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Analysis of the Factors Influencing the Changes in Beach Landforms of Weizhou Island and Environmental Protection

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Abstract

The beach is one of the main tourist resources of Weizhou Island. The quality of the beach landforms and coastal environment greatly influences the comfort and overall experience of tourists. This is primarily affected by both human and natural factors. Based on multiple field surveys conducted on Weizhou Island and previous research materials, this paper focuses on studying the changes in the Shiluokou-Dishuicun beach landforms of Weizhou Island and their impact on the ecological environment. The following four conclusions are drawn: 1) The degradation of coral reefs leads to coastal retreat; 2) Storm surges result in the destruction of coastal vegetation; 3) Headlands cause a large accumulation of coastal sediments; 4) Circulation is the main limiting factor for beach migration and expansion. Finally, based on the research conclusions, along with a superficial investigation and review of related materials on the coastal engineering at Yalong Bay, Hainan, specific suggestions for the protection of Weizhou Island's beach ecological environment are proposed.

Keywords: beach landforms, storm surge, cape, environmental protection, Weizhou island

1. Introduction

Weizhou Island is located in the central part of the Beibu Gulf Basin, north of Beihai City in Guangxi, facing the Leizhou Peninsula to the east and Hainan Island across the sea to the south. It is approximately 37 km from Beihai City (Figure 1, left). Weizhou Island is home to the northernmost coral reef group in China and is the largest island in Guangxi. Known as the "Penglai Island," it is a national 5A-level tourist destination, featuring a national volcanic geological park and the only island volcanic geological museum in China (Cen, 2003). Additionally, it has been established as a national marine park. Weizhou Island stretches 6.5 kilometers from north to south and 6 kilometers from east to west, with a land area of 26.88 square kilometers (including 1.9 square kilometers of Xieyang Island) and an intertidal zone of approximately 3.47 square kilometers (Cen, 2003). The average annual temperature of Weizhou Island is 23°C, with no frost throughout the year. The average annual precipitation is 1,297 mm, with distinct dry and wet seasons. The rainy season occurs from June to September, and the island experiences a South Asian tropical monsoon climate (Kuang et al., 2007), making it frequently affected by storm surges (Li et al., 2015).

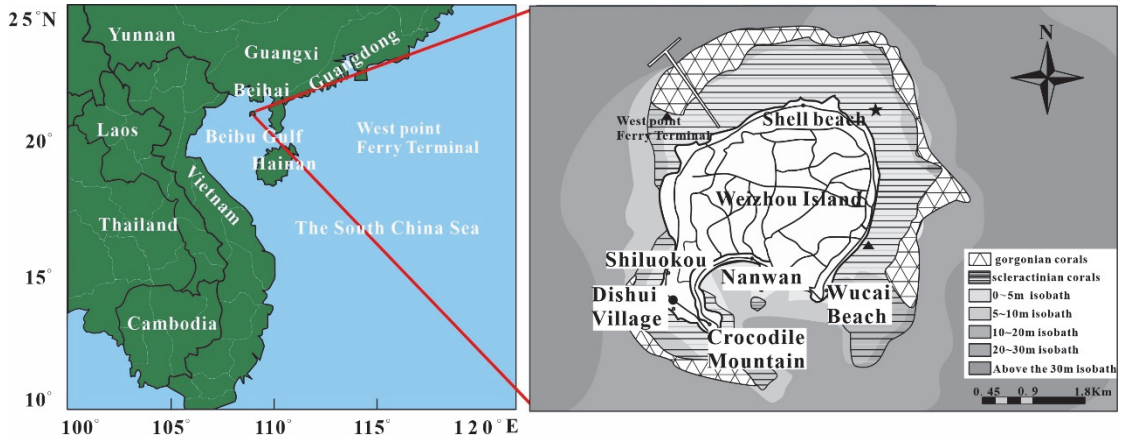

Figure 1. Location and Coral Reef Distribution of Weizhou Island (He et al., 2019)

(a) Star: Coral coverage greater than 20%;(b) Triangle: Coral coverage between 15% and 20%;(c) Circle: Coral coverage between 10% and 15%.

