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# Comparative Analysis of the Erosion Mechanism of Different Profiles in the Arcuate Foreshore under Typhoon Action

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ABSTRACT

The comparison results of three beach profile data repeatedly measured before and after the typhoon in Shuidong Bay, west Guangdong province which show that there are significant differences in beach profile erosion and response process. And the changes of beach profile can be divided into: strong downward overall low shoreline regressive type and overall slight erosion shoreline regressive type. Application of the modified mild-slope equation along three beach profile are simulated wave high reflection to the sea side, to the section vertical shore pressure gradient and including water roll force and radiation stress, the vertical shore forces one dimensional profile along the momentum conservation equation (radiation stress and water roll force) bottom friction and lateral mixing reaction between numerical solution, the momentum conservation equations of the wave increases the water flow velocity and section along the profile distribution of wave height and related forces. The analysis shows that the extent and difference of coastal erosion depend on the shoreline erosion mode stimulated by the maximum surge water of the coastal current and the maximum velocity of the coastal current and the dynamic state of the profile topography under the action of the profile location, morphology and incident wave elements.

## 1. Introduction

The erosion mechanism of sandy coast is an important research content of the land-sea interaction of coastal zone and regulation of blue bay under the changing environment. It is well known that high winds, high waves and storm surges caused by tropical cyclones are the main disastrous events which lead to coastal erosion in southern China. Since the beginning of the 21st century, the trend of

global warming has become more and more obvious. The intensity and frequency of storm surges superimposed under the background of global sea surface rise are likely to increase, which will further intensify coastal erosion.

Among them, coastal wave increase water and coastal current are one of the priority scientific problems to be explored in the study of dynamic process of profile topography. During recent years, domestic scholars have

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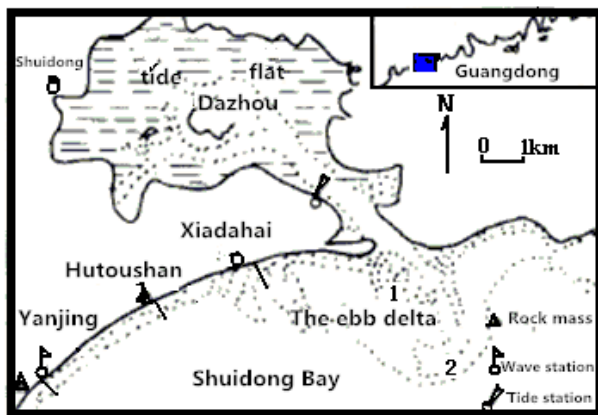
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used mathematical models and physical models to study coastal current distribution, wave increase and decrease and wave height along the profile under the condition of uniform bank slope topography<sup>[1,2]</sup>. The profile distribution of main driving force has been simulated abroad by combining actual near-shore bar profiles<sup>[3,4]</sup>. The morphodynamic coastal profile models are easy to operate, which has been used as a standard tool in coastal management to predict the change of nearshore topography<sup>[3]</sup>. Based on the measured beach profile topography, wave and tidal level data before and after the 1986 Typhoon No.16 in Shuidong Bay, western Guangdong, this paper analyzes dynamic distribution characteristics of the profile topography, discussing profile topography erosion mechanism in combination with Beach States<sup>[5]</sup>.

## 2. Basic Characteristics of Shuidong Bay Environment

### 2.1 Basic Hydrometeorological Characteristics of the Bay

The research area is located in Shuidong Bay, Maoming city, Guangdong province. From April in 1986 to December in 1987, a coastal hydrometeorological observation station was set up in the Yanjing section on the west side of Shuidong Bay in accordance with the coastal hydrological observation specifications. A coastal wave meter was used to observe daily nearshore waves, measuring wind speed and direction of the coast. And a tide measuring station was set up in the tidal channel of Shuidong Bay to observe the tide level (Figure 1).



