Early Stage Evolution of Nourished Beach under High-energy, Macro-tidal Environment

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Abstract. Beach planform evolution, profile equilibration and sediment grain size change have been studied during the first 4 months from 4th September to 24th December 2011 after the construction of beach nourishment project at Longfengtou Beach, Haitan Bay. Monthly beach profiles, shoreline surveys, sediment sampling and nearshore wave measurements were carried out after implementation of the 1.3km long nourishment project which was completed on 20th August 2011. This study indicates that: (1) rapid beach profile equilibration occurred in the early stage after the construction of the project. A null point was observed, which is equal to the height of mean high tide, basically kept dynamic stable during the process of profile evolution. Shoreface sediment accumulated beneath the height of this point while erosion happened above it, the slope between the beach berm and the landward edge of low tidal zone became more gradual accompanied with seaward transportation of beach sediment. The velocity of beach slope adjustment in earlier period is faster than later. (2) Beach planform adjustment initiated simultaneously with the combination of the process of profile equilibration and longshore sediment transport. Shoreline retreated with an average distance of 11.1m and maximum of 31.02m from 4th September to 24th December, erosion in the south part was more serious than in the north, and 3 erosion hot spots were found along the coast. (3) Sediment redistributed with cross-shore profile equilibration, it showed a pattern across beach profile as medium sand (0.4-0.5mm) in beach berm, smaller (0.3-0.4mm) in high and middle tidal zone, coarse sand(0.6-1mm) in beach slope transitional zone, fine sand(0.1-0.25mm) in low tidal zone. The sediment grain size change of foreshore was rapidly response to the passage of storm surge.

1. Introduction
Over the last two decades, beach nourishment has become a more and more popular solution to erosion problem and coastal restoration in China (Cai et al., 2012), meanwhile, the debates over the effectiveness of this young technology continues, especially in some serious erosion beaches with high energy. Often, data produced from inadequately planned monitoring programs after nourishment is unable to address the pertinent issues, and crucial performance questions remain unanswered (NRC, 1995). It is noted that immediate high-resolution post-nourishment monitoring is seldom (Davis et al., 2000; Gravens et al., 2003). Nourished beaches are almost always constructed with sediment that differs from the native grain size of the natural beach, they also been constructed on considerably steeper slopes than natural profiles. Nourishment projects tend to be highly scrutinized by the public during construction and after project completion (i.e. Pilkey and Clayton, 1989). Understanding the project adjustment has an important implications (Elco & Wang, 2006), not only to coastal engineer...
but also to public. Nourished beach profile and planform adjustment must be explained to avoid misinterpretation of early stage adjustment as a permanent loss of sand or a misuse of public funds (NRC, 1995; Elko, 2005).

This study contributes to the understanding of processes governing profile equilibration and planform adjustment, particularly the appearance of erosion hot spot. The objective of this study was to understand the early stage of profile, planform, and sediment evolution responding to a high-energy and macro-tidal environment.

2. Study area
Pingtan Island is the fifth biggest island in China and locates in the west of the Taiwan Strait, Haitan Bay was formed in the right east of Pingtan Island (Figure 1). The study area Longfengtou Beach is located in the southeast of Haitan Bay. It is a high-energy, macro-tidal zone with an annual average $H_{1/10}$ (10% highest waves) of 1.56 m, dominant wave direction is ENE with a frequency of 67.43% (Figure 2). The mean tidal range is 4.29 m with an average tidal cycle of 12.5 hours (Wang et al., 2014). Affected by the monsoon, the seasonal wind direction shows an obvious variation in the study area, the annual average wind speed is approximately 8.4 m/s. The statistical data also indicates the predominance of northeast (NE) wind in the autumn, winter and spring seasons, whereas south (S) wind in the summer. Normally, this area is attacked by Typhoon from June to September every year.