Previous studies have thoroughly explored various aspects of the coastal erosion and sedimentation conditions of Weizhou Island (Chao, 2018), coastal erosion characteristics(Yao et al., 2013), distribution of hazardous rocks on sea cliffs(Zhong, 2013; Li et al., 2013), the current status of marine water quality(Liang, 2018; Tan et al., 2021), heavy metal pollution in seawater (Yang et al., 2017), and coral distribution(He et al., 2019; Huang et al., 2009). The author has also conducted research on the ecological environment of Weizhou Island (Chen et al., 2024), preliminarily analyzing the impact of storm surges on coastal erosion. The study particularly emphasizes the destruction of volcanic geological landscapes and coastal landforms caused by early human quarrying activities, as well as the impact of tourism on water pollution in the sea areas of Weizhou Island. The paper also mentions that coral reefs have protective functions for beaches and coasts and offers some preliminary protection suggestions.

Coastal and beach environments are influenced by a variety of factors, typically categorized into natural and human-induced factors, often intertwined and exacerbating each other. This paper focuses more on natural factors and conducts an in-depth study of the geomorphological changes of the Dishui Village–Shiluokou Beach on Weizhou Island, analyzing the influencing factors on the coastal ecological environment. Lastly, specific and actionable suggestions for beach ecological environment protection are provided for reference.

2. Coral Reef Degradation Leading to Coastal Retreat

Coral reefs are excellent natural barriers for coastlines, possessing the remarkable ability to dissipate wave energy, reduce coastal erosion, and effectively protect subtropical coastal landforms. In addition, the formation of calcareous beach sediments is closely related to coral reef ecosystems (Chen et al., 2024). Reef-building corals rely on biological calcification to form calcareous skeletons, and the life activities of these corals, along with symbiotic algae, promote the formation of calcium carbonate (Kangwe, 2006; Barott et al., 2014; Roth, 2014; Putnam et al., 2017). The carbonate budget is critical for the growth and restoration of coral reefs (Harney et al., 2003; Kench, 1998; Perry et al., 2011; East et al., 2023). If the rate of carbonate production exceeds the dissolution rate, the coral reefs can continue to grow; otherwise, they may degrade. Studies show that beaches protected by coral reefs lose only 3% of their volume even under the erosion of waves (Bitterwolf et al., 2024).

A large number of coral reefs have developed in the shallow waters around Weizhou Island (He et al., 2019; Huang et al., 2009) (see Figure 1, right). Bleached coral skeletons are more easily broken down by waves, tidal currents, and storm surges, transported to the shore, and become the primary source of sand on the beaches of Weizhou Island. In addition, calcareous coralline algae, calcareous foraminifera, and mollusks such as shells and snails are also important sources of calcareous sediment (Yu et al., 2004). These skeletal remains of marine organisms, after mechanical fracturing and abrasion, form calcareous beach sand with varying degrees of roundness and sorting. Coral reefs can absorb wave energy, effectively protecting the coast from erosion and playing a crucial role in coastal protection.

Coral reefs around Weizhou Island began to develop in the Holocene (Xia, 2000), but have been repeatedly damaged by extreme weather and human activities, leading to a decline in coral growth, particularly in the

southwest, where coral reef degradation is most pronounced(Chen, 1999; Liang, 2002; Yan, 2011; Zhou et al., 2014; Ye et al., 1988; Wang et al., 1991; Wang et al., 2009; Liang et al., 2010). According to survey data (Table 1), whether in the more complete data from the southwest, southeast, and north, or in terms of average values, the overall coral reef coverage area on Weizhou Island shows a significant decline. Specifically, the coral reef coverage in the southwest has decreased from 80% in 1991 to 8.45% in 2010. Local residents report that the coastline near Dishui Village has retreated by several dozen meters. According to statistics from 2006 to 2013(Yao et al., 2013), the average annual erosion in the southwest coast section reached 0.18 m. In September 2024, Typhoon "Capricorn" caused some trees along the beach to be eroded by storm surges, exposing their roots to a depth of 0.6 m (as discussed in the next section).

