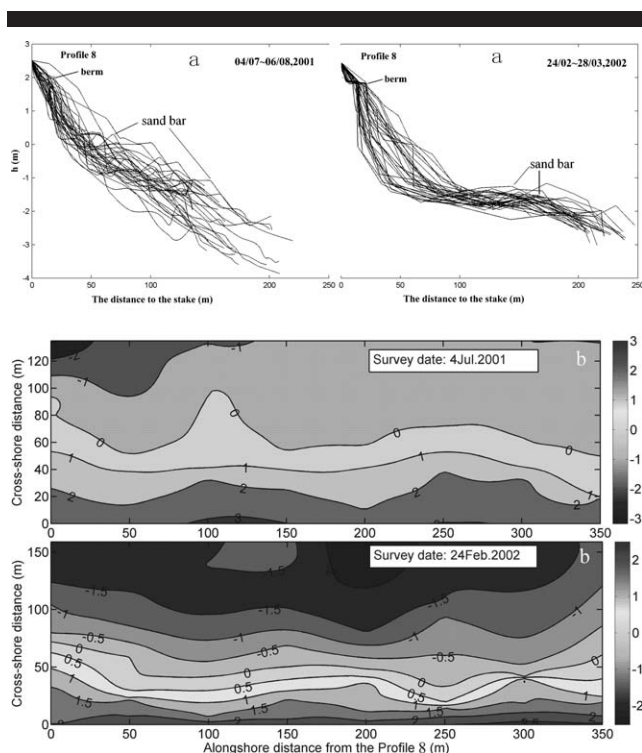


Figure 3. Changes in beach measurements.

1999). Moreover, the study area is bounded by rock headlands that tend to isolate sediment and current from outer influences. The seabed of the study area is composed of sand, whereas at depths of more than 10 m, the seafloor consists of clay and silt (Dai and Li, 2008; Ying, 1999). Thus, sediment transport in the study area is a self-governed system with little influence from the outer sediment plume of the Pearl River estuary.

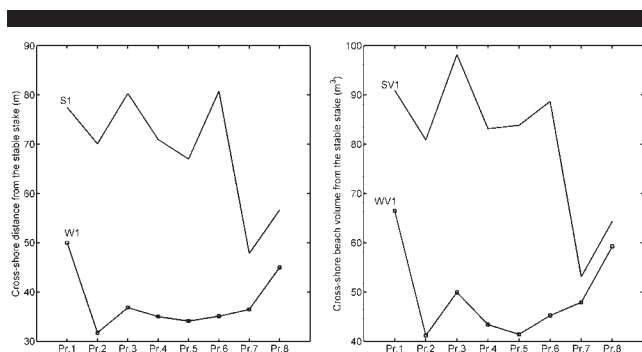


Figure 4. Changes in beach width and beach volume. S1: The mean location of the 0-m isobath from the stable stake during the measured period in summer; W1: The mean location of the 0-m isobath from the stable stake during the measured period in winter; SV1: The mean beach volume of the over 0-m isobath with unit width during the measured period in summer; WV1: The mean beach volume of the over 0-m isobath with unit width during the measured period in winter.

Table 2. The percentage of variance explained by the first two eigenfunction modes describing onshore-offshore sediment movement.

Profile	1st (% Contribution)	2nd (% Contribution)	Total of the First Two Contributions (%)
Summer			
1	143.66 (62.19)	49.74 (21.53)	83.72
2	151.61 (65.63)	39.39 (17.03)	82.66
3	145.48 (62.98)	35.39 (15.36)	78.34
4	152.72 (66.11)	36.04 (15.60)	81.71
5	164.73 (71.31)	34.91 (15.11)	86.42
6	151.77 (65.71)	42.19 (18.26)	83.97
7	156.75 (67.86)	39.96 (17.30)	85.16
8	167.31 (72.43)	30.10 (13.03)	85.46
Winter			
1	181.70 (81.12)	30.99 (13.84)	94.96
2	145.22 (64.83)	32.91 (19.71)	84.54
3	139.72 (62.37)	40.42 (18.05)	80.42
4	162.15 (72.39)	33.87 (15.12)	87.51
5	167.41 (74.74)	36.89 (16.47)	91.21
6	183.61 (81.96)	30.17 (13.46)	95.42
7	161.83 (72.24)	36.57 (16.32)	88.56
8	188.06 (83.95)	28.71 (12.82)	96.77

