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Coastline configuration and geomorphologic development mode of arc–shaped coast in South China

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Abstract: Coastline configuration indexes of 34 typical arc-shaped coasts in South China are investigated by the method of principal component analysis, and meanwhile deposition and geomorphologic features of arc-shaped coast are also analyzed. The results show: (1) The configuration of arc-shaped coast in South China is of the characteristic of variability and complexity. (2) The wave power and the openings of the bay are the decisive factors to result in the changes of the configuration of the arc-shaped coast in South China, however, incidence direction of the wave has no effect on configuration development of the coast. (3) Commonly, geomorphologic modes of the arc-shaped coast system in South China consist of barriers, lagoons and tidal-inlets, and can be divided into four types: the openings of the bay leaning to the east, the openings of the bay leaning to the south, the openings of the bay leaning to the west and the openings of the bay leaning to the north.

Key words: coastline configuration; geomorphologic mode; arc-shaped coast; South China; principal component analysis

1 Introduction

Arc-shaped bays are quite common on exposed sediment coast in South China, where the crenulate-bay beaches occur with the presence of two consecutive headlands and a predominant wave approach oblique to the alignment of the upcoast and downcoast headlands (Yasso, 1965). Oblique persistent swell striking a shoreline transports sediment alongshore and sculptures a coast into arc-shaped beaches. The shoreline of beach appearance mainly consists of straight segment and shadow segment, and the latter is similar to the spiral line of the mathematics. Numerous theoretical studies concerning arc-shaped beach morphology have been carried out since Yasso (1965), who examined the plan forms of a number of prototype bays and reported their equivalence to the logarithmic spiral (Hsu *et al.*, 1989, 1993). It is comparatively perfect that the spiral coast theory comprises the shoreline configuration factors, the principle to judge the spiral coast and the factors to control the spiral coast has formed since the end of the 20th century. Until today, in the minds of many researchers, it is common knowledge for wave action to control the development of the coast configuration. However, they analyze little about the relationship between the dominant controlling factors and the other factors, let alone do research on the geomorphologic mode of the arc-shaped coast. Based on the coastal dynamics, sediment and geomorphologic characteristics of arc-shaped coast in South China, this paper, using the principle component analysis (PCA), analyzes the development principle of coastal configuration and geomorphologic organization. This study is meaningful to realize the protection of coastal environment and its land-ocean interaction, and is of great benefit to answer some questions on the exploitation of harbors and waterways and coastal erosion.

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2 Study area

In order to obtain information on the arc-shaped shoreline, 34 arc-shaped bays, all crenulate-shaped and respectively more than 4 km in length in South China are selected to analyze shoreline configuration and geomorphologic mode. Their localities are shown in Figure 1. Every bay develops by the control of the headland topography, and is dominated by a low to moderate energy deep-water wave regime characterized by persistent south to southeast swell. Commonly, in this region, the average tidal ranges is less than 1 m, the wave here is mild, with an average significant wave height being 1.1 m, only even tropical or sub-tropical cyclonic depressions pass by, the wave heights of more than 4 m often occur.