**Figure 1.** Shuidong Bay, observation section and station location

According to statistical analysis, the usual wind direction in Shuidong Bay is E (frequency 16%) and ESE (26%). The strong wind direction is mostly southwest wind in summer, such as SSW, SE, ESE and E. The tides in the sea area belong to the irregular semi-daily tide

type with an average tidal range of 1.75m and an average spring tide range of 2.6m. The wave types are mainly wind waves with an average annual wave height of 0.68m and an average period of 4.1s. The normal wave direction is SE and SSE direction. From May to September, the frequency of S, SSW and SW was relatively high and annual frequency of SE to SW reached 82.4%.

### 2.2 Sedimentary Geomorphologic Units, Sediment Distribution and Bay Beach Topography

Shuidong Bay sedimentary topography units include: lagoon, tidal channel, deep trough, tidal flat, flood tide delta, ebb tide delta, Shoreface slope, especially the ebb tide delta is quite developed. Due to the control of Liantouling cape in the east and Yanjingling cape in the west, the shape of the shoreline outside the mouth of the tidal inlet is curved. The foreshore is wide in the east and narrow in the west. From the east to the west, the slope of beach surface increases and particle size becomes coarser, which reflects differences of dominant waves opening along the bay coast.

There are no large rivers inflow in the sea area and nearby coast, but the bay's sediment along the east coast can be driven by dominant waves to go around the cape into the bay and deposit. The wave-induced alongshore currents play an important role in coastal transport of sediment in the ebb delta. The surface sediments in the shallow zone 10m from the shore are composed of sand and silty clayey sand.

During the observation of coastal hydrometeorological elements, a number of beach profiles were set up along coastal zone west of tidal inlet. Repeated measurements were made at unequal intervals of 3 to 15 days and sediment samples were repeated irregularly at different heights of the profile. From the west to the east, Yanjing section, Hutoushan section and Xiadahai section were selected as the representative sections of different shore sections (Figure1). The beaches of different bank sections have following basic characteristics: the Xiadahai beach located at the western edge of the ebb delta is flat with fine sand, and the main characteristic topography of this foreshore section is formed from the vicinity of Hutoushan to the beach berm of Yanjing profile with accompanying rhythmic topography of beach cusp and the quasi-periodic formation and subsidence of the low-tide zone<sup>[6]</sup>.

## 3. Research Methods

### 3.1 Incident Wave Propagation Deformation Mode

The modified mild slope equation under combined action of near-shore wave refraction and diffraction is adopted<sup>[7]</sup>:

$$|\nabla S|^2 = k^2 + \frac{1}{CC_g H} \nabla \cdot (CC_g \nabla H) \quad (1)$$

$$\nabla \cdot (H^2 CC_g \nabla S) = 0 \quad (2)$$

The equation of the irrotationality of a wave

$$\nabla \times (\nabla S) = 0 \quad (3)$$

The phase function gradient

$$\nabla S = \vec{i} |\nabla S| \cos \theta + \vec{j} |\nabla S| \sin \theta \quad (4)$$

Substitute equation (4) into Equation (3) and get

$$\frac{\partial}{\partial x} (|\nabla S| \sin \theta) - \frac{\partial}{\partial y} (|\nabla S| \cos \theta) = 0 \quad (5)$$

Above all,  $S(x, y)$  is phase function;  $C$  and  $C_g$  are wave phase velocity and wave group velocity respectively.  $k$  is wave number;  $H(x, y)$  is wave height;  $\vec{i}, \vec{j}$  are the unit vectors along the X-axis and Y-axis respectively.  $\theta$  is the Angle between wave direction and X-axis.

Equations (1), (2), (5), wave dispersion equation combined with values of boundary conditions can calculate wave height and direction distribution in the near-shore sea area.

