

Analysis of Sedimentary Morphology and Forming Environment of Coastal Dune in Donghai Island of Zhanjiang, China

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Abstract: As an important environmental factor of the coastal zone, the coastal dune is influenced by land system, coastal dynamic system, monsoon, and human activities. By means of grain size analysis, particle size parameters, characterization of sedimentary structure, and characterization of distribution patterns, this study carried out research on sediment sampling, sediment granularity, quantitative characterization of sediment bedding, and sedimentary dynamic environment analysis of the coastal dunes in Donghai Island of Zhanjiang, China. The results show that there are differences in the grain composition of sediments in different parts of the coastal dunes in East Island (interdune, windward slope, dune top, and leeward slope). Cross-bedding and wavy bedding are common in the coastal dune section, the inner layers of the bedding intersect at low angles. The orientation of dune distribution is relatively consistent, with a NW - SE direction, and the orientation is between 280° and 295°. The coastal dune sediments in the study area mainly come from Longhaitian Beach, which are transported to different parts under the influence of coastal wind dynamics, and are gradually deposited under the influence of terrain, vegetation, and other factors to form the basic form of coastal dunes. The analysis of its sedimentary characteristics is helpful in revealing sediment morphology and formation environment, which is of great significance for exploring the evolution history of the coastal environment.

Keywords: Coastal Dune, Sediment Grain Size, Sedimentary Morphology, Forming Environment

1. Introduction

As an important environmental factor of the coastal zone, the coastal dune is influenced by land system, coastal dynamic system, monsoon, and human activities. The analysis of its sedimentary characteristics is helpful in revealing its sediment morphology and formation environment, which is of great significance for exploring the evolution history of the coastal environment [1-3]. Modern coastal dunes in China are widely distributed, ranging from temperate subhumid areas in the north to subtropical and tropical humid areas in the south [4]. The Leizhou Peninsula is one of the main distribution areas of coastal dunes in China, and the Donghai Island is located on the east side of the

Leizhou Peninsula. The coastal dunes in Donghai Island are affected by land, seashore, monsoon system, and human activities. There is a lack of systematic studies on the genesis, distribution, morphology, development, and evolution of coastal dunes [5, 6], and systematic assessment of the basic morphology and sedimentary environment of coastal dunes is the basis for strengthening the protection of the coastal ecological environment and the utilization of coastal resources. It can be seen that an effective and comprehensive assessment of coastal dune sediment morphology and sedimentary environment has certain economic and social significance.

The Donghai Island of Zhanjiang is located on the east side of the Leizhou Peninsula, and the coastal dunes are

well-preserved and distributed in continuous areas. At present, there is little research on Zhanjiang coastal sand dunes. For example, Feng carried out relevant studies on the morphology, sediment, and spatial distribution characteristics of scrub dunes on the east coast of the Leizhou Peninsula, focusing on the mechanism of interaction between the *Spinifex littoreus*, the *Sesuvium portulacastrum* and the spatial distribution of dunes [7]. Bai et al. analyzed the distribution range and basic characteristics of the Holocene coastal dunes in Guangdong province through remote sensing image analysis, field investigation, and laboratory experiment discrimination, and found that the dunes in Donghai Island were greatly affected by water area (fish pond), vegetation, agricultural land, and construction land [8]. This study can be used as a good supplement to regional-related research.