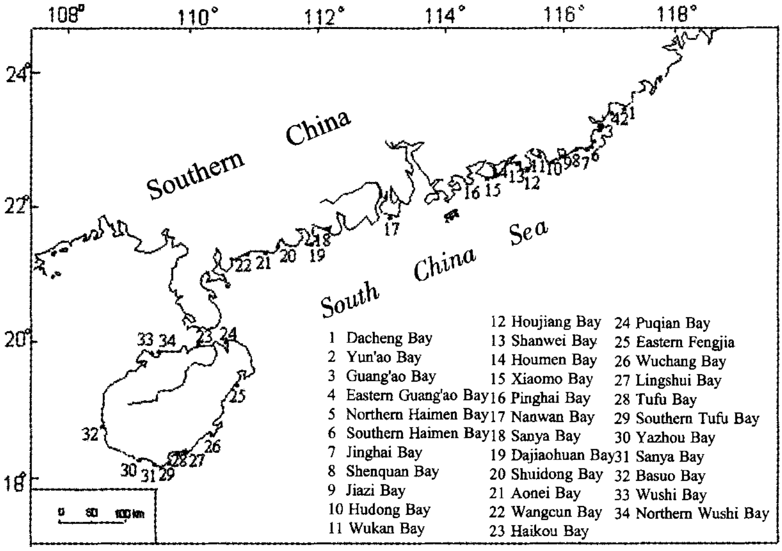

Figure 1 The sketch map of the arc-shaped bay in South China

3 Research method and data collection

3.1 Research method

Based on the intrinsic relationship between the variables, principal components analysis (PCA) can be described as a method to project a high-dimensional measurement space onto a space with significantly fewer dimensions. Usually, for industrial process data, many variables are highly correlated, because they relatively reflect fewer underlying mechanisms that drive the process. In PCA, this correlation between the variables is used to obtain principal components (PCs) that represent the underlying mechanisms. The original variables are projected onto the PCs as scores. To compare variables with different amplitudes and variability, data are normally mean centered and scaled prior to PCA analysis (Rosen and Lennox, 2001; Huang, 1984). By application of PCA to analyze natural processes, principal components are selected in order to decrease superfluous noise and the number of the variables which is a considerably large part of the total squares. The computing steps are as follows:

(1) Standardizing primitive data matrix x_{ij} ($i = 1, 2, 3, \cdots, m$; $j = 1, 2, \cdots, n$) and forming a square, covariance matrix S, where m refers to the number of the factors, and n refers to the number of the samples.

(2) Based on the characteristic equation $|R - NI| = 0$, working out all of the eigenvalues λ_1, λ_2, λ_m, for the equation, and then computing corresponding eigenvectors u_{ij}.

(3) Obtaining variance contribution rate and cumulated variance contribution and ascertaining the principal components.

(4) Obtaining principal component load of each factor from $a_{ij} = u_{ij}\sqrt{\lambda_{ij}}$ ($i = 1, 2, 3, \cdots, m$; $j = 1, 2, ..., n$) and singling out corresponding significant factors which act against the samples were also obtained.

3.2 Data collection

The configuration indexes of each arc-shaped coast include the largest indentation of the bay, a, the length of controlling line, b, and its angle, β, indentation, a/b, and wave incidence angle, α. In order to reflect the characteristics of the arc-shaped coast in South China, variably of arc-radius, R, and azimuth angle of the bay opening, γ, are also obtained (Figure 2).

