Monitoring and evaluation of sand nourishments on an embayed beach exposed to frequent storms in eastern China

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Abstract

Beach nourishment is a proved effective protection approach which has been widely used in recent years. An Argus video monitoring system has been set up to monitor morphological changes and effects of continuous nourishments at Dongsha beach, an embayed beach in Zhoushan Archipelago, eastern China. Video-derived shorelines along with their morphological parameters, such as dry beach width, dry beach area, beach orientation and unit width volume were analyzed during the monitoring period from June 2016 to July 2017. Analysis of video monitoring data shows that shorelines retreated during autumn and winter when storms were intensive, while advanced in spring and summer, with a lot of bulges occurred after nourishment projects. Abrupt variations in the beach orientation were always followed by gradual recoveries to the average beach orientation, while continuous counter-clockwise rotation occurred after March, 2017 when storm events were sparse. Comparing the different beach responses to individual storm events, we found that small-scale and short-interval sand nourishment implemented timely after storms can compensate for sediment loss more effectively on this beach. This study can provide a reference for local beach management.

Keywords: Argus video monitoring; beach nourishment; storm erosion; occurrence time of nourishment; beach management

1. Introduction

Due to the global climate change with sea level rise and more frequent and severe storms, serious beach erosion is observed all over the world (Castelle et al., 2007; Houston and Dean, 2014; Qi et al., 2010; Scott et al., 2016; Smith et al., 2014). At least 70% of sandy beaches experienced widespread erosion around the world (Bird, 1985), and approximately 50% of sandy coasts were regressed in erosion in China (Third Institute of Oceanography, 2010). Under this circumstance, there are growing numbers of beach protection or restoration projects in China, particularly in the tourism hotspots, to meet increasing public requirements (Kuang et al., 2011).

The common approach adopted in the past to protect or restore beaches is the hard engineering based (Cai et al., 2011; Pan, 2011). Although hard engineering, such as artificial coastal structures, can effectively mitigate shoreline retreat caused by storms, it may have negative impacts on its adjacent beach (Hamm et al., 2002). For decades, beach nourishment has become a preferred method to protect beaches in developed countries (Castelle et al., 2009; Cooke et al., 2012; Hamm et al., 2002; Hanson et al., 2002; Pan, 2011), which has also been frequently applied in China in recent years (Luo et al., 2016).

However, beach nourishments can often cause large-scale nearshore disturbances that affect the balance of alongshore and cross-shore sediment transport (Dean, 1983). Under natural conditions, storm-eroded sandy beaches may recover gradually over seasons to a decade timescale (Harley et al., 2015; Scott et al., 2016), while the beach processes with nourishment disturbance vary significantly (Elko et al., 2005; Seymour et al., 2005). Previous studies focused on nourishments with regular frequency and fixed implement timing in European countries (Hanson et al., 2002), the USA (Leonard et al., 1989) and Australia (Cooke et al., 2012). However, the beach protection approach at Zhoushan Archipelago in China is different due to frequent occurrence of storms. To prevent the severe storm erosion and maintain the recreational beach, small-scale and irregular nourishments have been frequently implemented and the occurrence time of those nourishments is often close to the storm period. Up to the present, beach morphodynamic evolution involved with this beach protection approach remains unclear.

Understanding the self-adjustment of beaches after nourishments is important for management (Elko and Wang, 2007), while there is always no regular monitoring of changes in beaches after nourishments (Chiva et al., 2018; Leonard et al., 1989; Stauble, 1988). Video monitoring systems are proved to be adequate in detecting and quantifying spatial and temporal beach responses (Archetti and Romagnoli, 2011). Especially, Argus system has been widely used in beach morphodynamic research in recent decades (Angnuureng et al., 2017; Balouin et al., 2013; Karunarathna et al., 2014).

Nourishment can be further evaluated based on the continuous imagery data obtained by video monitoring. Beach morphological variations and longevity of borrowed sediments are criteria to evaluate the effectiveness of beach nourishment (Liu et al., 2019; Psuty and Moreira, 1992). Factors affecting the beach nourishment longevity include parameters of nourishment projects and physical characteristics of beaches. The former mainly includes sediment characteristics, such as grain size distribution (Chiva et al., 2018; Pranzini et al., 2018; Stauble, 2007), mineral component (Pagán et al., 2018), volume scale (Basterretxea et al., 2007; Stauble, 2007) and spatial location (Karambas and Samaras, 2014) of borrowed sediments. The latter consists of wave/wind regimes (Karambas and Samaras, 2014) and the native morphological characteristics of beaches (Liu et al., 2019). Different combinations of those factors will result in different nourishment impacts on the beach.

In this study, we selected Dongsha beach, a 1.5 km-long embayed sandy beach in Zhoushan Archipelago of China, to observe its morphodynamics and evaluate the effectiveness of nourishments. An Argus video monitoring system was used to record variability of beach morphology. Beach morphological parameters including: dry beach width, shoreline displacement, dry beach area, beach orientation and rotation, and unit width volumetric change for more than a year were analyzed using Argus imagery data. Beach responses to individual storm events in five different cases were also revealed in detail. Based on morphological analysis, the evaluation of nourishment effectiveness and factors affecting nourishment longevity were discussed. Beach nourishment implications were proposed for further beach management.