### 3.2 Profile Morphodynamic Model

The dynamic model of beach profile topography is as follows:

The one-dimensional momentum conservation equation between pressure gradient in vertical direction and driving force  $F_x$  is

$$-gh \frac{d\bar{\eta}}{dx} + F_x = 0 \quad (6)$$

The one-dimensional momentum conservation equation between the shoreline direction driving force  $F_y$ , the bottom shear stress and the lateral mixing force is

$$F_y - c_d \langle |u|v \rangle + \frac{d}{dx} \left( \rho h \frac{d\bar{v}}{dx} \right) = 0 \quad (7)$$

Among them, vertical driving force  $F_x$  and coastal driving force  $F_y$  are respectively

$$F_x = -\rho^{-1} \frac{d(S_{xx} + R_{xx})}{dx}; \quad F_y = -\rho^{-1} \frac{d(S_{xy} + R_{xy})}{dx} \quad (8)$$

Among the above equations,  $\bar{\eta}$ : wave increasing water;  $\bar{v}$ : mean coastal current velocity over time and water depth;  $h$ : water depth;  $g$ : gravitational acceleration;  $i$ : vor-

tex viscosity coefficient;  $c_d$ : friction coefficient;  $\langle \rangle$ : time average;  $u, V$ : instantaneous velocity vector and instantaneous coastal velocity component respectively;  $S_{xx}, S_{xy}$ : radiation stress component;  $R_{xx}, R_{xy}$ : water rolling force:  $R_{xx} = 2E_R \cos^2 \theta$ ;  $R_{xy} = E_R \sin 2\theta$ ;  $E_R$ : water rolling energy per unit area;  $E_R = \rho AC / (2T)$ ;  $A$ : water rolling area.  $\bar{\rho}$ : water density;  $T$ : wave period.

According to boundary conditions and relevant parameter values on both sides of profile, the profile distribution of Morphodynamic characteristic values such as wave height, wave direction, wave setup, alongshore current velocity, vertical shore driving force and alongshore driving force can be obtained by numerical iterative solution of above ordinary differential equation.

### 3.3 Longshore Sediment Transport Rate

Bailard et al. [8] extended Bagnold [9] formula to uniformly inclined beach bottom slope under wave current action and obtained instantaneous alongshore bedload and suspended load formula as follows:

$$\vec{q}_{yb}(t) = \frac{0.5C_f \rho e_b}{(\rho_s - \rho) g \tan \gamma} \left[ |\vec{U}(t)|^2 \vec{U}(t) - \frac{\tan \beta}{\tan \gamma} |\vec{U}(t)|^3 i_\beta \right] \quad (9)$$

$$\vec{q}_{ys}(t) = 0.5C_f \rho e_s / \left\{ (\rho_s - \rho) g \omega_s \left[ |\vec{U}(t)|^3 \vec{U}(t) - \frac{e_s \tan \beta}{\omega_s} |\vec{U}(t)|^5 i_\beta \right] \right\} \quad (10)$$

In the two equations,  $\tan \beta$ : bottom slope Angle,  $\tan \gamma$ : friction Angle,  $\vec{U}(t)$ : instantaneous near bottom velocity vector,  $\omega_s$ : sediment settling velocity,  $e_b, e_s$  are effective coefficient of sediment transport for bedload and suspended load respectively.  $\rho_s, \rho$  are sediment density and water density respectively;  $C_f$ : bed drag coefficient of the longshore current  $i_\beta$ : local bottom slope.

## 4. Dynamic Mechanism of Profile Topography Erosion

### 4.1 Hydrometeorology and Wave Elements of Coastal Breaking Wave Zone in Shuidong Bay before and after Typhoon

Typhoon 8616 generated off the coast of the Philippines on August 16, 1986, turned around in the northeast part of the South China Sea for more than ten days, and landed on the coast of Xuwen on the west of Shuidong Bay at 12:00 on September 5. In the center of the typhoon, the maximum

speed of wind reaches over 38m/s and the minimum pressure in the center is 960hPa. During the passage of typhoon, sea conditions in Shuidong Bay changed dramatically. Due to the astronomical spring tide on the second day of the lunar calendar, measured coastal storm surge increased by more than 1m. The maximum wave height is 4.42m, the wave period is 6.0s and wave direction is SSE. The wave height decreased rapidly after the typhoon landfall.