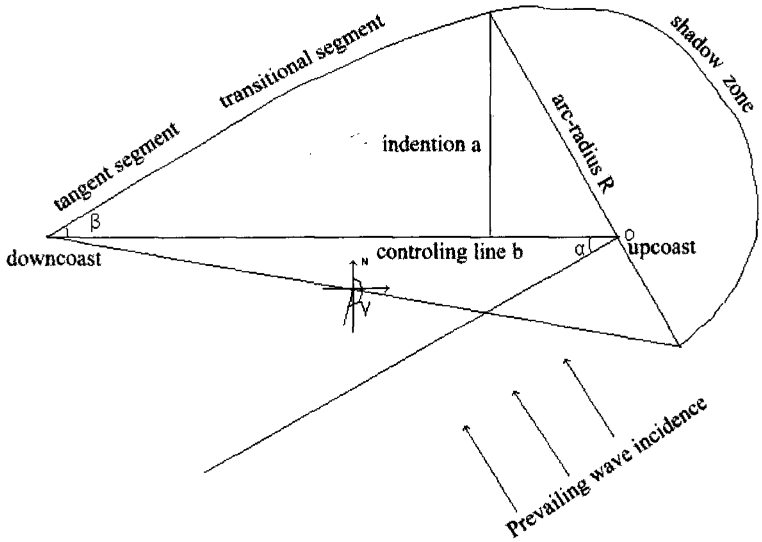

Figure 2 Plan situation of log-spiral coast

Silvester (1970, 1974) and Hsu *et al.* (1989) proposed a new approach to measure configuration indexes of the arc-shaped coast. By using this approach, the plan shape data of 34 bays are obtained from the contour charts and sea maps with a scale of 1:50000. Commonly, index a refers to the wave erosion intensity which acts against the coastline under the shade of the headlands. Coastal erosion grows seriously when index a becomes larger. Clearly, index a represents synthetically ability of the wave which sculptures a coastline. Index b refers to the control scope of the headlands and relates to the rock attributes located at the coastline. Index b increases when the affected scope of the headlands becomes smaller. Index a/b refers to the relative intensity between the wave dynamic action and the shade ability of the headlands. As concerned with spiral tangent angle β, when it becomes larger, the projected length of the upcoast headland grows longer, which makes the shade ability of the upcoast headland become stronger. Index R is the arc-radius that the length between the wave incident line perpendicularly passed the pole line and coastline, and R refers to the biggest erosion intensity of the wave action to a great degree. γ refers to the azimuth angle of the bay opening (Table 4), which is controlled by the alongshore mountain trends. Obviously, these selected 7 indexes basically describe geologic structure, rock attribute, geomorphologic appearance and nearshore dynamics, etc. So, based on these factors, this thesis discusses not only the main controlling factors of the arc-shaped coastline configuration, but also the geomorphologic mode in South China.

4 Results and discussion

4.1 Correlation analysis of the indexes

The correlation attributes of the above mentioned indexes are analyzed in Table 1, where r and n respectively refer to the correlation coefficient and the number of the arc-shaped coast in South China, and after t distribution test, the results are as follows: When n = 34, $r_{0.01}$ = 0.427 and $r_{0.05}$ = 0.339, if $r > r_{0.01}$, there is an obviously positive correlativity between the indexes, if $r > r_{0.05}$, there is a positive correlativity between the indexes (Huang, 1984). Obviously, a closely related relationship exists between a and each of b, a/b and R, which shows that indention length is determined by numerous indexes and to some degree, the relationship exists between the intension of the wave erosion and the distance of the headlands. The ability of the wave erosion and the space of the wave reflection and refraction are larger when the distance of the headlands grows, which makes the indention of the coastline become larger. A closely related relationship exists between b and each of a and R, which shows that a relationship exists not only between

Table 1 The index correlated coefficient matrix

r index	a	b	a/b	β	α	R	γ
Indention length (a)	1.0000						
Control line length of the bay opening (b)	0.8813	1.0000					
Indention ration (a/b)	0.5499	0.1284	1.0000				
Spiral tangent angle (β)	0.1832	-0.1158	0.6734	1.0000			
Wave incident angle (α)	0.0607	0.0243	0.0099	0.2335	1.0000		
Arc radius (R)	0.8600	0.7499	0.4775	0.3400	0.2499	1.0000	
Bay opening azimuth (γ)	-0.1110	-0.0396	-0.1414	-0.0920	0.0162	0.0692	1.0000

Table 2 The eigenvalues (l) and variance contribution rate of the principal component

Principal component	λ	Contributed rate of the square	Cumulated contributed rate of the square (%)
The 1st	3.0644	43.777	43.777
The 2nd	1.5346	21.923	65.700
The 3rd	1.0640	15.201	80.901
The 4th	0.9232	13.188	94.089
The 5th	0.2719	3.884	97.973
The 6th	0.1293	1.848	99.821
The 7th	0.0125	0.179	100.000

Table 3 Loads of the index factor in principal component

Index factors	a	b	a/b	β	α	R	γ
The 1st	0.5412	-0. 2120	0.0700	-0.0529	0.2089	-0.2305	0.7468
The 2nd	0.4370	-0.4921	-0.0147	0.0374	-0.1719	-0.4801	-0.5525
The 3rd	0.3839	0.4550	0.2261	-0.2695	0.6288	0.0371	-0.3537
The 4th	0.2535	0.6614	-0.0485	-0.1258	0.6105	-0.3197	0.0719

the control line and the erosion ability of the wave to some degree, but also between the control line, indention length and antecede topography. A relatively close relationship exists between the spiral tangent angle β and a/b, which shows that the relative ability of the wave erosion become strong, which makes the indention of the bay as well as the spiral tangent angle to become larger. Neither wave incident angle nor bay opening azimuth depends on the other indexes, but relates to the prevailing wave incidence and reflects the coastal configuration in response to the geography, respectively. In the author's knowledge, if a research on a coast takes no notice of it which is the notion of the geophysical space, such a research is incomplete. Accordingly, in this study, both the engineering configuration factors of the coast and the geophysical indexes are used to analyze the configuration of the arc-shaped coast in South China.