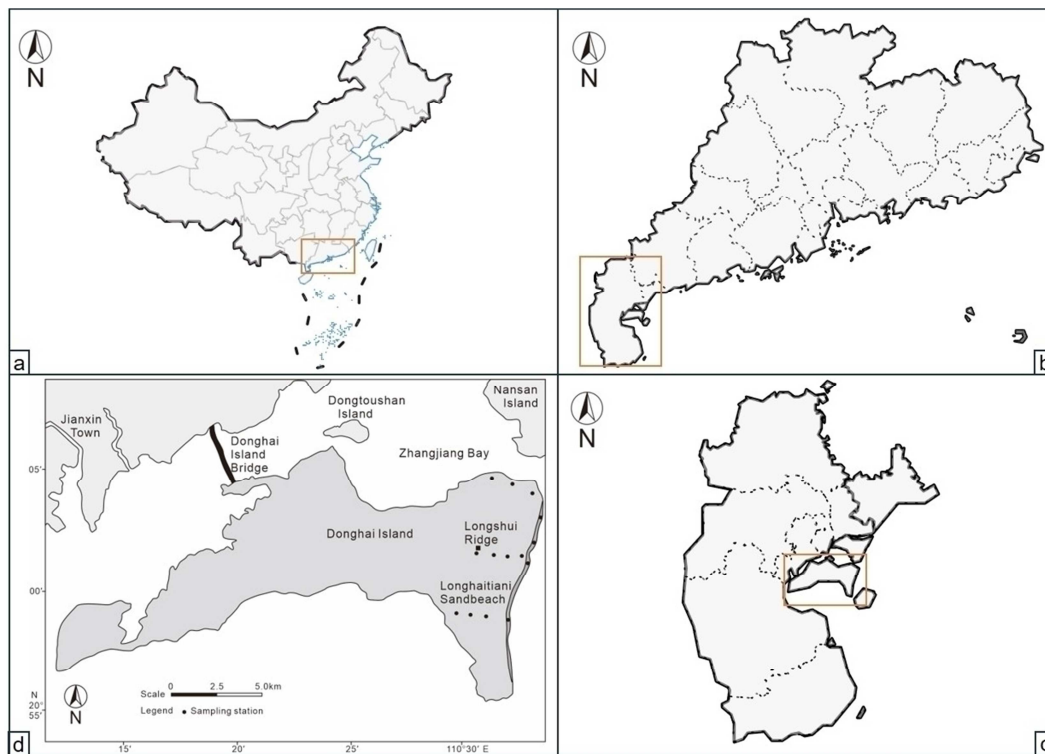
By means of field sampling, analysis and testing, and field quantitative description, this paper carries out research on the sediment particle size analysis, quantitative characterization of sediment bedding, and sedimentary dynamic environment of the coastal dunes in Donghai Island of Zhanjiang, aiming at systematically, accurately, and quantitatively analyzing the morphology and sedimentary environment of the coastal dunes. It provides a scientific basis for environmental protection and reasonable development of coastal zones.

2. Geological Background

The study area is located in the Leizhou Peninsula, southwest of Guangdong Province, China. The Leizhou

Peninsula is one of the three major peninsulas in China. It borders the South China Sea to the east, the Beibu Bay to the west, the Qiongzhou Strait to the south, and the Hainan Island to the south. There are many islands on the east coast of the Leizhou Peninsula. The east coast is a sandy-silty coast. The coastal sand dunes are distributed in a large area in the coastal area, and the beach is backed by a tall coastal sand embankment, a lot of sandy vegetation grows between the beach and the coast.

The Donghai Island is located in the east of the Leizhou Peninsula, with Leizhou Bay and Zhanjiang Bay on both sides (Figure 1). It covers an area of 289.45 km² and is the largest island in Guangdong Province. The main body of the island is the Beihai Formation and Zhanjiang Formation strata. The surface is flat, and the elevation is about 15-60m, low in the west and high in the east. The Longshui Ridge in the east is a volcanic cone, with an elevation of 111m, and is the commanding height of the island and erupted in the late Middle Pleistocene. The eastern coastline of the island is flat and straight, with a large sand embankment 18-30m above sea level and about 2 km wide [7]. The coastal aeolian sand has a wide area and various types of dune landforms are developed, among which the climbing dune is the most typical. On the eastern slope of the Longshui Ridge volcanic cone, aeolian sand is blown along the slope and climbs up to 80m above sea level. Most of the island's wind-blown sand has been fixed by *Casuarina*. The tidal flats on the south and west coasts of the island are widespread and the siltation is strong.



(a), (b), (c) Location of Donghai Island; (d) Sampling station in Donghai Island

Figure 1. Location of study area.