The average wave elements ( $\bar{H} = 3.3\text{m}$ ,  $\bar{T} = 5.45\text{s}$ , wave direction: SSE) of Typhoon 8616 observed on September 5 were used to simulate incident wave deformation during its propagation in the coastal waters of Shuidong Bay. The results are shown in Figure 2. It can be seen from the figure that bottom friction effect of incident wave in the ebb delta outside the mouth of Shuidong Bay tidal inlet causes wave height to decrease, the broken wave distribution of the ebb delta is broad, and the wave is deflected by the “lensing effect” of stacked cape of the sand tip on both sides of channel edge<sup>[10]</sup>. From the ebb delta to the west, calculation results of sea-side boundary wave elements in the foreshore beach section are shown in Table 1.

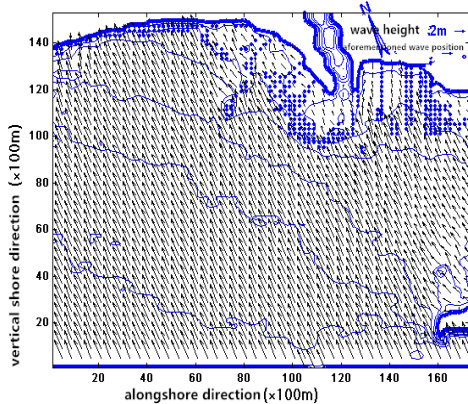


Figure 2. Propagation and deformation of storm waves on Platform 8616 in Shuidong Bay

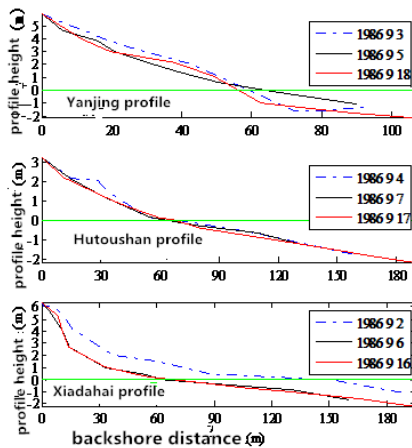


Figure 3. Beach foreshore profile changes before and after typhoon

Table 1. Wave elements of the sea side surf zone in Shuidong Bay beach profile

Profile	Yanjing profile	Hutoushan profile	Xiadahai profile
Hrms/m	1.54	0.91	2.07
$\theta / \circ$	3.90	10.63	22.07

### 4.2 Beach Profile Erosion Difference

Typhoon 8616 lead to serious coastal erosion<sup>[11]</sup>. The variation of beach profile topography repeatedly measured in half a month before and after typhoon was calculated from variation of single width and profile volume and coastline advance and retreat. The calculated results (Table 2 and Figure 3) show that this foreshore beach topography suffers from widespread erosion while there are significant differences of three beaches along profile erosion and response: The Yanjing profile, located at the westernmost point of Shuidong Bay mainly consists of erosion above 0m. The shoreline of Hutoushan profile is scoured back but absolute amount is small.

The Xiadahai profile is an area with the most serious erosion. The overall beach scour is strongly cut down with shortline receding by more than 80m.

Table 2. Changes of profile single width and volume and shoreline advance and retreat

Profile position	Changes above mean sea level(m3/m)	Changes below mean sea level(m3/m)	Total variation(m3/m)	Changes in 0m line(m)	Changes of starting and ending position for 0 m line(m)
Yanjing profile	-24.2	-4.9	-29.2	-3.0	59.4~56.4
Hutoushan profile	-10.4	-13.9	-24.2	-5.9	71.7~65.8
Xiadahai profile	-113.9	-96.9	-210.9	-81.5	151.3~69.8

According to response process or variation difference of beach profile to Typhoon 8616, it can be divided into: strongly downward overall brush with low shoreline receding type---Xiadahai profile; Overall slightly eroded shoreline regressive type--- Yanjing profile and Hutoushan profile.