4.2 PCA result

Based on the PCA computing steps, eigenvalues of the matrix x_{ij} are obtained (Table 2). The accumulative squares of the leading four principal components make up over 94% of the total squares, which makes these four components enough to represent all the information of the primitive factors, so only the loads of the four principal components are computed according to the corresponding eigenvalues (Table 3).

(1) Since the principal components are independent from each other and the sum of the squares of the leading four principal components is over 94%, the principal components are enough to include the main information of the indexes. Thus, it suggests that the leading four principal components control the main processes of the development of different arc-shaped coastal formations (Dai *et al.*, 2002; He, 1999). Moreover, it indicates that the configuration of the arc-shaped coast is various and complex as the sum of squares of the first three principal components is only 80%.

(2) Loads of the principal components are also called as correlated coefficient in the PCA. Based on Table 3, it shows that both the indention length and bay opening r has a strong

positive correlation with the first principal component (respectively for 0.5412 and 0.7468). It also indicates that the configuration of the arc-shaped coast in South China is formed with the sculpture of the wave action, which, as a research conclusion, turns out to be similar to that of some engineers obtained through the test in the wave-tank (Hsu *et al.*, 1989; Silvester, 1974). Meanwhile, the opening azimuth of any of the 34 bays is the prior term of the configuration changes of arc-shaped coast. As the correlated coefficient matrix is concerned (Table 1), it is clear that both the wave dynamic intensity and the bay opening are the two important factors for the formation of the arc-shaped coast.

(3) There is a strong positive correlation (0.437) between the indention length and the second principal component. The control line b, the largest erosion ability of the wave action and the bay opening respectively have a negative correlation with the second principal component (being respectively -0.4921, -0.4801 and -0.5525). Obviously, the control line of the bay and the indention of the bay are related not only to the erosion intension of the wave action, but also to the geography and rock attribute of the bay. Thus these reflect represented wave dynamics and geographical environment status. Accordingly, wave dynamics and the bay opening azimuth are the important controlling action in the development of the coast formation. As a result, the rock attribute of the shoreline is the base for the evolution of the arc-shaped coast formation, which almost turns out to be the result obtained from the previous research on the arc-shaped coast in South China (Yuan, *et al.*, 1992).

(4) There are the biggest loads for coastal control line and wave incidence angle in the third and the fourth principal components, but loads were small for the other indexes, respectively. However, the sum of the squares for the third and the fourth components is less than 30%. As the correlated coefficient matrix is concerned (Table 1), this indicates that the other six indexes in the remnant principal components not only play a minor part on the development of the configuration of the arc-shaped coast, but also wave incidence.

(5) Based on geographical coastal attribute, the bay opening azimuth is added to the configuration indexes. The scores of the bay opening azimuth in the first and second principal components are higher than that of the others. Additionally, the intension of wave dynamics is almost the same as in the nearshore region of the arc-shaped coast in South China. Thus, the bay opening azimuth can be regarded as a dominant index to classify the arc-shaped coast in South China.

5 Geomorphologic characteristics and mode of the arc–shaped coast

5.1 Geomorphologic characteristics of the arc–shaped coast

Arc-shaped coast is one of the main coast types in South China. Commonly, based on the arc-shaped barrier, arc-shaped coast consists of lagoon and inlet, etc. Combining some other researchers' work with field studies carried out by the authors, the characteristics and common geomorphology of the arc-shaped coast in South China are as follows:

(1) Mostly, arc-shaped coast (possibly has lagoon, inlet or ebb deltas, etc.) is located in arc-shaped bays whose two ends, academically named rock headlands made up of mountainous, mound and mesa projected to the sea.

(2) Barrier: A barrier here consists of Holocene beach sands and aeolian deposition and sometimes remnant deposition of the Pleistocene "old red sand". Barrier is the trunk of the arc-shaped coast. The appearance of barrier is arc-shaped, and has a length about from several kilometers to several ten kilometers, and a width of several kilometers. Commonly, a barrier has ancient barriers made of "old red sand" deposition to support from the back (Zhang *et al.*, 1995). An arc-shaped barrier consists of tangent segment and arc-shaped shadow zone (Li, 1986): (a) The tangent segment near the downcoast headland is a region of wave directing incidence, and is a related accretion area. The tangent segment is erected or beveled the prevailing wave incidence. The accretion is high. The berm is big and located in the tangent all the year around.