Table 1. Changes in Coral Coverage of Active Reef-Building Corals in Different Regions of Weizhou Island (%)

Year	Northern	Northeastern	Eastern	Southeastern	Southwestern	Northwestern	Average	Source
1991	-	-	-	60.00	80.00	-	69.28	(Wang, 1991)
2005	63.70	-	-	-	35.30	-	47.42	(Huang, 2009)
2009	30.00	-	15.00	-	55.00	-	29.14	(Wang, 2009)
2010	12.10	24.58	-	17.58	8.45	25.30	16.21	(Liang, 2010)

In addition, the coral reef coverage in the northern area has decreased from 63.7% in 2005 to 12.10%, which is also one of the reasons for the significant changes in coastal landforms. According to statistics from 1979-2012(Chao, 2018), the area of beaches (tidal flats) in the northern part of Weizhou Island has decreased by more than 320,000 m². Compared to 1979, by 2016, both the area and volume of erosion in the subtidal zone beaches exceeded the corresponding area and volume of sedimentation by an order of magnitude. After the storm surge in June 2013, the maximum erosion of the northern coastline reached 0.4 m (Yao et al., 2013).

Coral reefs, known as the "tropical rainforests" of the sea, not only reduce wave erosion on the coast but also provide abundant sand particles for "coastal defenders" through the large amount of coral skeletons. The significant degradation of coral reefs, coupled with a drastic reduction in the supply of beach debris, and the long-term repeated erosion caused by storms and tidal waves, are the main reasons for the retreat of the coastal erosion.

3. Impact of Storm Surges on the Beach Environment

According to data from 1956-2014(Li et al., 2015), the storm surges that affect Weizhou Island mainly occur in the summer, with 25 occurrences in July, followed by 21 occurrences in August and 12 occurrences in September. The powerful storm surges cause significant damage to the coastal vegetation along the beaches, leading to the loss and displacement of beach coral debris and coastal soil, which results in substantial coastal retreat, demonstrating the strong erosive and transporting capacity of storm surges (Kuang et al., 2007; Li et al., 2015; Chen et al., 2024).

3.1 Damage to Coastal Protective Forests by Storm Surges

A study previously published by the author (Chen et al., 2024) indicates that before the "Senrak" tropical storm made landfall on Weizhou Island on July 31, 2020, the beach at Dishui Village was in a normal condition. However, after the typhoon made landfall, a large portion of the coral gravel embankment along the coast was eroded and washed away. The coastal embankment disappeared, exposing the roots of the front-row protective trees, and some of the trees fell.

After Typhoon "Capricorn" made landfall on Weizhou Island on September 6, 2024, the beach at Dishui Village also suffered severe erosion. The original gravel embankment, which had been raised above the beach, completely disappeared. The front-row protective forest, which was closest to the sea, suffered intense disturbance, with the exposed tree roots reaching a depth of 0.6 meters (Figure 2), causing some trees to fall. This occurred because the tropical storm, which passed through the South China Sea and entered the Beibu Gulf from south to north, struck the beach at Dishui Village on the southwestern tip of the island. Due to its direct exposure to the typhoon, the storm's erosive effect on the beach was more intense, with large amounts of sediment being transported away, and the previously massive gravel embankment (the coastal berm) disappearing. The front-row trees lost their original protection.

Figure 2. Exposed Tree Roots on Dishui Village Beach After Erosion by Storm Surges (Photographed on 2024.9.17)

Even three months after Typhoon "Capricorn," although most of the previously exposed tree roots were buried again, some tree roots were still exposed, with the exposed height reaching up to 0.3 meters, and some trees were completely dead (Figure 3). A closer inspection revealed that the leaves and branches of the front-row trees facing the sea were generally more yellowed, indicating poorer growth compared to those in the back row, which had not been exposed to storm surge erosion and whose roots had not been exposed.