### 4.3 Dynamic Distribution Characteristics and Erosion Mechanism of Beach Profile Topography

Under the effect of typhoon, data obtained from profile topography calculation of each profile are shown in Table 3, including  $\bar{\eta}_{max}$ , maximum wave water increase,  $\bar{V}_{max}$ , maximum alongshore current velocity,  $F_x^{max}$ , maximum driving force in section direction and  $F_y^{max}$ , maximum driving force in alongshore direction. The profile distri-

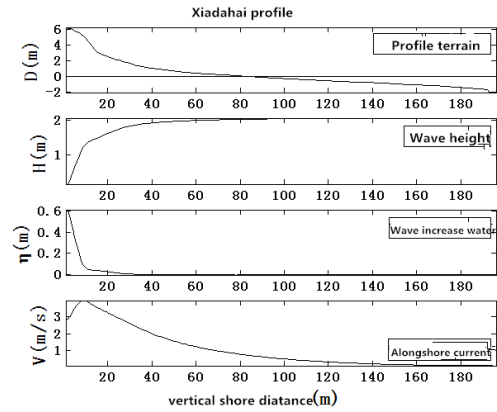
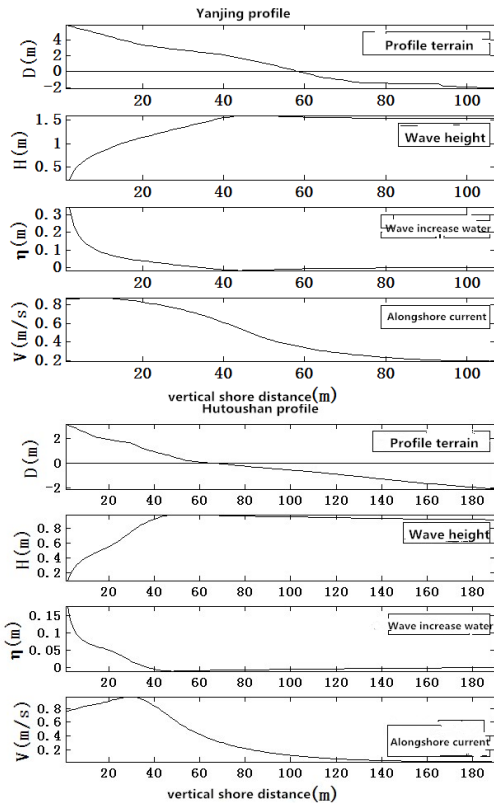
bution of each profile shape, wave height, wave setup and alongshore current velocity are shown in Figure 4.

By comparing four dynamic characteristic values of each profile, Xiadahai profile is the largest, Yanjing profile is the second and Hutoushan profile is the smallest.

According to profile distribution of wave setup, each profile shows that wave setup value increases to shore and reaches the maximum value at the shoreline. However, alongshore current velocity profile distribution is different: The alongshore current velocity in Xiadahai profile continues to increase to the shore while the alongshore current velocity distribution in Yanjing profile is completely opposite. The maximum alongshore velocity of Hutoushan profile appears in the middle. The above results show that wave setup amplitude in natural profile is mainly related to incident wave height, while influencing factors of coastal current velocity amplitude and distribution include profile form composed of incident wave height, wave direction and slope changes, which is basically consistent with analysis conclusion of Sun Tao et al. [2].

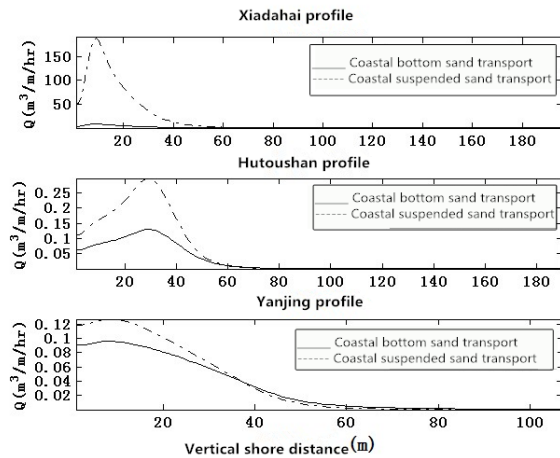
**Table 3.** Characteristic values of dynamic mode of profile terrain

