Sandy coast erosion under the conditions of a storm surge combined with a spring tide

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Abstract. By comparing the changes of beaches and features in the southeastern coast of Xiamen Island before and after Typhoon No. 9914, the beach cycle and coast erosion processes under the condition of superimposed the spring tide of storm surge were discussed. The study showed that during Typhoon No. 9914, the coastal water level rose to 4.04m above the main sea level (MSL). The storm surge elevation was 1.43m. The stormy waves with 22m/s onshore winds brought overwash onto Huandao Road, up to the main sea level of more than 8.5m, depositing about 8-10cm of beach sands on the road. It caused the beach berm to disappear completely. The sand prism lying in the high tidal zone was scoured. Part of the sand of the prism was washed upward away from the beach, part of which was brought to the low tide zone. The bare shoreface without sand prism was scoured directly by waves and currents. Although the sandy sediment which was brought to the deeper zone by the storm can come back to the shoreface, but the overwash sand could not be returned after the storm, and the prime failed to return to its original condition for a long time, eventually leading to beach erosion and coast retreat.

1. Introduction
The beach cycle is an active and frequent geomorphological process of sedimentation in coastal zones. It is also researched around the globe within marine science. The theory was first introduced by D.W. Johnson (1919), but it was an effort which required further research [1]. F.B. Phlegez, etc. (1972) researched the beach changes of the barrier-lagoon coasts in California with sedimentologic and hydrodynamic methods [2]. In the last half century, many experts have made great efforts to investigate and research the beach process. F.P. Shepard, a pioneer in marine geology, had performed long-term observations on Scrips Beach in California and collected many profile sketches in different beach cycles [3]. Furthermore, L.D. Immam (1953) and C.A.M. King (1959) further developed this theory with experiments [4, 5]. Recently, Morton, etc. (2003) have researched the beach and barrier change response to previous hurricanes in Mexico Bay and the Atlantic coast of America and proposed three storm morphological types [6]. Zhang, etc. (2005) compared the LIDAR data to analyze changes of a 4km-long beach along the Atlantic coast in the middle of Florida [7]. Switzer & Jonses (2008) twice studied the overwash sedimentology of different storms on the same coast in Australia [8]. Domestic researchers, such as Cai Aizhi (1989, 1995), Xia Yiming (1991) and so on, have primarily studied in this research field. They have been working on the researches about beach cycle under the action of storm in the Shandong Peninsula and Xiamen Island [9-12]. The response characteristics of different coastal geomorphological types to Typhoons were studied at the Cai Feng
etc. (2006) [13]. Kai Yin, etc. (2019), applying mathematical model to study the change of beach profile caused by storm surge, it is considered that high water level is more influential than wave impact [14].

However, their past researches on beach changes did not involved the beach erosion process and its essential conditions in the storm surge combined with a spring tide. This extreme condition and its process are the decisive factors leading to asymmetric beach circulation and coastal damage. In the 20 years since 1999, the southeastern sandy coast of Xiamen Island has experienced a frontal attack by the super-strong typhoons No.9914 (1999) and No.1614 (Meranti, 2016). Typhoon Meranti landed with a maximum wind speed of 52m/s, the strongest and most destructive typhoon in the last 60 years [15], but it was near a low tide at the time of landing and did not cause damage to the coast. Typhoon No. 9914 landed with a maximum wind speed of 34.2m/s, at the climax of the astronomical tide, causing unprecedented damage to the southeastern coast of Xiamen Island. It is clear that the hydrological conditions at the time of storm landing are critical to the impact of coastal erosion. Although nearly 20 years have passed since Typhoon No. 9914, it is still important to study its coastal erosion process and conditions for today’s coastal protection.

2. Study Occasion and Methods
The severe typhoon attacked Xiamen on Oct 9, 1999. Although we got the prediction before its landfall, field observations could not be performed because of extreme weather and hydrodynamic conditions. The damaged conditions of original ground objects and constructions were the only useful evidence. Consequently, usable ground objects must be chosen before the storm, and how to select evidence after the typhoon with these ground objects should also be determined.

2.1. Severe damage of the seawall
We had anticipated that some unqualified coastal constructions would be destroyed in this storm. Therefore, we paid attention to these weak sites and took photos as evidence before the typhoon. We researched the coast immediately after the storm on the morning of October 10th. Unexpectedly, almost all of the seawall on the south and east coasts of Xiamen Island were destroyed except for two sections, Zhenzhu Bay and Taiyan Bay, altogether 900m long. Even those indestructible granite dams were also shattered in this storm.