Sediment Transport over the Subaerial Beach

Cross-Shore Sediment Transport over the Subaerial Beach by the First EOF

The results of EOF analysis of the seven horizontal data layers for each beach profile are summarized in Table 2. The functions are ranked according to the percentages of the mean square value of the data that have been explained. These percentages are interpreted by each function and enable evaluation of the relative importance of each function in explaining the variability of the onshore-offshore movement of sediment transport. From Table 2, the first two EOF functions cover more than 80% of the total mean square values. Therefore, the first eigenfunctions for seven slices of each beach profile (Table 2) are determined by the basic processes of sediment transport in different seasons and reflect the main shore-normal components of the profile. The first spatial EOF of each segment of typical beach profile 8 is shown in Figure 5, which indicates that the values of the first spatial eigenfunction of each beach segment in summer is positive. It implies that the whole beach is accreted in summer. Furthermore, the range between the curve of each spatial eigenfunction and the transverse axes keeps increasing from the lower intertidal zone (segment 1) to the upper beach (segment 7). This represents an onshore-offshore sediment movement along the whole profile. The net transport path was from the lower intertidal zone to the upper beach and caused an increase in the volume of the beach from the seaward sector to the upper beach, as previously reported at other locations (e.g., Winant, Inman, and Nordstrom, 1975). The associated first temporal eigenfunction (Figure 5) for each beach segment had both negative and positive values during the measurement period, but the frequency of occurrence of positive values was greater than those of negative values. Also, the trends in values of the first temporal eigenfunction of these segments increased at the end of the measurement period. Therefore, the basic processes of sediment transport can be evaluated by the direction of

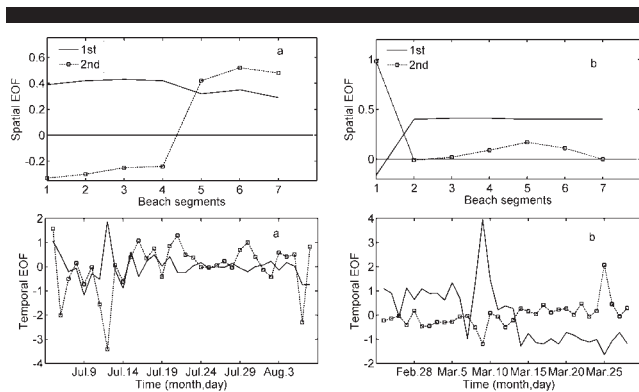


Figure 5. Eigenfunction modes describing cross-shore sediment movement in summer and winter, Nanwan Beach.

sediment movement along the beach, from the low tidal zone to the high tidal zone.

Figure 5 also shows a typical pattern of most of the curves of the first spatial eigenfunction in winter that cross over the transverse axes. The range between the curve of each spatial eigenfunction and the transverse axes increased from the upper beach to the swash zone. Also, there are zero crossings (nodal points) between the curve of the first spatial eigenfunction and the transverse axes. In addition, the curve of the first spatial eigenfunction from the swash zone to the lower intertidal zone is relatively stable. In most cases, the associated first temporal EOF is positive in the beginning of the winter survey period and negative at the end. A negative temporal EOF value implies that the material moves from inshore to offshore (Larson *et al.*, 1999). Thereafter, the trends of the changed values of this temporal EOF indicate a time scale for the adjustment of the beach toward an eroded state (Larson *et al.*, 1999). Thus, the first eigenfunction reveals that the basic mode of net sediment transport pathways in winter is from the upper beach to the low intertidal zone and is associated with sediment onshore-offshore movement between the upper beach and the intertidal zone.