Profile	$\bar{V}_{max}$ (m/s)	$\bar{\eta}_{max}$ (m)	$F_{y max}$ (m <sup>2</sup> /s <sup>2</sup> )	$F_{x max}$ (m <sup>2</sup> /s <sup>2</sup> )
Yanjing profile	0.88	0.344	0.018	0.362
Hutoushan profile	0.97	0.178	0.006	0.009
Xiadahai profile	3.94	0.613	0.073	0.09



**Figure 4.** Beach profile topography, wave height, water increase and coastal current distribution

According to Bailard’s instantaneous sediment transport rate formula, the one-hour bed load and suspended load transport in coastal direction of three profiles under the action of 1986 typhoon can be calculated. The results are shown in Table 4 and Figure 5. It can be seen that alongshore sediment transport is mainly suspended sediment transport and sediment transport intensity of Xiadahai profile is hundreds of times higher than that of the Hutoushan profile and Yanjing profile. Under the effect of typhoon, longshore sediment transport is an important mechanism leading to profile erosion.



**Figure 5.** Sediment transport results in coastal direction of three profiles during Typhoon 1986

**Table 4.** Maximum sediment transport in coastal direction under the action of wind and waves(m<sup>3</sup>/m/hr)

Profile	Maximum bedload transport	Maximum suspended load transport
Xiadahai	8.74	189.02
Hutoushan	0.13	0.30
Yanjing	0.10	0.13

It has been pointed out that beach state determines erosion mode and wave energy under abnormal wave conditions<sup>[5,12,13]</sup>. The beach berm of Yanjing profile is up to several meters high and the slope of beach surface composed of coarse sand can reach 30°. The main beach state always tends to reflexive state development. Although part of waves can be reflected back to deep water area during a typhoon, the reflection wave caused by foreshore steep beach surface and incident wave superposition to form sub-harmonic edge wave can stimulate the strong uprush wave crossing process, which results in beach berm erosion. Due to steep slope of beach surface, the shoreline retreat is small.

The backshore of Hutoushan profile is connected with the lower fore dune, where swash bars moving along the edge of ebb delta and sediment migrate westward under the action of dominant waves. When the sand body is connected to the shore, the process of uprush flow builds up a small beach berm topography. However, the wave crossing process during typhoon can completely destroy beach berm and the beach tends to dissipative state, which belongs to intermediate type of beach state with frequent changes of beach topography along the transitional coast.

The Xiadahai coastal beach is composed of fine sand with wide and flat beach surface. The back edge of beach is connected with the low weathered earth cliff. The beach is an dissipative type. During large waves, incident wave directly strikes backshore cliff and forces it to retreat. However, the vertical circulation can be formed by the superposition of storm surge and wave setup and sediment is transported to sea by backflow or rip currents. The sediment transport trend of severely eroded beach is to the west during constant wave period after typhoon. As a result, the beach in this section suffers sustained sediment deficit and the profile is difficult to recover the regular shape. Therefore, if abnormal wave conditions are encountered in the future, the shore will further erode and retreat.

The relationships between each profile change and wave setup, alongshore current velocity, wave elements and beach state show that coastal erosion difference depends on erosion mechanism which is stimulated by morphodynamic process of profile, such as amplitude of maximum wave setup and maximum velocity of alongshore current under the joint action of profile location, shape and incident wave elements.

## 5. Conclusion

Conclusions and further research assumptions can be drawn on dynamic response process of three beach pro-

files in different segments of shore along the western coast of Shuidong Bay after Typhoon 8616 action:

(1) The wave setup of beach profile is mainly related to the incident wave height. The wave height, wave direction of incident wave and profile shape determine the longshore velocity amplitude and distribution.

(2) The differences in the range of beach characteristic topography combination, profile morphology, sediment composition and shoreline trend on the dominant wave openness of the sea and other factors determine dynamic distribution of beach profile topography and erosion mode during the period of abnormal wave conditions.

(3) The dynamic characteristic value of the profile determines the range of erosion and shoreline change during typhoon, while the profile morphodynamic distribution pattern leads to differences of sediment transport direction and erosion or deposition position in the profile.

(4) In the future, it is necessary to further explore the role of transverse sediment transport in extreme wave condition on profile erosion.

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