In the tangent segment, the acclivity of the beach profile was steep, where the cross-shore transportation along beach profile prevails and has a seasonal cycle. Beach cusps occur in the region near the mean sea level. The upper part of the backshore develops into aeolian dune, parallel with the shoreline. Grain composition of the beach sand is coarse, and the sort coefficient of the beach sand is larger than that of the shadow zone. (b) Arc-shaped shadow zone is located in semi-circularity segment of the upcoast, where the refraction of the prevailing wave dominates over the region near the upcoast zone. In the shadow zone, cross-shore transportation of the sediment is weak and acclivity of the beach profile is mild. There few berms occurred. Beach sand mainly consists of fine sand and medium fine sand, and the sort coefficient of the sand is ideal. There are no coastal dunes which are developed or they exist in the shadow zone. (c) Transitional segment or the medium segment is located between the shadow zone and tangent zone, where the geomorphologic characteristics of the cells which include berm, beach cusps and alongshore sediment transportation has seasonal changes, for example, cusps develops in winter but not in summer.

(3) Lagoon: Lagoon here is a semi-closed water field resulted from the foundation of barrier. It has an area of not more than 50 km^2. Most of the lagoons have an area of less than 10 km^2, some even below 5 km^2 with a water depth of 1 m or so, for example, Jieshi and Wukan. The other characteristics of the lagoon are a tidal flat which submerged with flood and emerged with ebb.

(4) Tidal inlet: Briefly, an inlet here is a passage for lagoon to cross a barrier, and it is maintained by the to and fro motive action of the tidal dynamics. Thus an inlet is so called as "tidal inlet". An inlet is a system consisting of the inlet-gate, flood tide delta and ebb delta. Furthermore, a scouring channel developed by tidal current is located at the inlet gate, whose site is the crest of arc-shaped coast or shadow zone, for example, Shenquan and Jinghai arc-shaped coast is located at the west of the headland and the shadow zone of leaned east wave action (Wang *et al.*, 1986).

5.2 Geomorphologic mode of the arc-shaped coast

Arc-shaped coast in South China has the same characteristics as that of the normal arc-shaped coast. However, it has its particular features. Some scholars have studied the classification of the coast in South China (Yuan *et al.*, 1992; Li, 1986; Zhao, 1980) since 1980, but no special discussions on the geomorphologic development mode of the arc-shaped coast have been conducted.

Affected by the geologic structure and trends of the mountain topography, the openings of the arc-shaped bays in South China differ greatly: some bays leaning to SW or W, some to S or to E. If the bays openings are different, their dynamic environments, sediment transportation and the geomorphologic modes will also be different. Thus, seen from Table 4, the four notion modes of the geomorphologic development for arc-shaped coast in South China can be generalized as follows (Figure 3):

(1) The type of leaning to the east: In this type of geomorphologic mode, the dynamic actions of wave (SE, or E leaning to S) are the strongest modes, and the sediment supply is ample; The arc-shaped coastline mostly presents positive dynamic equilibrium state with nonexistence of forward spits. The area of the beach berm of the tangent segment is broad and high, and aeolian dunes in response to the shoreward wind in winter can be found. This type has Dacheng bay, Guangao bay, Jinghai

