Research Article

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The response of Chudao’s beach to typhoon “Lekima” (No. 1909)

https://doi.org/10.1515/geo-2022-0394
received October 14, 2021; accepted July 06, 2022

Abstract: The response of beaches to typhoons has always been a hot topic at home and abroad. The study of beach changes during typhoons is helpful to deepen the understanding of beach evolution and is important for the coastal ecological environment. Based on the observation results of ten profiles and the sediment samples in Chudao before and after the typhoon Lekima, this article explored the response characteristics of the beach to the typhoon. The results showed that the study area was located on the right side of the typhoon’s forward path, and the double superposition of onshore waves and storm surge resulted in erosion along the beach. In order to alleviate the energy brought by storm waves, the beach was transformed into a more dissipated state. The mean particle size of the beach sediments was coarse on the whole, with poor sorting ability, and that in the wash zone was particularly obvious. The results showed that different profiles responded to Lekima in different ways: while the profiles of N01–N05 in the southwest changed little, those of N06–N10 in the northeast changed from the type of beach shoulder to the type of sandbank as a result of morphological differences in different profiles.

Keywords: Chudao, typhoon, beach response, beach erosion, beach profile

1 Introduction

Beach-dune erosion is a major coastal hazard on the China coast that is mainly caused by natural (e.g., sea level rise and climate change) and anthropogenic (e.g., development of infrastructures) factors, and the typhoon-induced storm surge and waves can cause serious erosion and morphological changes to the beach in a short time [1,2]. The response of a beach to a typhoon depends on many factors, such as the path of the typhoon, coastal morphology, and wave and wind direction to the coast [3]. After a strong typhoon, the beach needs a long time to recover, ranging from months to years [4]. In 1–2 months after a typhoon, the beach has a rapid recovery period [5], and it will finally recover to its historical average shape after several years of adjustment [6].

Weather systems are also being significantly impacted by global climate change [7,8]. Palamakumbure et al. examined sea-level inundation during the middle Holocene high stands based on paleo sea-level indicators along the south and southwest coasts of Sri Lanka [9]. Typhoon frequency has a tendency to increase year by year [10–12]. Beaches affected by typhoons are increasingly attracting the attention of researchers. Larson and Kraus presented a storm erosion model and gave data about the experience profiles [13]. Basco analyzed 37 beaches on St. Martin Island and found that the impact of typhoons on beach erosion and restoration varied from site to site [14]. Qi et al. found that the responses of beaches to typhoon were different with different geomorphologic types [15]. Studies have shown that the more dissipative beaches respond less intensely and show moderate changes in beach profile during cyclones, while the more reflective beaches respond more intensely and show significant short-term topographic changes during cyclone conditions [16]. And some researchers also discussed the relationship between beach erosion and typhoon paths, beach profile shapes, and so on [17,18]. Meanwhile, many studies have investigated the beach profile variation of artificial coastal structures. Ratnayake et al. [19] analyzed the change in beach profile following the Colombo Harbor Expansion Project. However, there are
few studies on the response of the different areas of the same beach to typhoons. In addition, the research on the response of beaches to typhoons in China mainly focuses on the beaches in the southeast coastal areas of the country, and few focus on the beaches in Shandong province, with a coastline of 3,000 km long. Moreover, coastal erosion disasters occur frequently in Shandong Province, and extreme weather such as storm surges and giant waves has caused huge economic losses. The economic loss caused by typhoon Lekima in 2019 was up to 2.631 billion RMB in Shandong Province [20]. Therefore, the research on Chudao beach’s response to typhoon Lekima could fill the blank. This article studied the variation characteristics of different profiles under typhoons based on continuous observation before and after the typhoon at Chudao beach. Based on the observational elevation data and continuous wave dynamic data of the Chudao beach before and after the typhoon, this article studies the variation characteristics of different profiles under the action of the typhoon and focuses on the analysis of the beach profile’s response to the typhoon, and the results may provide a scientific basis for the development and conservation of Chudao Island.