Figure 3. Part of the Vegetation on Dishui Village Coast Has Wilted or Even Died (Photographed on 2024.12.17)

Clearly, the erosive and transporting power of storm surges is immense. Storm surges are the main cause of damage to coastal protective forests. Trees that had their roots exposed before are now even more deprived of nutrients and water. Furthermore, the lack of timely maintenance of damaged trees has aggravated the ecological disaster in the protective forest.

3.2 Destruction of Beach Geomorphology by Storm Surges

Storm surges also affect the geomorphology of Shiluokou Beach. After Typhoon "Capricorn" made landfall on Weizhou Island, a large deep trench appeared along the coral gravel embankment (the coastal berm) behind the beach (Figure 4), with steep cliffs reaching up to 70 cm in height.

There was originally a small stream flowing through Shiluokou Beach into the sea. With the formation of the coastal berm, the outlet of the stream was blocked, creating a small dammed lake (Chen et al., 2024). When a storm surge arrives, or during extreme tidal high water periods, the tidal flow carries a large volume of seawater over the berm and into the dammed lake. Once the water level in the lake becomes too high, the volume and energy of the outgoing tidal flow exceed the capacity of the dam, causing a breach in the berm. After repeated erosion from the powerful storm surges, a large trench is formed, allowing the water from the dammed lake to flow back into the sea, thus reviving the stream on the beach.

Figure 4. Formation of a Large Erosion Trench in the Dammed Lake at Shiluokou Due to Storm Surge (Photographed on 2024.9.16)

From an aerial view, a stream runs across the beach, like a scar left on the beautiful shoreline, evoking sadness. The appearance of the deep trench has caused significant harm to the popular Shiluokou Beach, damaging its integrity and continuity, and creating significant inconvenience for tourists. How to minimize this damage remains a matter worth considering!

4. Control of Large Sediment Accumulation by Headlands

The coastline of Weizhou Island is characterized by a combination of cape-bay and straight shorelines. The western part is cape-bay type, while the eastern and northern parts are straight shorelines. A cape-bay coastline consists of a cape and a bay. Erosion occurs at the cape and cliffs due to storm surges, tidal currents, and waves, while beach sedimentation occurs in the bay.

A study previously published by the author (Chen et al., 2024) indicates that after Typhoon "Senrak" made landfall on Weizhou Island on July 31, 2020, the coral gravel embankment to the south of the cape had significantly increased in size compared to before the typhoon, suggesting that under the influence of storm surges moving from south to north, the coral gravel embankment at Shiluokou Beach had grown considerably.

After Typhoon "Capricorn" made landfall on Weizhou Island on September 6, 2024, the author conducted another investigation. Comparing photos of the coral accumulations on the beach taken from the same angle before and after the typhoon (Figure 5), it was observed that after Typhoon "Capricorn," the coral gravel embankment had accumulated on a much larger scale. The embankment expanded further toward the sea and north, with a noticeable widening. The changes in the beach geomorphology near the cape were quite significant.

Figure 5. Comparison of Coral Gravel Embankment Development at Shiluokou Cape Before and After Typhoon

As mentioned earlier, when the typhoon made landfall on Weizhou Island, large amounts of sediment eroded from the Dishui Village beach were transported northward by the storm surges. Upon reaching Shiluokou Beach, these sediments were largely deposited on the southern side of the cape due to the blocking effect of the cape. The

sediment continued to accumulate, forming a large coastal berm. Once the width of the berm exceeded the range of the cape, it began to move further north. Similarly, the storm surges in front of the cape also caused significant erosion.

5. Impact of Circulation on Beach Development and Evolution

Multiple field surveys have revealed that the beach sediment at Shiluokou Beach, Weizhou Island, appears to be migrating northward along the coastline. To verify this observation, the author conducted fixed-point photography at two locations with similar beach sediment distribution under the cliffs to the north of the Shiluokou Cape over a period of six months (Figure 6). A comparison of six photographs from three sets clearly shows that the beach sediment beneath the cliffs at Shiluokou Beach has indeed expanded noticeably to the north. This continuous northward expansion of beach sediment has significantly altered the coastal landforms.