Sediment Transport over the Subaerial Beach by the Second EOF

The second eigenfunction for most of all the beach profiles accounts for 15% of the total mean square values and further reveals the sediment transport between different horizontal slices (Table 2), which is consistent with previous research (Clarke and Eliot, 1988). The slope change of the curve for the second spatial eigenfunction is larger than that of the first, and suggests that the spatial changes in sediment transport reflected in this eigenfunction are complex. The results from EOF analysis also show that nodes and antinodes of the second spatial eigenfunction are dominant, the pivotal points of which were found to occur in the intertidal zone in summer and swash zone in winter, respectively. Pivotal points (intersections between the spatial eigenfunctions and the transverse axes) show that sediment moves onshore-offshore in different beach segments. The antinodes identify places of high beachface mobility (Clarke and Eliot, 1988). Thereafter, antinodes of this

spatial eigenfunction in summer mainly reflect the frequent movement of material in the intertidal zone, which can be induced from the onshore-offshore movement of the sandbar (Dai, Chen, and Du, 2008). However, antinodes of the second spatial eigenfunction in winter imply that frequent sediment movement occurred in the swash zone (Figure 5), which can result from the driving action of the broken wave in the swash zone in winter (King, 1973). In addition, the location of the antinode in the swash zone in winter is higher than that in the intertidal zone in summer. The reason is that the broken wave height in the nearshore zone in winter is larger than in summer, which results in the upward shift of the area for the sediment movement. The associated second temporal eigenfunction reveals that onshore-offshore transfer of the sediment can have a short periodicity (Figure 5). Moreover, the effects of the typhoons and storms occurring during the measurement period can also be seen in the temporal eigenfunction as distinct peaks (Figure 5). Major storms hit the Nanwan Beach in March 2002, and typhoons passed over this region in July 2001 (Dai *et al.*, 2007). During these intense dynamic events, large amounts of sediment were eroded from the berm and deposited in the shallow portion of the beach, particularly in the vicinity of the sandbar. Thus, the second eigenfunction of both in summer and winter likely reflect the response of the beach changes to the action of the storms and typhoons. In addition, this eigenfunction represents onshore-offshore transfer of the sediment in the intertidal zone during summer and in the swash zone during winter, respectively.

Sediment Transport Pathways in the Nearshore Zone

Grain Size of Surface Sediment

Distributional patterns of grain size parameters are shown for the two different hydrodynamic conditions (Figure 6). The mean size of about 2.3ϕ is found over the collected sample area in summer, but a value of more than 2.6ϕ is commonly distributed in fair weather in winter. Moreover, compared with the grain size parameters in fair weather, sorting is better and the skewness resulting from the typhoon is much more negative.

Sediment Transport Pathways in the Nearshore Zone

Trends of sediment transport in summer and winter are shown in Figure 7. Although the Gao and Collis (1992) method has been widely used in the marine environment, some parameters, such as sampling interval, sampling depth, and deposition environment, can influence the identification of sediment transport (Héquette, Hemdane, and Anthony, 2008; Pedreros, Howa, and Michel, 1996). Here, the topographic changes of the study area have a simple relationship with the isolated deposition environment (Figure 1). A sampling interval of 50 m was rigorous followed according to the Gao and Collins' method. In addition, the sampling depth of 5–10 cm in the study area can be associated with a time scale of the season because of usual wave action. However, collected sediments by this sampling method also can be related to a much shorter time scale because sediment can be easily reworked in shallow marine environments during a single storm event. Thereafter,