2 The research area

Chudao is located in the Shandong Peninsula with geographical coordinates of 37°00′–37°03′N, 122°31′–122°34′E (Figure 1). Chudao covers an area of about 0.75 km², with a beach of 2.7 km long, and the widths of the foreshore and backshore bands are 43.2 and 33.4 m, respectively. The sediments are mainly medium sand (Figure 2). The study area belongs to the temperate monsoon climate; the main wind direction is N–NW; and the mean wind speed is 6.4–6.6 m/s. The sea area adjacent to Chudao is mainly dominated by wind waves. The main wave directions are SW and SEE.

3 Materials and methods

3.1 Overview of typhoon Lekima

The No. 9 typhoon named Lekima in 2019 was generated over the Pacific Ocean at 14:00 on 4th August, with the central coordinates of 17.4°N and 131.9°E. The maximum
wind speed in the center was 18 m/s. It strengthened to a super typhoon at 23:00 on 7th August and landed along the coast of Taizhou, Zhejiang Province, at 1:45 on 10th August. The maximum wind velocity reached 52 m/s, and it was the strongest typhoon in China in 2019; after landing, it went through Zhejiang and Jiangsu provinces and then to the Yellow Sea. It landed again in Qingdao, Shandong Province, at 20:00 on 11th August, with a wind velocity of 23 m/s. The maximum radius of the typhoon was about 330 km. Since then, Chudao has been affected until the typhoon disappeared [21].

The wave and wind data of the study area before and after the landing were obtained from the buoy launched by the Chinese Academy of Sciences at the location of 37.06°N and 122.58°E. The buoy can collect meteorological and hydrologic elements, such as wave height, wave direction, wind speed, and direction. The resolution can reach 1 cm for the wave height, and the data were recorded at a frequency of half an hour. Under normal conditions in August, the wind direction in the study area was mainly NW and W EW. During the typhoon, the wind direction in the study area was mainly S and SSE (Figure 3). The maximum wind speed in the study area reached 18.6 m/s at 16:00 on 11th August, which was three times the normal mean wind speed. During the typhoon, the main wave direction in the study area was SE (Figure 3), and the maximum wave height reached was 5.7 m (Figure 4). The nearest tidal station, Chengshantou, which is located at the coordinates of 37.3°N and 122°E observed a maximum storm surge of over 60 cm during Lekima.

3.2 Beach profile survey and sediment sampling

In order to obtain the topographic changes of the beach before and after the typhoon, the Real-Time Kinematic Global Positioning System (RTK-GPS) instrument was adopted to observe the profiles’ elevation on 10th and 13th August, respectively. The RTK-GPS measurement technology (Figure 5) is based on the provincial (Continuously Operating Reference Stations) CORS network and is completed by the cooperation of mobile station, base station, and processing software [22]. The advantage of RTK-GPS measurement is that it already has several base stations, which saves customers’ time from building their own base stations, and the signal between the base station and the mobile station is stable, which can reduce
the distance relative error caused by moving. In addition, the RTK measuring instrument based on the provincial CORS network can reduce the requirements of measurement time, conditions, and terrain, which can reduce the difficulty of the work and improve the flexibility of work. Besides, it can ensure the accuracy of the measurement, and the error of the elevation is less than 3 cm [23].

Ten fixed monitoring profiles were set up on the 2.7 km long beach of Chudao. The selection criteria for sandy coastal profiles are as follows: the starting point should be selected in places with landmark buildings such as street lamps, special steps, and landmarked buildings. And we should make some initial marks with stakes or paint. To ensure that a fixed profile is measured, a point setup is required before each measurement. Starting from the fixed piles on the shore, hand-held instruments were selected to measure the elevation at the lowest tide level. The distance between measuring points was set to about 2 m. The measurement distance is shortened to 50 cm in the scour zone [24].