Previous studies (Gao et al., 2017) suggest that the distribution of tropical island sediments is also influenced by circulation and monsoons. The Beibu Gulf lies within the South Asian monsoon zone, where from April to October, it is primarily driven by the southwest summer monsoon, and the ocean currents move in a clockwise direction. From December to March, the northeast winter monsoon takes over, and the ocean currents reverse, moving counterclockwise (see Figure 7 of the original text). Overall, the clockwise circulation in summer and autumn is much stronger than the counterclockwise circulation in winter and spring. Additionally, powerful typhoons that occur frequently in summer and autumn tend to move from southeast to northwest, causing the storm surge to overlap with the clockwise circulation. This combined effect is the primary reason for the continuous northward migration of beach sediment at the Dishui Village–Shiluokou Beach on the southwestern side of Weizhou Island.

Figure 6. Migration of Sand at Shiluokou Beach. Top row: Photos taken towards the south; Bottom row: Photos taken towards the north

6. Insights from the Coastal Protection Project at Yalong Bay, Hainan

The second author, while on vacation, conducted a preliminary investigation of the coastal protection project at the western section of Yalong Bay in Hainan (Chen, 2021) and found that in 2019, the eastern section (approximately 1.2 km) of Yalong Bay underwent remediation and restoration measures such as artificial sand replenishment, with a total investment of 57.16 million RMB. In 2021, the western section (2 km long) of Yalong Bay also underwent restoration, with nearly 300,000 cubic meters of sand replenishment, the construction of ecological protective slopes (Figure 7), and landscaping. The total investment for this project was 92.78 million RMB, with the total investment for the entire coastal restoration of Yalong Bay approaching 150 million RMB.

The newly constructed ecological protective slopes at Yalong Bay's western section consist of three layers (Figure 7, left 1-3): the lower layer is a concrete structure, the middle layer is a salt-tolerant marine snail ecological slope, and the upper layer is a protective forest ecological slope. The concrete structure of the protective slope also consists of three layers (Figure 7, right 1): the base is composed of large stones, the middle is a gravel leveling layer, and the top layer is a concrete surface layer made of gravel. The surface gravel is coated with paint, and the chosen color closely matches that of the beach sand.

Figure 7. Series of Photos of the Ecological Protective Slope Project at the Western Section of Yalong Bay (Photographed on 2024.12.16)

However, the concrete protective slope is not a permanent solution. Continuous wave erosion, along with material degradation, design flaws, and quality defects, can cause the structure to deteriorate (Figure 8). If small holes are not repaired, they will inevitably lead to larger cracks that are harder to fix.

7. Conclusion

Based on the analysis of the factors influencing the changes in the coastal geomorphology of Weizhou Island, the following conclusions can be drawn:

(1) Degradation of Coral Reefs Leads to Coastal Retreat

Coral reefs serve as an important natural barrier for the coastline of Weizhou Island, effectively reducing wave erosion and protecting coastal landforms. The growth of corals promotes the formation of calcareous sediments, reducing beach volume loss. Coral reefs around Weizhou Island began to develop in the Holocene, but have been repeatedly damaged by extreme weather and human activities, particularly in the southwestern region, where coral reef degradation is most severe, leading to a significant decrease in coverage. The degradation of coral reefs has caused the coastline to retreat, with the southwestern coast experiencing an average annual erosion rate of 0.18 meters, which has severely impacted the island's geomorphology.

(2) Storm Surges Cause Coastal Vegetation Damage

Storm surges frequently impact Weizhou Island, especially during the summer months, causing damage to coastal vegetation, loss of beach debris, and soil erosion, which leads to significant coastal retreat. Strong storm surges have powerful erosive and transporting capabilities. In 2020 and 2024, Dishui Village Beach experienced severe erosion from storm surges, with the original coral gravel embankment and coastal dikes disappearing, exposing the roots of protective vegetation, causing some trees to tilt or die. Storm surge erosion removed protection for the front-row trees, and even months later, many of these trees had not fully recovered, with their leaves yellowed and growth stunted. These phenomena highlight the severe impact of storm surges on the coastal and ecological environment of Weizhou Island.