3. Data and Methods

Based on the collected data of the coastal dunes of the Leizhou Peninsula and the pre-survey photo data, with the help of satellite images and positioning, it is determined that this study will carry out systematic observation and sampling of sediment in the coastal dune area of Donghai Island. The sampling area is located from Longshui Ridge to Longhaitian Beach on Donghai Island, and the dune profile morphology is mainly described in the eastern part of Longshui Ridge.

The sediment grain size sampling is along the backshore beach, coastal dune beach, coastal dune beach ridge, and Longshui Ridge on the plane, and 90 samples are collected on the windward slope and leeward slope of the dune respectively. Sand dune surface with an area of about 15*15cm is selected at the sampling point, sand samples with a depth of 1-5cm are collected evenly with a small shovel, and impurities such as plant roots are removed at the same time. Each sand dune sample weighs about 500g, each sample is numbered during sampling, and the orientation, type, color, humidity, and vegetation coverage of the sample site are recorded in detail. In the process of sample particle size analysis, the sample was first pre-treated, and then the laser particle size analyzer method was used. The particle size classification method was based on the

Udden-Wentworth particle size classification standard (Table 1), and the particle diameter was calculated according to the Krumbein formula: $\phi = -\log_2 d$, d is the particle diameter, and unit is millimeter [7]. The commonly used grading standards of particle size parameters are based on the classification standards of Folk *et al.* (1957) (Table 2) [9]. The calculation of Mean particle size (M_z), Sorting coefficient (σ), Skew (SK), Kurtosis (K_G), and other parameters refer to the calculation formulas in the references [10].

Sediment morphology characterization is mainly based on the observation and description of sediment morphology from sediment bedding, dune length, dune width, dune windward slope, dune long and short axis orientation, etc., and then analysis of dune formation environment.

Table 1. Udden-Wentworth particle size classification standard [7].

Name	Particle diameter (mm)	ϕ
Very coarse sand	1~2	0~1
Coarse sand	0.5~1	1~0
Medium sand	0.25~0.5	2~1
Fine sand	0.125~0.25	3~2
Very fine sand	0.0625~0.125	4~3
Silty sand	0.0039~0.0625	8~4
Clay	<0.0039	>8

Table 2. Folk particle size parameters standards [7].

Sorting		Skew		Kurtosis	
Sorting Degree	Range	Skew	Range	Kurtosis	Range
Excellent	<0.35	Extremely negative skewness	-1.0~-0.3	Very wide	<0.67
Very good	0.35~0.50	Negative skewness	-0.3~-0.1	Wide	0.67~0.90
Good	0.50~0.71	Near symmetrical	-0.1~0.1	Moderate	0.90~1.11
Moderate	0.71~1.00	Positive skewness	0.1~0.3	Narrow	1.11~1.50
Poor	1.00~2.00	Extremely positive skewness	0.3~1.0	Very narrow	1.50~3.00
Very poor	2.00~4.00			Extremely narrow	>3.00
Worst	>4.00				

4. Results

4.1. Grain Size Analysis of Coastal Dunes

Particle size characteristics are affected by factors such as sedimentary environment, transport medium, and transport mode, it can be used as an important indicator to clarify the source of sediments. At the same time, because the measurement of sediment particle size is simple and fast, easy to obtain, and sensitive to the environment, the analysis of particle size characteristics has become one of the important means for the study of the sedimentary environment [11, 12].

4.1.1. Grain Size Characteristics

The grain size composition of sediment can directly reflect the main grain size composition of the dune and the relative content of different grain size groups. According to the Udden-Wentworth grain classification method, the sediment grain classification characteristics of different parts of the

coastal dunes (interdune, windward slope, dune top, and leeward slope) and different landform parts of the beach transverse section (backshore beach, coastal dune beach, and coastal dune beach ridge) of Donghai Island were analyzed. The sediment grain size parameters of different parts of coastal dunes and the same landform part of the beach transverse section are averaged.