![Figure 1. Location of study area of Longfengtou Beach and distribution of monitoring beach profiles.](image)

Longfengtou beach used to be a famous leisure area which was destroyed by seawall building along the shoreface aiming to infrastructure construction in 1990s. To recover the beach view, nourishment project has been completed in August 2011, with a length of 1.3 km. The wider north part is 120 m in width and 200 m long, transitional middle part is 130 m long and the narrow south part with a width of 60 m and length of 1000 m.

It is worth to note that there are two specific geomorphologies which have significant impacts on the project. The first one is Longwangtou man-made offshore headland located about 100 m away from the south end of the project (Figure 1), it is a vertical elliptic construction with a long axis of 140 m, a minor axis of 70 m and a height of 6 m from the beachface, and higher than the height of spring tides. The second one is Guimoyu Island which locates about 550 m away from the north end.
of the project, the island is 200m long and 60m wide with a trend direction of NE. A training dyke was built in the middle of the project to drain away the wastewater and stormwater from urban city.

![Figure 2. Wave rose of Haitan Bay measured from July 2011 to July 2012.](image)

3. Methodology

Four beach profiles (Figure 1), shoreline position and sediment samples grain size were measured periodically from September to December 2011.

Based on the experience from previous monitoring efforts, traditional wading depth profiles were extended to approximately -2 m (85 Yellow Sea Height Datum) to capture nearshore changes and measure profile equilibration. These wading beach-profile surveys followed level-and-transit procedures using an electronic total station. Four surveys of the 4 profile lines were conducted during this field effort. Monthly beach profiles were surveyed 20 days after nourishment from 4 Sep. 2011 to December 24, 2011. Beach shoreline position was identified as berm crest during field survey and mapped with the RTK-GPS (Real Time Kinematic-Global Positioning System) in an space interval of 0.5m.

Beach topography measurement was also completed by RTK-GPS, from the edge in front of seawall to Mean Low Water line across the shore with the scale of 1:100. Two times of topographic survey were carried out on the date of 20 Sep 2011 and 21 Dec 2011 to compare the beach morphology change.

Sediment samples of top 5cm surface were collected synchronously with beach profile survey. The sampling locations were distributed along the profiles normally with an elevation interval of 30cm. Specifically, they would be more dense in some observed grain size transitional areas. The sediment grain size was determined using Mastersizer 2000 laser diffraction particle size analyzer. AWAC-Acoustic Wave and Current gauge was deployed about 5000 m offshore of the centre of Haitan Bay in depth approximately 15 m (Figure 1). Wave conditions were measured every 60 min and sampled at 2 Hz from July 23 2011 to July 21 2012. A large amount of detailed field data was collected over 4 months in the initial post nourishment phase of the project. The data allowed for analysis of the immediate post nourishment response, which is the focus of this paper.

4. Results
4.1. Shoreline change

After construction, morphologic changes were measured. Shoreline were surveyed at the first time on 4 Sep. 2011 about 20 days after the project finished, and then 3 times on 20 Sep. 2011, 6 Nov. 2011, and 20 Dec. 2011, respectively. The comparison of shoreline position in different periods was displayed in Figure 3. It is seen the shoreline has a steadily regression with an average distance of 11.1m and a maximum of 31.02m which was found in the right north of a training dyke. Shoreline retreat was characterized by 3 segments: (1) serious erosion happened in the south segment (from the south end to training dyke) with a mean erosion distance of 13.2m, shoreline retreated consistently and synchronously; (2) gentle erosion happened in the middle segment (from training dyke to 1100m from the south beginning) with a mean erosion distance of 7.1 m exceptional two erosion hot spots were found in both ends of this segment (see Figure 3); (3) beach shoreline remained basically stable in the north segment. It can be seen from Figure 4, shoreline retreated speed in last month during survey period was much less than earlier.