The sediment on the beach surface was collected at three fixed points: the scour zone, the beach shoulder, and the dune toe, and only the N01, N06, and N10 profiles were selected to collect sediment samples. We should remove the garbage and other attachments on the beach surface when collecting samples and collect about 200 g of sediment. Dry the sand sample in the laboratory and use the electric vibration sieving instrument to sample the sieving, with the sieving range of $-2.25 \Phi$ to $4 \Phi$ ($\Phi = -\log_2 D$, $D$ is the median particle size). Folk and Ward’s [25] formula is used to calculate the median diameter ($M_d$) and sorting coefficient ($\sigma_i$).

All the survey maps of each profile were superimposed to compare and analyze the topographic change features of the beach profile (Figure 6). Meanwhile, the erosion and deposition of the beach were represented by calculating the unit-width erosion discharge [15]. The formula is as follows:

$$\text{UED} = \int_{x_0}^{x_1} (Z_a - Z_b) \, dx,$$

where UED is the erosion and deposition amount of the profile, $X$ is the horizontal coordinate, and $Z$ is the profile elevation, as is shown in Figure 7.

### 3.3 Beach state parameter

The interaction between hydrodynamics and topography leads to the change of beach morphology, which can
clearly reflect the beach change in a typhoon. The variation of beach morphology is closely related to wave and sediment particle size. Wright and Short proposed a dimensionless sedimentation rate \( \Omega \) to classify beach types as follows [26]:

\[
\Omega = \frac{H_b}{W_s T},
\]

where \( H_b \) represents the height of the breaking wave (m), \( W_s \) represents the sedimentation rate (m/s), and \( T \) represents the wave period (s).

Since it is difficult to obtain the breaking wave height in the study area during a typhoon, it can be derived indirectly from the available data such as beach slope and sediment particle size. Sunamura obtained the calculation formula for the beach slope through dimensional analysis [27]:

\[
\tan a = \frac{0.12}{(H_b/8^{0.5}D^{0.5}T)^{0.5}},
\]

where \( \tan a \) represents beach slope, \( g \) represents gravity acceleration, and \( D \) represents the median grain size of sediment.

In accordance with the sedimentation rate formula and the average grain size of the sediment in the study area stipulated in the Hydrology Survey Specification published by the Ministry of Water Resources of the People’s Republic of China [28], \( D \) was selected from 0.15 to 1.5 mm, and the empirical formula of settlement rate in the transition zone was as follows [29]:

\[
w = 6.77 \cdot \frac{\rho_s - \rho}{\rho} D + \frac{\rho_s - \rho}{1.92 \cdot \rho} \left( \frac{t}{26} - 1 \right),
\]

where \( \rho_s = 2.65 \text{ g/cm}^3 \) is the density of sand, \( \rho = 1.02 \text{ g/cm}^3 \) is the density of seawater, \( t \) is the temperature (°C), \( D \) is the median particle size (mm), and \( w \) is the sedimentation rate (cm/s). In this study, the value of \( t \) was 28°C. The above three formulas can obtain the new formula simultaneously:

\[
\Omega = \frac{0.03 \cdot \sqrt{D}}{\tan^2 a(6.77 \cdot D + 0.02 \cdot t - 0.52)}.
\]

When \( \Omega < 1 \), the beach slope is steeper and tends to be the reflected type; (2) when \( \Omega > 6 \), the beach slope is gentle and tends to be the dissipated type; and (3) when \( 1 < \Omega < 6 \), the beach type is transitional between the two types.
4 Results and discussion

4.1 Change in beach profile and sediment before and after typhoon

4.1.1 Response of the Chudao beach profile to Lekima

During the influence of Lekima, the beach of Chudao made a rapid response. The N01–N04 profiles have the same beach type (Figure 8) with an obvious beach shoulder and a wide backshore; after the typhoon, these profile types basically maintain their original condition. The backshore parts got slightly eroded, and the erosion of the beach shoulder was very small; the erosion position was mainly concentrated in the high and middle tide belt. The underwater parts had slight erosion. There was deposition on the backshore of the beach, and the unit-width erosion discharges in four profiles were $-9.3$, $-16.4$, $-9.2$, and $-10.6$ m$^3$/m from west to east, respectively.