The analysis results show that there are differences in the composition of sediment grains in different parts of the coastal dunes (interdune, windward slope, dune top, and leeward slope), but the largest proportion of sediment grain is medium sand (58.12%-60.35%), followed by fine sand (18.35%-31.76%), and the lowest proportion of sediment grain is silt (0%). Other granular components such as coarse sand, very fine sand, and very coarse sand have very little or no content (Table 3). The grain size composition characteristics of the sediments on the windward slope and interdune are obviously different from those on the top and leeward slopes. The coarse grain composition between the windward and interdune is greater, the proportion of coarse sand and medium sand is larger, the proportion of fine sand is

smaller, the proportion of coarse grain composition between the dunes is higher, and the percentage of coarse sand is 21.1%. However, the grain composition of the sediment on the top of the dune and the leeward slope is consistent, the percentage of each grain composition is not different.

The sediment grain composition analysis result of the transverse section from the backshore beach to the dune beach, the proportion of medium sand in the sediment of the beach surface is the highest (45.15%-60.15%), followed by

coarse sand (20.36%-38.68%), fine sand is relatively low (12.21%-25.12%), and the proportion of silt is the lowest, almost 0. The proportion of very coarse sand components in the dune beach is much higher than that in other terrain parts of the beach cross-section, reaching 38.68%. The proportion of very coarse sand components in the dune beach is the highest, it is about 3.74%, and the proportion of coarse particles in the dune beach is the highest on the whole.

Table 3. Grain size composition of dune sediments on Donghai Island (N=35).

Type	Grain size composition /%					
	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Very coarse sand
Interdune	0.00	0.02	19.35	59.12	21.10	0.41
Windward slope	0.00	0.05	20.56	60.35	19.04	0.00
Dune top	0.00	0.53	31.76	58.14	9.56	0.01
Leeward slope	0.00	0.62	32.65	58.86	7.87	0.00
Backshore beach	0.00	0.02	13.82	60.15	26.01	0.00
Coastal dune beach	0.01	0.21	12.21	45.15	38.68	3.74
Coastal dune beach ridge	0.00	0.45	25.12	53.72	20.36	0.35

4.1.2. Particle Size Parameter Characteristics

Using the grading standard of grain size parameters of Folk et al. (1957), the grain size parameters of different samples of coastal dunes on the Donghai Island of Leizhou Peninsula were analyzed. For example, Mean particle size (M_z), Sorting coefficient (σ), Skew (SK), and Kurtosis (K_G) [13-15]. According to the content percentage of each grain grade, the sediment particle size parameter data were calculated (Table 4).

The analysis results show that the average particle size in different places ranges from 1.23 ϕ to 1.78 ϕ . In the dune area, the average particle size on the windward slope and interdunes are small (1.52 ϕ and 1.42 ϕ , respectively), while the average particle size on the leeward slope and dune top is large (1.78 ϕ and 1.72 ϕ , respectively). The sediment grain size between the windward slope and the interdune is coarser than that between the leeward slope and the dune top. The mean particle size at each position of the beach is smaller than that of the dune, and the sediment particle size is coarser. The sorting coefficient is an important index to measure the

dispersion degree of sediment particle size. Generally, the smaller the sorting coefficient of sediment particle size is, the more concentrated the particle size distribution is, otherwise, the more dispersed it is. There is little difference in the sorting coefficient of each part, and it belongs to the range of good sorting, but the beach part is slightly larger than the dune part, and the sorting of the dune is better. Skew is an important index to measure the symmetry degree of sediment grain size distribution. The more the value tends to 0, the higher the degree of symmetry will be. If the value is regular, it is positive skewness, and if the value is negative, it is negative skewness. The value of skew in the study area basically tends to 0, the overall distribution is symmetric or nearly symmetric, and all are positive skewness. Kurtosis is a measure of the sharpness of the grain size frequency curve of sediments. The larger the value, the narrower the kurtosis will be, while the other way around, the wider the kurtosis will be. In the study area, the kurtosis value is between 0.93-0.94 (Table 4). The kurtosis of each part of the sediment is the same, belonging to the moderate kurtosis.

Table 4. Grain size composition of coastal dune sediments on Donghai Island (N=35).