The first research object we had chosen in advance was a 600m-long newly-built seawall between Baishi emplacement and Zengcuoan (Figure 1). Before construction of this seawall, we realized and brought to light two design flaws, the design elevation was not high enough and the foundation treatment was not suitable.

![Figure 1](image-url). The position of research area and the observation profiles.
The seawall was attacked by this severe storm after the project was completed and it collapsed entirely (Figure 2, P-1).

![Figure 2. Wave wash over and erosion action under the beach cycles.](image)

Profiles clearly show that the seawall’s cement framework was still linked together after it collapsed. Because at the base of the seawall was loose sand, strong waves dredged the bottom of the seawall at low tide during the initial stage. With the water level rising and waves strengthening, dredging and erosion at the bottom became worse. Finally, the whole seawall collapsed by the momentum of the wave.

At the beginning of stage 2, the strong waves overtopped the seawall whose height was less than 6m, then impacted the cracked coastal soil behind the seawall, inducing 5-7m of coastal retreat (Figure 2, P-1).

2.2. Breakage of the sewage pipe buried in the beach
The 60cm diameter sewage pipe (Figure 2, P-2) broke as a result of the erosion and dredging of the energetic waves. The outlet on the slope break of shoreface was also damaged in the stormy waves. The sewage pipe buried in the beach also broke in many places under the impact of the stormy waves. The records reflect that the pipe was buried in the beach, but the prismatic sand washed away in stage II induced damage to the pipe.

3. Coastal Environmental Parameters

3.1. Combination of storm surge and spring tide
The predicted syzygial spring surge level was 2.1m above the main sea level (MSL). During the landfall of the No.9914 typhoon, the storm surge was about 1.43m. The summated elevation was 4.04m upon the MSL.

3.2. Wind measurements
The wind speed measured by the Xiamen meteorological station was stronger because it is located on the top of Huwei hill (a.out 140m high). The Xiamen oceanographic station is located near the coast, so its wind data was more accurate and can be used in this study. The maximum wind speed measured by the oceanographic station was a 34.5m/s east wind and a 22.5m/s south wind. The severe anticlockwise wind duration was 5–6 hours.
3.3. Wave conditions
The incident wave direction mainly was east, southeast and south. The wave height (H) was 1.69–2.38m and wave rise (R) was 2.0–2.5m. The relationship between H and R depended on many factors, such as wind speed, bathymetric gradient and coastal strike. The value of R is inversely proportional to the backshore slope and roughness.

3.4. Beach geomorphology and sediment
The coast in the southeast of Xiamen Island has been retreating in the last few decades. Huangcuo beach, which runs northeast to southwest, has been left with a thin layer of sand, its berm only 30m wide and and its peak only reaching 3.9–4.6m above the main sea level. The shoreface gradient is 7.5–8.5°. The sediment is medium-fine sand (Mz=1.3~2.1φ,σt=1.1~1.5) in prismatic sand and well-sorted fine sand in foreshore (Mz=2.1~2.6φ, σt=0.5~0.8).

4. Hydrodynamic Energy Dissipation in the Beach Cycle

4.1. Energy transmission of stormy waves in high water level
Waves are a carrier body which transport energy from the water to coasts. Under the same wave conditions, water depth is inversely proportionate to the dissipation of the seabed by friction. There are three hydrodynamic dissipation zones on the beach profile, including the nearshore shoal zone where water depth is less than half of the wavelength, the wave breaking zone lying between the lower slope and sand ridge, and the overwash zone and erosion scarp above the shoreface. However, hydrodynamic energy dissipation varies in the different zones. The dissipation proportion in the different zones changes with the maintenance time of water level and wave parameters. Water is deeper in the nearshore shoal zone and hydrodynamic energy will be transported to the overwash zone. To understand the relation between the beach cycle and energy dissipation and erosion, the energy dissipation (Figure 2) was divided into three stage: Stage 1, Stage 2 and Stage 3(Figure 3).