The backshore of N05 and N06 profiles (Figure 9) developed a narrow and sharp storm beach shoulder. After typhoons, a dune was formed on the backshore of the N05 profile, and the beach shoulder retreated. There

![Figure 8: The change of N01–N04 profile topography (MHW: mean high water level; MSL: mean sea level; MLW: mean low water level; Green spot: the location for sediment samples).](image-url)
Figure 9: The topographic change of the N05 and N06 profile (MHW: mean high water level; MSL: mean sea level; MLW: mean low water level; Green spot: the location for sediment samples).

Figure 10: The change of N07–N10 profile topography (MHW: mean high water level; MSL: mean sea level).
was a slight stacked at the backshore beach of N06, and the beach shoulder was washed away to basically disappear. The foreshore and intertidal zone of the two profiles were eroded seriously, and the low tide zone formed the undulating terrain. The values of unit-width erosion discharge from west to east were $-12.9$ and $-17.7$ m$^3$/m, respectively. As can be seen from Figure 9, it started to change from the beach shoulder profile to the sandbank profile between N05 and N06, and to the west of the N05 profile, the beach profile shape was relatively stable.

Four profiles (N07–N10) on the east side of the beach (Figure 10) responded very fiercely to Lekima, and all profiles were heavily eroded, with a large number of erosive scarps developing on the beach surface, with a maximum drop of 60 cm (Figure 11). The overall downward erosion in the high tide zone was serious, and the foreshore sediment was washed away by waves, resulting in the sagging of the beach surface. The sediment moving toward the sea was accumulated into underwater sandbanks, and the profile changed into a typical sandbar profile. The values of unit-width erosion discharge for the five profiles were $-19.8$, $-17$, $-5.2$, $-7$, and $-5.7$ m$^3$/m, respectively. The erosion amount showed a gradually decreasing trend from southwest to northeast.

### 4.1.2 Response of beach sediments to Lekima

Table 1 shows the situation of beach surface sediments in the study area under normal conditions and during a typhoon’s period. As can be seen from Table 1, in a typhoon-free period, the beach sediment particle size fluctuated very little. During the typhoon, the beach sediment in the study area changed significantly, with sediment coarsening, especially in the scour zone. The median diameter of the beach changed from $2.02\Phi$ to $2.56\Phi$ before the typhoon to $0.36\Phi$ to $2.43\Phi$ after the typhoon. Before the typhoon, the sediment sorting coefficients of each profile were concentrated in the range of $0.64$–$1.08$, with the sorting coefficients mainly concentrated between good ($0.5 < \sigma_i < 0.71$) and medium ($0.71 < \sigma_i < 1.0$). After a typhoon, the sorting coefficient ranges from 0.62 to 2.09, and the sorting ability of sediments becomes worse.

The results showed that the sediment particle size in the scour zone of the three profiles became coarser, followed by the beach shoulder area and the toe area of the dune. Storm surges and high waves caused by typhoons can create strong turbulence on the beach bed, causing sediment suspension and loss. This is why the particle size becomes coarser. The variation of the sorting coefficient ($\sigma_i$) was consistent with the average particle size ($\Phi$).

During the typhoon, the strong dynamic conditions carried away the fine sediment on the surface and exposed the coarse sediment in the lower layer (Figure 12), which was an important reason for the coarsening of the grain size after the typhoon.

### 4.1.3 Response of the beach topographic dynamic state to Lekima

In extreme wave conditions, the topographic dynamic state will change with the response of the beach to the typhoon. Before and after the typhoon, the beach topographic state characteristic values of N01, N06, and N10 profiles in the study area are shown in Table 2.