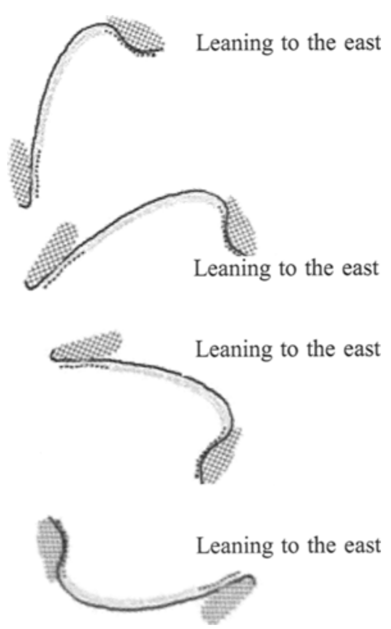

Figure 3 Geomorphologic modes of the arc-shaped coast in South China

Table 4 Geomorphologic classification of arc-shaped coast in South China

Type	Bay	Opening angle (degree)	Coastal dune	Tidal inlet	Spit
The openings of the bay leaning to the east	Dacheng	161	about 3.5 km	V	against spit
	Guangao	162	parabolic dune, 2 km	—	direct and against spit
	Northern Haimen	162	about 1 km	V	direct spit
	Jinghai	135	about 2 km	V	
	Shenquan	158	about 3 km	V	direct spit
	Hudong	165	existing alongshore	V	
	Wukan	168	existing alongshore	V	direct spit
	Houjiang	110	existing alongshore		
	Xiaomo	150	existing alongshore	V	direct and against spit
	Wangcun	155	about 5 km	—	against spit
	Fengjia	150	existing alongshore, 3 km		
	Wuchang	135	mostly existing tangent segment		
	Tufu	150	existing alongshore but bay crest segment, about 5-30 m in height		
The openings of the bay leaning to the south	Yunao	190	few existing forshore	—	direct spit
	Jiazi	190	about 6 km	V	
	Houmen	188	few accumulation		
	Nanwan	190	existing the tangent segment	—	
	Dajiaohuan	170	small scale	V	against spit
	Aonei	170	big scale, existing the tangent segment		
	Lingshui	185	existing the tangent	V	direct and against spit
The openings of the bay leaning to the south	Shanwei	215	small scale	V	against spit
	Pinghai	215	small scale	V	against spit
	Sanya	205	medium scale	V	direct and against spit
	Shuidong	195	existing the tangent segment	V	against spit
	Yazhouw	200	small scale		
	Sanya	215	existing the tangent segment, height lower than 10 m		
	Basuo	275	small scale		
	Wushi	270	small scale alongshore	V	direct and against spit Northern
	Wushi	205	small scale		
The openings of the bay leaning to the north	Eastern Guangao	60	about 3 km	—	
	South Haimen	95	about 1 km	—	
	Haikou	0	medium scale	V	direct and against spit
	Puqian	0	medium scale		
	Southern Tufu	85	existing alongshore, big scale		

* Part of the data on coastal dune from reference: Research on Aeolian sandy landform of the coast in South China (Wu et al., 1995).
* "V" means has tidal inlet, "—" means has none.

bay, etc.

(2) The type of leaning to the south: In this type of geomorphologic mode, the dynamic actions of wave (SE) are stronger than those of the next two modes, and the sediment supply is moderate. Berm and aeolian dunes developed into the tangent segment. This type has Yunao, Jiazi, Houmen, Dajiaohuan, and Nanwan.

(3) The type of leaning to the west: In this type of geomorphologic mode, the dynamic actions of wave (SE) are weaker than those of the above mentioned two modes, and the continental zone of this mode is short of sediment supply. Berm is small and aeolian dunes are undeveloped in the tangent segment. This type has Shanwei, Pinghai, Sanya, Shuidong, etc.

(4) The type of leaning to the north: In this type of geomorphologic mode, the dynamic actions of wave (N) are the strongest among the four modes, where dunes exist in the alongshore area. This type has Haikou bay, Puqian bay, etc.

6 Conclusions

Based on the deposition and geomorphologic features of arc-shaped coast in South China, coastline configuration indexes of 34 arc-shaped coasts in South China were investigated with the method of principal component analysis. The results show:

(1) Configuration of arc-shaped coast in South China is of the characteristic of variability and complexity.

(2) The decisive factors controlling the configuration of the arc-shaped coast in South China are the openings of bays and wave power, however, the incidence direction for waves has no effect on configuration development of the coast.

(3) Geomorphologic modes of the arc-shaped coast system in South China consist of barrier, lagoon and tidal-inlet, which are classified into four types as follows: the openings of the bay leaning to the east, the openings of the bay leaning to the south, the openings of the bay leaning to the west and the openings of the bay leaning to the north.

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