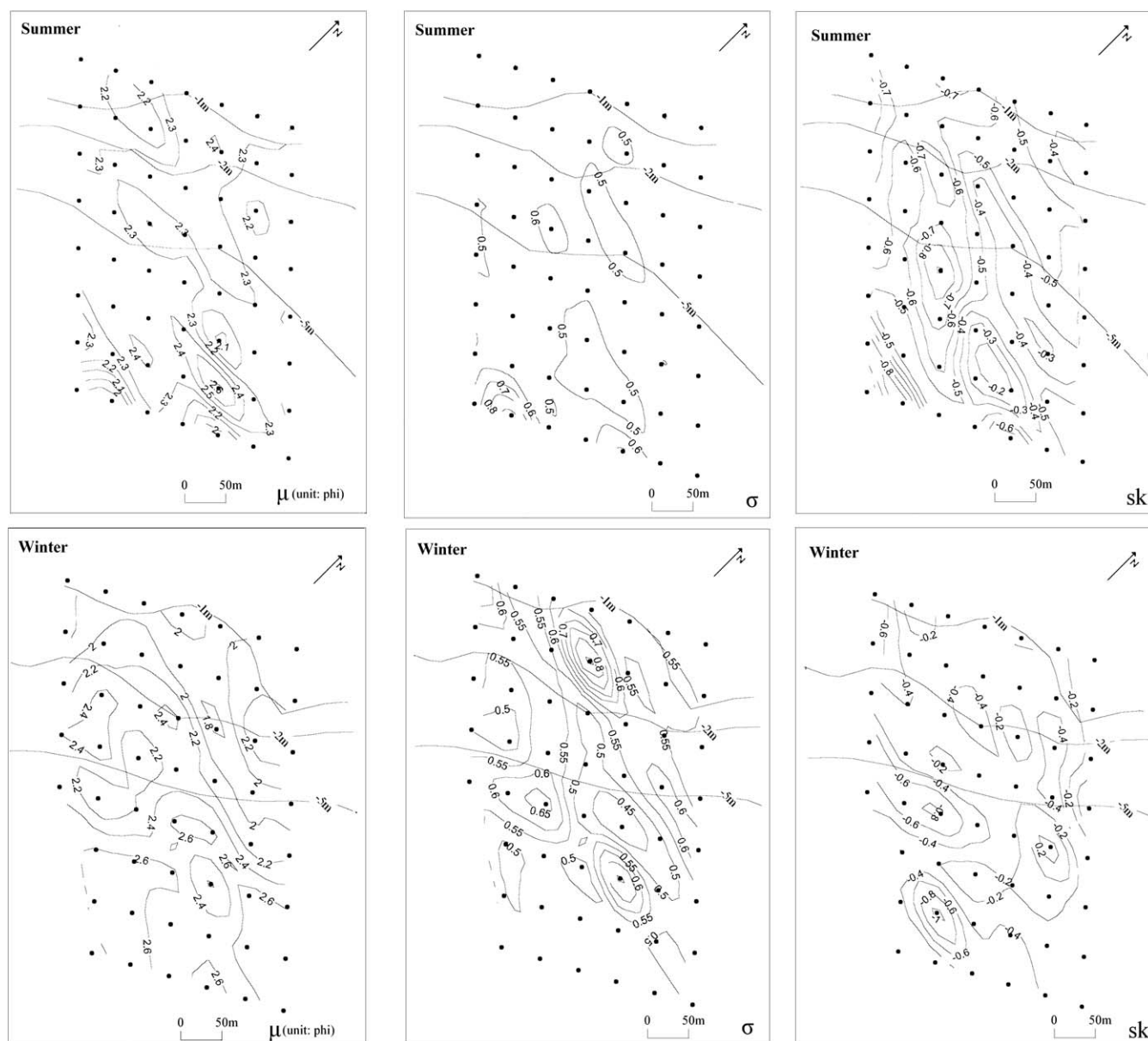


Figure 6. Spatial distributions of grain size parameters in summer and winter, Nanwan Beach.