![Figure 3. Shoreline position measured in 4 different periods.](image)

Three erosion hot spots were found during survey (see Figure 4). The original definition of an Erosion Hot Spot (e.g., Bridges 1995; Dean, Liotta, and Simón 1999) was intended to cover erosional phenomena that were unanticipated and primarily local (e.g., a well-identified area located within a beach fill). Erosion hot spots are herein defined as local sections of beach—alongshore—that show obvious anomalous erosion or higher erosion rates compared to the adjacent segment. As statistics indicate (Table 1), the maximum retreat distance of each erosion hot spots are 31.02m, 30.3m and 30.01m from the south to the north respectively with different scales varied from 20m to 150m owing to the locations along the coast.

| Erosion hot spot | Location (from the south beginning m) | Scale (m) | Average retreat (m) | Maximum retreat (m) |
|------------------|----------------------------------------|-----------|---------------------|---------------------|
| 1                | 210-360                                | 150       | 15.85               | 31.02               |
| 2                | 665-730                                | 55        | 25.84               | 30.3                |
| 3                | 1075-1095                              | 20        | 21.13               | 30.01               |
4.2. Beach profile evolution
Longfengtou beach was a dissipative beach with a gentle original slope which is 1:35 for upper beach above MHW and 1:80 for shore face between MHW and MLW. As noted, beach nourishment projects are generally placed with profiles which are steeper than the natural profile for the coarser size of sediment that is used in the beach nourishment project. Thus over several tidal circles affected by the wave action beach profile will tend to equilibrate to a new shape. Figure 5 shows the evolution of different beach profiles from 4th Sep. 2011 to 20 Dec. 2011, it indicates that upper beach slope has become gentler especially for profile LFTP2 which is located in the area of erosion hot spot 1. There was an obvious transitional zone in each cross-profile, which is normally equal to the height of local mean high water, basically kept dynamic balance during the process of profile change. Sediment accumulated beneath the transitional zone while the beachface eroded above it, the slope between the beach berm and the landward edge of low tidal zone became gentler accompanied with seaward transportation of beach sediment. At the first month, beach slope changed tremendously, and then the velocity of beach slope adjustment in later stage was slower than earlier.

4.3. Sediment variation
It was found that choosing sampling sites along the profile based on hydrodynamic zonation on the beach (i.e. area of maximum run-up, mid-tide area and mean low tide area) gives the best representative picture of grain size distribution. The mean grain size of sediment sampled from original beach profile showed the distribution trend as 0.15-0.25mm in high tide zone, 0.2-0.4mm in middle tide zone and 0.1-0.2mm in low tide zone. Ideally, for any given beach nourishment project, the borrow material should be similar in grain size distributions to the native beach. Often the composition of fill material in available borrow areas is not the same. Fill material placed in Longfengtou beach nourishment project was borrowed from offshore in the north of Pingtan Island, the mean grain size is 0.47mm.

Fill was placed in the intertidal area and sediment redistribution occurred violently owing to the action of wave, tide and wind forces. 211 samples were collected during field survey synchronously with beach profile measurement, the change of sediment mean grain size distribution in each profile for 4 times is shown in Figure 6.
Figure 5. Beach profile changes during 4 months after nourishment project construction.

(a) The character of sediment grain size distribution across beach profile
For each profile at the upper beach higher than 3.3m (which is about the height of Mean High Water Spring), sediment shows a slight variation and the mean grain size is about 0.45-0.55mm generally. Beneath this height, sediment grain size varied significantly. For profile LFTP3 and LFTP4 sediment grain size varied quickly and enormously from the height 3.3m to 1.2m seaward, the coarsest mean grain size of about 0.8-1.2mm was found in the height between 1.7m-2.3m, and the grain size decreased to ~0.2mm where in the height of 1.2m, and beneath it the grain size showed only slight change. For profile LFTP1 and LFTP2, the span of sediment varying cross shore was not as large as the other profiles, showed a decreasing trend generally.

(b) Variation of beach sediment distribution in different periods
Four profiles distributed from the south to the north showed different performance of sediment change in each survey period. For profile LFTP1, there was a slight change of sediment distribution characteristics during each time mainly happened in low tide zone. For profile LFTP2, the change is significant with a wide grain size variation span from 0.2mm to 0.6mm in middle tide zone. For profile LFTP3 and LFTP4, as mentioned above the particle size distribution cross shore was roughly similar in each period, except on the date of 22 Sep. 2011, it was 3 days after the landfall of typhoon Nanmadol.