After the typhoon, the $\Omega$ values of N01, N06, and N10 profiles all became larger, and the topographic state was more dissipated than before the typhoon. The variation of
value in the N01 profile was the smallest, and that in the N10 profile was the largest, which gradually increased from southwest to northeast. During the typhoon, the maximum wave height in the study area was up to 5.7 m; the marine dynamic environment in the study area was enhanced; and the beach responded quickly. The profiles of N01, N06, and N10, which originally belonged to the dissipative type, became more dissipative. The beach shoulder disappeared and the slope decreased to buffer the energy brought by big waves. The small dock on the left side of the N01 profile weakened the wave strength, and the wide beach shoulder also made it relatively less vulnerable to typhoons.

4.2 Analysis of the causes of variation in each profile before and after the typhoon

Under the action of a typhoon, all profiles of Chudao beach were eroded, with the erosion concentrating primarily on the beach shoulder and intertidal zone. The fine sand on the surface of the foreshore was carried away by large waves, resulting in a large amount of gravel being exposed under the beach surface. During the storm, the large waves caused by the typhoon directly impacted almost all profiles of the beach, resulting in serious damage to the beach.

According to the analysis of sand-beach stability factors presented by You et al. [30], profiles of N01–N05 on the southwest side of the beach have a relatively stable state due to the wide beach shoulder, the higher dune toe, and the gentle slope. Therefore, although there was erosion during the typhoon, the amount of erosion was small, and the change in profile morphology was not obvious. The profiles N06–N10 on the northeast side of the beach had no beach shoulder and the slope was steep, so the erosion was serious during the typhoon, and the profile morphology changed obviously, becoming a typical storm-type profile.

In our other studies, we used the Mike21 numerical model to calculate the hydrodynamic conditions during the typhoon in the study area. The results show that the coastal current of Chudao flowed from southwest to northeast, with a maximum value of 0.5 m/s. The tidal current can transport suspended sediment from southwest to northeast, resulting in greater erosion on the southwest side of the beach than on the northeast side, which is in good agreement with the measured results. The water level rose significantly, and the maximum water level increase was about 0.7 m. According to the calculation formula for coastal current

\[ V = (gH_b)^{1/2} \sin \alpha_b, \]

where \( \alpha_b \) is the angle between the wave crest line and the coastline line.

As the orientation of the beach changes, the incidence angle \( \alpha_b \) of the oblique wave becomes smaller, and there is also a decreasing gradient of coastal current.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Beach zone</th>
<th>Median diameter ((M_d))</th>
<th>Sorting coefficient ((\sigma_i))</th>
</tr>
</thead>
<tbody>
<tr>
<td>N01</td>
<td>Dune toe</td>
<td>2.38</td>
<td>2.39</td>
</tr>
<tr>
<td></td>
<td>Beach shoulder</td>
<td>2.36</td>
<td>2.39</td>
</tr>
<tr>
<td></td>
<td>Scour zone</td>
<td>2.51</td>
<td>2.56</td>
</tr>
<tr>
<td>N06</td>
<td>Dune toe</td>
<td>2.15</td>
<td>2.18</td>
</tr>
<tr>
<td></td>
<td>Beach shoulder</td>
<td>2.21</td>
<td>2.12</td>
</tr>
<tr>
<td></td>
<td>Scour zone</td>
<td>2.39</td>
<td>2.4</td>
</tr>
<tr>
<td>N10</td>
<td>Dune toe</td>
<td>2.01</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>Beach shoulder</td>
<td>2.1</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td>Scour zone</td>
<td>1.9</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 2: Beach profile types of Chudao Island before and after Lekima