Type	Particle size parameter			
	Mean particle size / M_z	Sorting coefficient / σ	Skew / SK	Kurtosis / K_G
Interdune	1.42	0.52	0.01	0.93
Windward slope	1.52	0.53	0.01	0.93
Dune top	1.72	0.53	0.02	0.93
Leeward slope	1.78	0.54	0.01	0.93
Backshore beach	1.35	0.55	0.02	0.94
Coastal dune beach	1.23	0.56	0.02	0.94
Coastal dune beach ridge	1.32	0.58	0.04	0.94

4.2. Characterization of Coastal Dunes Morphology

The morphology of coastal dunes reflects the external conditions when dune sediments were deposited. The morphology of dune sediments is characterized. The length,

width, and height parameters of their bedding structures are described in detail [16-18]. In this study, the types of bedding structures and the parameters of length, width, height, and distribution orientation of dunes were measured and statistically analyzed, and the sedimentary morphology and formation environment of dunes were analyzed.

The observation and statistical results show that cross-bedding and wavy bedding occur in the coastal dune section in the study area, and the inner layers of the bedding intersect at low angles. The statistical analysis results of dune morphology parameters show that the maximum value of the dune long axis is 13.5 m, the minimum value is 1.15 m, the average value is 5.22 m, and the standard deviation is 2.11. The maximum value of the dune short axis is 6.4 m, the minimum value is 0.54 m, the average value is 2.13 m, and the standard deviation is 1.32. The height is between 0.15 m and 1.32 m, and the size of the dune varies. The distribution

area is affected by local vegetation to some extent. The windward slope length of the dune ranges from 0.35 m to 4.2m, with an average of 1.32 m. The leeward slope length ranges from 0.8 m to 9.3 m, with an average of 3.23 m. The leeward slope length is slightly longer than the windward slope. The windward slope degree ranges from 12° to 35°, with an average of 22°, and a standard deviation of 1.21. The orientation of dune distribution is relatively consistent, with a NW - SE direction, and the orientation is between 280° and 295°.