The sediment grain size change in foreshore was complicated, and rapidly responded to the passage of storm surge. Normally, sediment across beach profile showed a distribution regulation as medium sand (0.4-0.5mm) in beach berm and dry beach, smaller (0.3-0.4mm) in high and middle tide zone, coarse sand(0.6-1mm) in beach slope transitional belt, fine sand(0.1-0.25mm) in low tide zone.

Figure 6. Variation trend of mean grain size of beachface sediment at different elevation along the beach profile.

5. Discussion

5.1. Early stage beach evolution

Study area is characterized by high-energy and macro-tidal environment, stronger nearshore hydrodynamics contributes to rapid nourished beach profile equilibration which also results in a violent adjustment of beach planform. During the process of profile equilibration, most of the volume of placed material remains within the project area landward of the closure depth, and is simply redistributed across the profile, the dry beach width is usually reduced during this process (Elco & Wang, 2006). Comparing the value of accumulation and erosion across beach profile during the first 2 months, net sediment deficit is small except in some erosion hot spot area. And in the later period after then, net sediment deficit was observed gradually.

A new equilibrium beach profile was created in high energy macro-tidal environment by fill material cross-shore sediment transport which was the dominant process causing profile re-equilibration in the early stage. Nourished beach planform adjustment in early stage was result from combined action of cross-shore and longshore sediment transport, and the former is the controlling process.

5.2. Erosion Hot Spot (EHS)
An EHS is an area that experiences sediment transport potential without having adequate sediment supply. EHSs erode more rapidly than the adjacent beaches or more rapidly than anticipated during design. Some coasts to be nourished are sediment deficient, obscuring the presence of latent EHSs that emerge once material is in place. Kraus & Galgano (2001) identified and classified all known types of EHSs and points to possible underlying causes as presently understood. In this study 3 EHSs observed along the Longfentou Beach can be classified as two types: 1) Structure-induced, and 2) Non-uniform offshore translation of beach. EHS2 was a structure-induced erosion because the training dyke was located in the south and blocked the sediment transport from the south to the north. The training dyke was made of geotextile with sand inside, the protruding part of the dyke could be easily destroyed by wave action. EHS1 and EHS3 can be classified as the type of Non-uniform offshore translation, the former was affected by Longwangtou man-made offshore headland and the latter might be induced by the complicated bathymetry comprised by Guimoyu Island and a series of submerged reefs arranged in the direction of ENE.

5.3. Cross-shore distribution of sediment
The cross-shore distribution of sediment grain size is not always uniform even in different parts of same bay beach. The distribution pattern of grain size across the surf zone is determined mainly by the rate of wave-energy dissipation (e.g., Dean 1977, 1991), local balance in the transport energetics (e.g., Inman and Bagnold 1963; Bowen 1980; Bailard and Inman 1981), and sediment supply. High wave energy and macro tidal hydrodynamic characteristic in study area determine the sediment distribution pattern of coarse sediment in middle zone and fine sediment in upper and lower zone. Owing to the complexity of nearshore bathymetry, attached morphology and man-made coastal constructions, hydrodynamic condition varied significantly from the north to the south part along Longfentou beach, thus result in a regional difference of sediment distribution even developed from same fill material after beach nourishment construction.

6. Conclusion
Beach morphology evolution happened soon after beach nourishment project completed, the primary performance of beach change showed as beach profile equilibration, beach planform adjustment and sediment distribution tends to be in corresponding zones gradually. High wave energy macro-tidal environment is the main reason for quick beach change. Beach profile evolved to new equilibration adapting to macro-tide and fill material composition. Nourished beach shoreline change resulted from the combination of two processes as beach profile equilibration and longshore sediment transport, the complexity of nearshore bathymetry and attached man-made constructions induced hydrodynamic difference along study area caused the regional distribution of erosion hot spots. Accompanied with cross-shore profile evolution, sediment distribution was formed in a pattern as fine sediment in upper zone, coarse sediment in middle zone, and finer sediment in lower zone.

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