<table>
<thead>
<tr>
<th>Profile</th>
<th>N01</th>
<th>N06</th>
<th>N10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before typhoon</td>
<td>Dissipative</td>
<td>Dissipative</td>
<td>Dissipative</td>
</tr>
<tr>
<td>Beach state</td>
<td>8.98</td>
<td>3.14</td>
<td>2.09</td>
</tr>
<tr>
<td>After typhoon</td>
<td>Dissipative</td>
<td>Dissipative</td>
<td>Dissipative</td>
</tr>
<tr>
<td>Beach state</td>
<td>9.11</td>
<td>3.95</td>
<td>4.60</td>
</tr>
</tbody>
</table>
velocity at the position where $\alpha_0$ becomes smaller. In the process of a typhoon, sands were carried by the high-speed coastal current in the surf zone and splash zone at the south of the coastal inflection point, and they were transported from southwest to northeast. However, as the speed of the coastal current slowed down at the change point in the direction of the shoreline, the fluid shear stress became smaller; therefore, the sediment with larger particle size settled at the point of the maximum curvature of the shoreline. Therefore, in the scour zone of the N10 profile, the particle size changed from 2.1$\Phi$ to 0.85$\Phi$, and the sorting coefficient changed from 1.08 (medium) to 2.09 (poor).

Based on the above research, we can conclude that different types of original profiles, such as the surface length and slope of the beach, have different responses to typhoons.

4.3 Impact of storm paths on beach scour and siltation

The beach’s response to a storm is closely related to the path of the storm. Chudao beach has a SW–NE trend, the mouth of the bay is southeast, and the wave with the SE direction has the biggest influence on the topography. For Chudao, the SE wave hits the beach frontally, resulting in great changes in scour and siltation in the profiles. The wind field of a tropical cyclone is asymmetrical. On the right side of the forward direction, the wind direction is the same as the forward direction, and the moving speed and wind speed are superimposed on each other. As a result, the wind on the right side of the forward direction of the tropical cyclone is larger, and the typhoon wave energy induced by the typhoon is higher. Chudao beach is located on the right side of the forward direction of Lekima, and its coastal sea is basically dominated by shoreward waves, which causes damage intensification, and has resulted in significant changes to the beach morphology.

This is the same as the research conclusion of Basco, that is, the beach erosion caused by typhoons is different in different locations [14]. N01–N05 in the Southwest had little change in morphology, and N06–N10 in the northeast had changed into a sandbar profile. Otvos compared the response of the same beach to two storms and found that in several locations of the beach, weaker storms even led to siltation. In our study, the foreshore in all sections showed erosion status, and some foreshore showed siltation status [31].

5 Conclusions

This article discussed the response characteristics of the beach to typhoon Lekima based on observations of Chudao before and after the landfall of Lekima.

Under the influence of typhoon Lekima, most of the beach profiles of Chudao were eroded, and the responses of different profiles to the typhoon were different. The morphology of N01–N05 on the southwest side changed little, and the morphology of N06–N10 on the northeast side changed from beach shoulder type to sandbank type. In profile N10, the incidence angle of oblique waves decreased, which led to the slow velocity of coastal current here. Sediments with larger particle sizes settled here, resulting in the maximum variation of particle size in the scour zone of profile N10.

Under the action of a typhoon, the surface sediment of Chudao beach became coarse, especially in the scour zone. The mean particle size changed from 2.02$\Phi$ to 2.56$\Phi$ before the typhoon to 0.36$\Phi$–2.43$\Phi$ after the typhoon. The sorting coefficient of sediments changed from 0.64–1.08 to 0.62–2.09. The values of dimensionless settling rate ($\Omega$) in the beach profiles all increased, indicating that the beach states changed towards a more dissipated state to buffer the high intensity of marine dynamic conditions.

Funding information: This work is supported by the National Key Research and Development Program of China (2021YFB2601100) and the National Natural Science Foundation of China (Grant No. U1806227, U1906231, 51909114).


Conflict of interest: Authors state no conflict of interest in this paper.

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