(3) Cape Blockage Leads to Significant Beach Sediment Accumulation

Weizhou Island’s coastline is a combination of cape-bay and straight shorelines, with the western part characterized by cape-bay features, and the eastern and northern parts being straight. The interaction of storm surges, tidal currents, and waves causes erosion at the capes and deposition in the bays. After Typhoon "Senrak" made landfall in 2020, the coral gravel embankment at Shiluokou Beach significantly increased in size, as the storm surge drove sediment accumulation from south to north. Following Typhoon "Capricorn" in 2024, the coral gravel embankment continued to expand, with the coastal berm extending further into the sea and north, significantly altering the beach geomorphology near the cape. The erosive and accumulating effects of storm surges, particularly the blocking effect of the cape, accelerated the northward migration of sediment, resulting in a larger coastal berm.

(4) Circulation is the Main Constraint on Beach Migration and Expansion

Multiple investigations have shown that sediment on Shiluokou Beach of Weizhou Island exhibits a northward migration trend. Fixed-point photography and comparison confirmed that the beach sediment has significantly expanded to the north, dramatically altering the coastal geomorphology. Research indicates that the circulation monsoon in the Beibu Gulf affects sediment distribution, with clockwise circulation in the summer and autumn months, coupled with the effects of typhoons, driving beach sediment northward, particularly in the area of Dishui Village Beach.

8. Strategies for the Ecological Environment Protection of Weizhou Island's Beaches

Based on the above research findings and a preliminary investigation of the coastal protection project at Yalong Bay in Hainan, along with related data review, the following specific suggestions for the ecological environment protection of Weizhou Island's beaches are proposed:

(1) Strengthen Coral Reef Protection and Restoration: Continue supporting coral reef protection and ecological restoration projects (Wu et al., 2024), increase the efforts for coral reef restoration, and invest in artificial reefs and coral seedlings. Expand the coral reef area and enhance experimental research to improve the coral's resistance to waves. Establish a comprehensive coral reef monitoring and restoration system to promote natural recovery of coral reefs.

(2) Enhance the Maintenance of Coastal Protective Forests: Pay special attention to the artificial maintenance of the coastal protective forest in Dishui Village. After each typhoon passes, immediately organize personnel to repair the damaged vegetation, straighten and support tilted trees, and bury the exposed roots of trees that have suffered erosion to prevent their death due to lack of nutrients and water.

(3) Reasonably Establish Coastal Protection Projects: Learn from the experience of the Yalong Bay coastal protection project. Based on the tidal, wave, and current dynamics around Weizhou Island, especially design a reasonable coastal protection project for Dishui Village. Ensure the quality of construction and include local materials, such as coral branches and shells. Timely maintain and repair damaged protection structures.

Figure 8. Series of Photos Showing Damage to the Protective Slope Project (Photographed on 2024.12.16)

(4) Build Protection Facilities for Dammed Lakes: Since dammed lakes often experience dam breaches, construct protective dikes in front of the lake and install drainage pipes that lead to the intertidal zone. This will improve the exchange of lake water with seawater, reduce lake water pollution, and discharge excess water before the tide comes in and during storm surges and high tidal periods, preventing breaches from causing large stream flows on the beach.

(5) Enhance Environmental Awareness Among Residents and Tourists: The local government should strictly implement all ecological protection measures for Weizhou Island (Beihai Municipal People's Congress Standing Committee, 2018), strengthen publicity of ecological protection regulations, encourage local residents to participate in ecological protection, and prohibit the discharge of domestic waste and sewage onto the beaches. Control uncivilized behaviors of tourists and reward those who actively participate in conservation efforts.

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