4.2. Beach cycle and erosion
As Figure 3 shows, the energy dissipated at the foreshore on the front of the seawalls at stage 1 resulted in washing and erosion on the beach. The erosion area moved up with the rising water level and the washing of the waves. The strong waves can wash all of the prismatic sand near Stage 2, and the hydrodynamic energy reached its peak in the middle of stage 2. With the stormy waves breaking, they can directly wash and erode the prismatic sand on the beach. The most sediment was brought down to the foreshore, while other sediment was brought up to the supralittoral zonen, even on Huan Dao Road during the overwash process. Meanwhile, the bare shoreface was impacted directly by the storm waves. At its peak, the water level rose to its highest, about 4.04m over the main sea level (MSL). Wave breakers induced huge energy dissipation on the eroded surface and caused overwash with the help of storm winds. At the same time, a powerful scour of scarp above the sand prism leaded to a retreat of the coastal line.

4.3. Overwash of beach sands
During the high water levels of stage 2, with the drive of wave breakers and strong winds (>20m/s), water-mixed sand currents caused overwash 7-8m over the main sea level or higher in places along the slope, even reaching the coastal road (8.5m over MSL). In some sites, the mixed current overwash ran through the lawns to the coastal road, depositing about 8-10cm of sand on the road (Figure 2, P-3) and 5cm of sand on the lawn. During stage 3, the water level and energy of the waves simultaneously decreased. The sediment transported to the foreshore moved back to the beach.
In the case of such a powerful typhoon and the high water level superimposed by the astronomical tide, the intensity and range of the wave to the coastal erosion are bound to expand. But two coastal seawalls, in Pearl Bay and Sun Bay, were not damaged because of their solid foundation and structure. The sea walls consists of the following parts, including: A. a foundation whose top is at the main sea level, B. a stone-made bottom slope whose elevation is from 0 to 2.5m, C. a trapezoidal slope whose elevation is from 2.5 to 5.5m, D. an arc retaining wall whose elevation is from 5.5 to 6.8m. During the storm surge, the foundation and bottom slopes successfully resisted the erosion of the storm, the trapezoidal slope efficiently dissipated waves, and the curved wall consumed the last part of the storm energy. It has been proved that the projects have achieved the dual effect of shore protection and beach preservation.

4.4. The asymmetry of the beach cycle
In stage 3, with the water level and waves gradually decreasing, the beach cycle turned to its recover stage. The sediment which had been transported to the low tidal zone gradually returned to the beach. Based on our subsequent observation, the height of the prismatic sand cannot be recovered completely. Mostly, this asymmetry of the beach cycle is presented as follows: it can recover to its approximate original height by moderate wave processes in several spring, neap tidal cycles. The lower water level during the spring tides and the moderate wave processes can help the sediment which was brought to the deeper zone by the storm come back to the shoreface and recover the beach. But on some sandy coast such as Huangcuo beach, the huge waves washed some parts of the sand prism up to Huandao Road and the other parts back to the low tide zone. The naked beach would be washed directly by strong waves before they retreated. When the energetic waves calmed, the sediment which was transported to the low tidal zone would come back to the shoreface, but the sands of overwash couldn’t return. So the sand prism decreased and the coast retreated due to the overwash.

5. Conclusions
This storm surge combined with the spring tide resulted in abnormally high water levels. Due to this, more hydrodynamic energy was transferred to the coast. The sediment on the foreshore was washed away in the low water levels. The dredging and erosion at the foot of the seawall resulted in the firm seawall collapsing completely. At stage 2, the prismatic sand was washed away and the buried sewage
pipe was broken by the stormy waves. The prismatic sand lying in the high tidal zone was scoured and induced offshore and onshore sediment transport. The bare shoreface which was originally covered by sand was directly washed by the stormy waves and currents, finally leading to coastal retreat. With the water levels and the energy of the waves increasing to a peak, the water-mixed sand current crossed the artificial slope run-up to a height of 8.5m above MSL, even encroaching onto the higher Huandao Road.

The strong waves impacted the protuberant erosion scarp and dissipated its energy through erosion. At the same time the coastal cliffs were retreating, the trees fell down, the sewage pipe was exposed and broke, and many structures were destroyed in the storm.

After stage 2, water levels and wave energy gradually decreased and entered the recovery stage, a slow beach process. Although the sediment which was brought to the deeper zone by the storm can return to the shoreface, the washover sediment never returned. Doubtless, the sediment lost in the storm from the beach and shoreface eroded and retreated. If there was no source to replace the sediment, the beach would decline, even disappear. Whether the beach berm can completely recover depends on sufficient sources of replacement sediment.

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