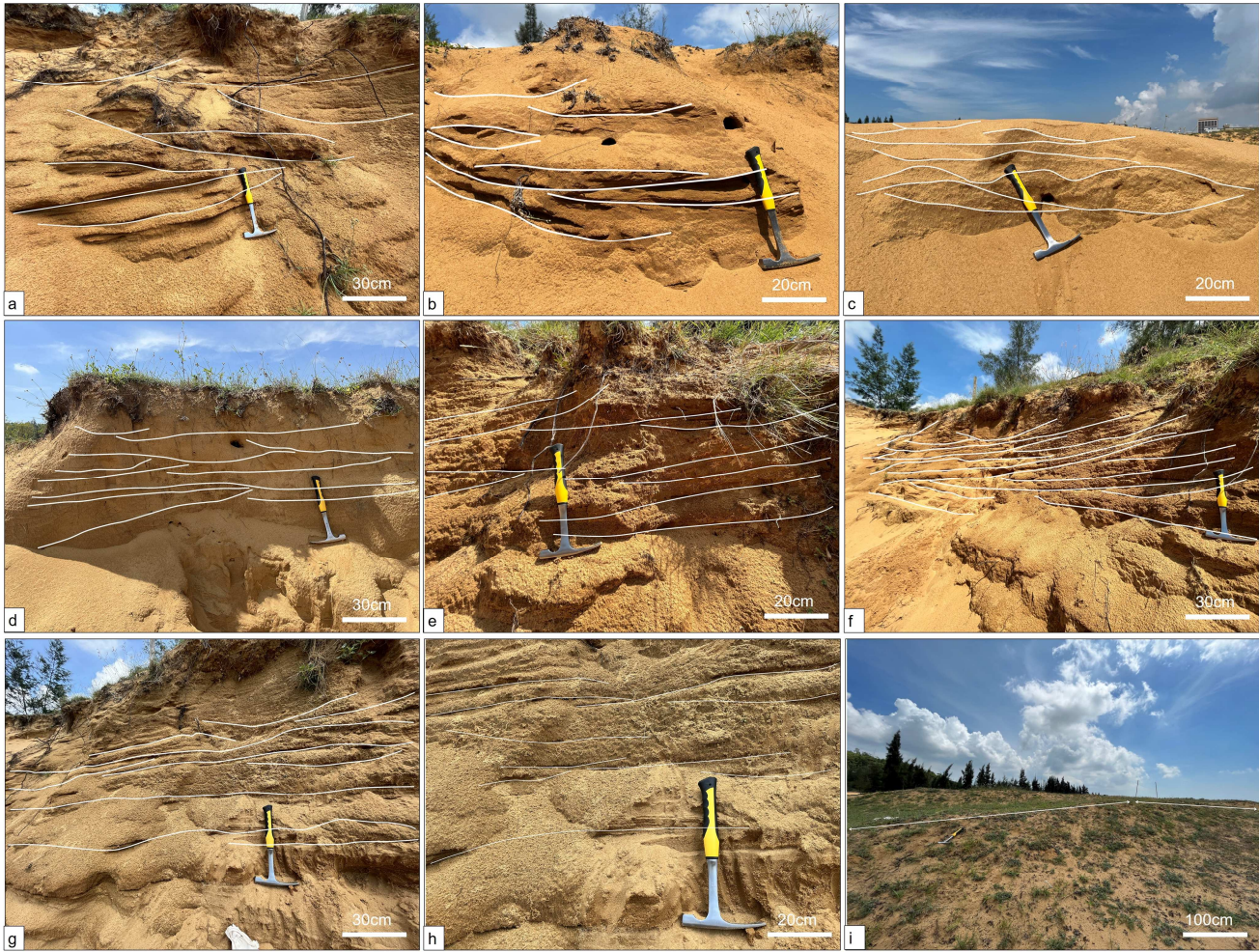


Figure 2. Coastal dune bedding on Donghai Island.

a: cross-bedding, left of the road in Longshui Ridge; b: cross-bedding, right of the road in Longshui Ridge; c: cross-bedding and wavy bedding, left of the road in Longshui Ridge; d: cross-bedding, east side of the village in Longshui Ridge; e: cross-bedding and wavy bedding, east side of the village in Longshui Ridge; f: cross-bedding and wavy bedding, north side of the village in Longshui Ridge; g: cross-bedding and wavy bedding, west side of the village in Longshui Ridge; h: cross-bedding and wavy bedding, west side of the village in Longshui Ridge; i: coastal dune, east of the road in Longshui Ridge.

Table 5. Statistical analysis of dune morphology parameters in Donghai Island (N=20).

Parameters	Long axis /m	Short axis /m	Height /m	Windward slope /m	Leeward slope /m	Slope degree /°	Orientation
Maximum value	13.5	6.40	1.32	4.2	9.3	35	NW 295°
Minimum value	1.15	0.54	0.15	0.35	0.80	12	NW 280°
Average value	5.22	2.13	0.52	1.32	3.23	22	NW 287°
Standard deviation	2.11	1.32	0.18	0.92	1.44	1.21	/

5. Discussion

Many previous studies have shown that the grain size composition of sediments in different parts of the coastal dunes is different, and the average grain size of the windward slope of the dunes is larger than that of the leeward slope [7]. In this study, the grain size change characteristics of sediments in four different parts of the longitudinal section of coastal dunes (interdune, windward slope, dune top, and leeward slope) are basically the same. The sediment in the interdune is the coarsest, followed by the windward slope, and then the dune top, leeward slope is the smallest. The grain size characteristics of sediments show changes from coarsest to fine, with the fine sand component gradually increasing and the coarse sand component gradually decreasing. This distribution feature is related to the formation environment of dunes, which reflects the process of dune sediments gradually thinning along the downwind direction [7-8]. When the regional wind conditions are the same, the sediments in the interdune land form aeolian sand flow under the action of wind. The coarse particles in the aeolian sand flow have the shortest transport distance and the lowest saltation height under the same wind conditions due to the high sand driving wind speed, so they are most easily blocked and accumulated, while the relatively fine particles are more likely to climb along the windward slope of the dune. The fine particles below the very fine sand are easy to be lifted up and transported far, climb to the top of the dune along the windward slope, and deposit on the leeward slope after jumping over the highest point of the dune, while the coarse particles (the medium sand, coarse sand, and very coarse sand) are more difficult to be transported.