the sediment transport paths in the study area can be identified by Gao and Collins' method. As can be seen in Figure 7, the trends of sediment transport in water depths of *ca.* -2 m in summer show a complex behavior. The direction of sediment transport above the 2-m isobath is from SW to NE, which can be a result of the action of prevailing SW waves. However, the trends of sediment transport below the 2-m isobath is from SE to NW, which is not in agreement with the measured wave direction, which is SW. The reason is that the intense typhoon with a S to SE direction destroyed the previous pathways of the sediment transport (Table 1). It appears that the effect of the typhoon on the lower intertidal zone diminished rapidly when the wave direction returned to the SW. In addition, some

studies of grain size trend analysis also showed that computed transport paths could be the result of currents that recently acted on the seabed (Héquette, Hemdane, and Anthony, 2008; Pedreros, Howa, and Michel, 1996). On the basis of grain size trend analysis and *in situ* current measurements on a sandy shoreface, Héquette, Hemdane, and Anthony (2008) showed that sediment distribution over a small-scale area could change rapidly under the action of tidal currents, resulting in varying patterns of sediment transport vectors. Thus, some of the residual transport vectors within the adjacent area of -2 m move northward/eastward in response to the action of subsequent SW waves (Figures 2 and 7).

The trends of sediment transport inshore of about -2 m in

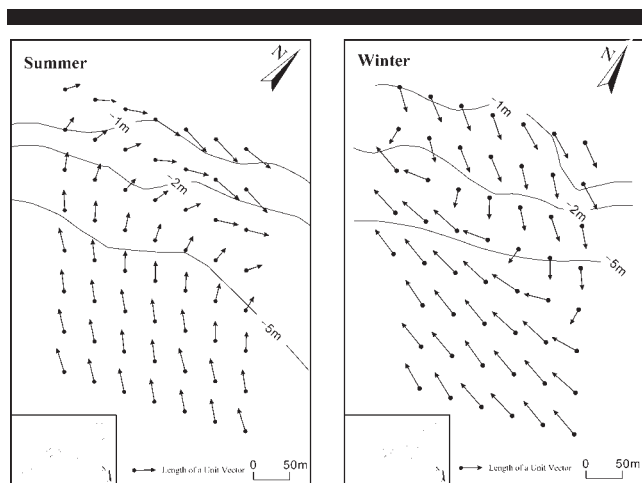


Figure 7. Distribution of residual transport vectors in the study area.

winter do not correspond to the current produced by the SE waves that approach the shoreline during winter either. However, the sediment transport vectors located offshore at -4 to -5 m are in good agreement with the prevailing winter waves. Furthermore, there is convergence within the adjacent area of -2 -m isobaths for the sediment transport trends during the typhoon event and in fair weather, respectively. Actual measured profiles indicate that the sandbar locates at *ca.* -1 m in summer and *ca.* 2 m in winter as the result of movement from wave action (Dai, Chen, and Du, 2008).

CONCLUSIONS

The results of this study identify net sediment transport pathways in a headland bay beach during winter and summer that included high-energy storm events in South China. On the basis of grain size trend and EOF analysis, the results show that onshore-offshore movement of sediment is a basic transport mode in the study area, with associated seasonal alongshore sediment transport. The trends of sediment transport over the subaerial beach are seaward in winter and landward in summer. Frequently, onshore-offshore sediment exchange occurs in the intertidal zone in summer and swash zone in winter. Moreover, sediment transport pathways are from SE to NW in winter, with sediment deposited in the nearshore zone. In summer, sediment transport is to the north under typhoon conditions. This study also indicates that onshore-offshore exchange of sediment in the nearshore zone can be a result of the formation and movement of the sandbar.

The studied Nanwan beach is a typical landscape around the southern China coast, and it is important to know other similar beach behavior throughout southern China. Therefore, to understand such beach morphologic evolution is significant for coastal engineering and coastal zone management.

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