The coastal dune is the product of the close movement of sand material under the action of wind, which is formed in the interaction process of wind and sand. Wind is the main external force for dune formation, while sediment is the material basis for dune formation. The study on the grain size of coastal sand dunes is helpful in judging the dynamic process of sand dune deposition, the formation, and development process. In general, as sediment gradually moves away from the source area, the average particle size decreases and the sorting ability becomes better [19-21]. The average particle size of the backshore beach, dune beach, and beach ridge near the seaside is larger than that of the coastal dune behind the beach. From the seaside to the inland, the average particle size of the sediment shows the characteristics of coarse to fine, and the sorting becomes better. Therefore, the material source of the sand dunes on the Donghai Island of Leizhou Peninsula should be from the nearby Longhaitian Beach. The sediment of the beach is transported inland to the back edge of the beach under the action of shore wind, and deposited under the interception of vegetation and terrain. The dune at the rear edge of the beach is the result of the short-distance transport and sorting of beach sediments under the action of wind, and the grain size changes of the sediments reflect the changes in the sedimentary dynamic environment and the law of sediment

differentiation [7, 12-13]. All the coastal dunes in the study area are located above the highest tide line, and the formation of these dunes basically occurs in the area above the limit of high tide. Besides the action of seawater, the external force in this area can only be wind. Due to long-term exposure to air, the moisture content of the sediments in the sand dunes on the beach shoulder and behind the high tide line (including the backshore beach) is low, and the dry sand particles only need a small wind speed to generate sand, resulting in the aeolian sand flow being carried away from the source area by the shore wind and transferred to the rear of the beach. The coastal sandy land above the high-water line usually has shrubs and other pioneer vegetation, which increases the surface roughness of the sandy land and reduces the wind speed at the same time, so that the wind-sand flow transferring inland will be deposited near the shrub, forming coastal dunes of different scales [20, 21]. The surface material composition of coastal sand dunes in different regions and sediments in different parts are different due to the influence of particle size and coastal dynamics in different provenance areas.

6. Conclusion

Through the analysis of coastal dunes in Donghai Island of Zhanjiang, it is considered that:

- 1) There are differences in the grain composition of sediments in different parts of the coastal dunes in East Island (interdune, windward slope, dune top, and leeward slope). The coarse grain composition is more in the windward slope and interdune, the proportion of coarse sand and medium sand is larger, and the proportion of fine sand is smaller. The grain composition of the sediment on the top of the dune and the leeward slope is more consistent, and the percentage of each grain composition is not different. The proportion of coarse sand in the sediment grain composition of the transverse section from the backshore beach to the dune beach is much higher than that of other terrain parts of the beach cross-section, and the proportion of coarse sand is the highest on the whole.
- 2) The average particle diameter value on the windward slope and between the dunes is small, while the average particle diameter value on the leeward slope and the top of the dunes is large. The average particle size at each position of the beach is smaller than that of the dune, and the sediment particle size is coarser. The sorting coefficient of each part is not different and belongs to the range of good sorting, but the value of the beach part is slightly larger than that of the dune part, and the sorting of the dune is better. The skewness values of each position in the study area tend to be 0 basically, the distribution is symmetric or nearly symmetric, and all are positive skewness. The value of kurtosis is between 0.93-0.94, and the grain size kurtosis of all sediments is the same, which belongs to the medium kurtosis.
- 3) Cross-bedding and wavy bedding are common in the

coastal dune section in the study area, and the inner layers of the bedding intersect at low angles. The statistical analysis of sand dune morphology parameters shows that the size of sand dunes is different, the distribution is contiguous, and the distribution area is affected by local vegetation to a certain extent. The orientation of dune distribution is relatively consistent, with a NW - SE direction, and the orientation is between 280° and 295°.

- 4) The coastal dune sediments in the study area mainly come from Longhaitian Beach, which are transported to different parts under the influence of coastal wind dynamics, and are gradually deposited under the influence of terrain, vegetation, and other factors to form the basic form of coastal dunes.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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