2. Materials and methods

2.1. Study area

Approximately 50% of sandy coasts were regressed in erosion in China over past several decades (Third Institute of Oceanography, 2010). Thus, a large amount of beach nourishment projects have been accomplished along China's coast since the 1990s (Cai et al., 2011; Kuang et al., 2019; Luo et al., 2016). Zhoushan Archipelago is a popular tourism destination with more than 30 embayed beaches (Xia, 2014), at a location connecting the Hangzhou Bay and the East China Sea. Typhoon is a common coastal hazard affecting the Archipelago with a frequency of 6 times a year on average (Lu, 2010), which has a significant impact on beach morphology and even threatens the tourism. Dongsha beach was selected as the study area, which is located at Zhujiajian Island in Zhoushan Archipelago (Fig. 1a). It is an embayed beach bounded by headlands with a total length of about 1500 m and is a typical tourism beach. To monitor the detailed evolution of the beach, an Argus video monitoring system with six cameras (Fig. 1a and Fig. 2) was installed on 2015.

Slope of Dongsha beach varies alongshore, with measured values between 2.9% and 3.5%. The steepest transects were found at the northern beach and the southern transects were the flattest (calculated according to Guo et al., 2018). The median grain size (D_{50}) of sediments on the beach range between 0.15 mm and 0.38 mm (fine sand). The beach sediments mainly come from the erosion of coastal rocks eroded by the wind and wave (Cheng et al., 2014). There is no direct river input around the Dongsha beach (Xia, 2014). Fine-grained sediments are rich in the adjacent sea area of the Zhoushan Archipelago due to the coastal current induced southward transportation of sediments from the Yangtze River(Hu et al., 2009; Li et al., 2018), and there is a sand-mud transition located on the 5 m of isobath in the ajacent sea area of Dongsha beach (Cheng et al., 2014). There were sand dunes in the backshore of the beach, while the construction of the seawall has broken the balance of cross-shore sediment transport on the beach (Cheng et al., 2014; Guo et al., 2018), further resulting in the disapperance of dunes.

Tidal data provided by Shenjiamen tidal gauge station (29.93°N,122.3°E) shows that tides are mainly semi-diurnal and the mean tidal range is 2.6 m. Wave measurements were simultaneously obtained hourly by a wave buoy (29.8°N,122.5°E) located about 12 km offshore in 20 m depth. The offshore wave climate is characterized by low to moderate wave energy (mean H_{sig}≈0.82 m, T_{peak}≈6.2 s). Fig. 1b indicates the overall wave rose for the buoy. The prevailing waves come from the East, and direction of high waves range from Northeast to Southeast with a maximum significant wave height of 3.1 m.

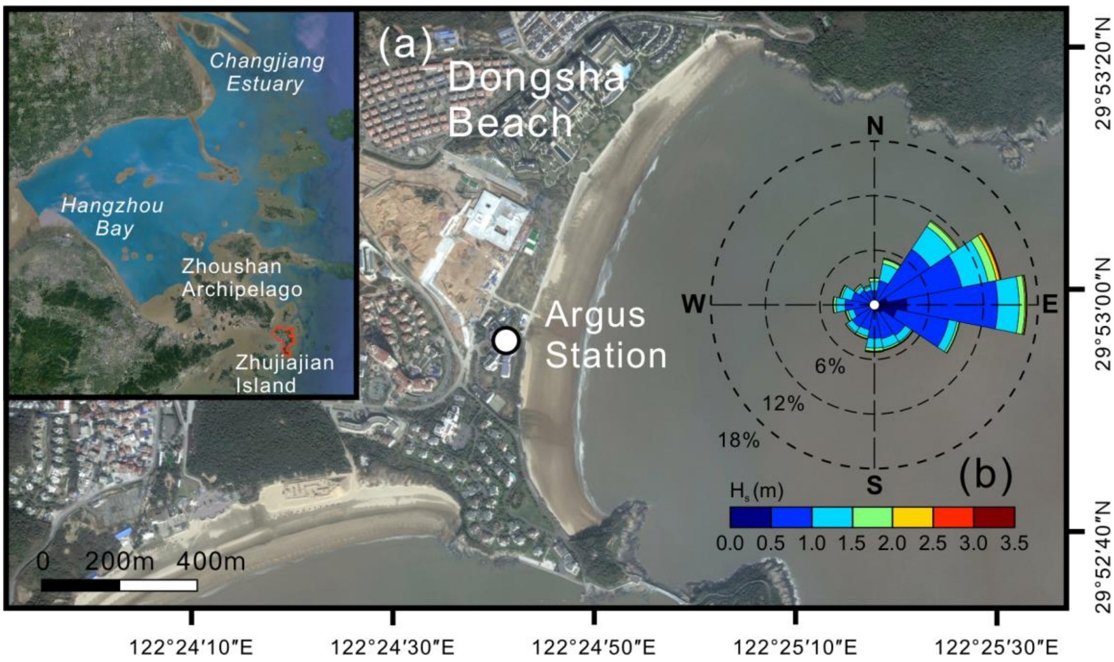

Fig. 1. Sketch of study area (a) and wave rose of the study area (b), in which H_s is the significant wave height. The satellite images obtained from Google Earth.

2.2. Beach nourishment

Seawall construction and the intensive storm events resulted in long-term erosion of Dongsha beach (Guo et al., 2018). To prevent storm erosion and widen recreational beach, beach nourishment projects were initiated in September 2016. Nourishment with irregular time, small scale and limited spatial distribution is the main beach maintenance pattern implemented on Dongsha beach, which is also common in China. The beach management department carried out 10 beach nourishment projects during 2016 and 2017 (Table 1, Fig. 2) with a total sand volume of ~52,000 m^3. The borrowed sediments were mainly placed in the area between transect 16 and transect 28, and the alongshore sand placement was limited in the area between transect 10 and transect 29 (Fig. 2) due to the restraints of transportation condition on the beach. All the nourishments have the same operations and materials which has the similar characteristics with the native sediments.

Table 1

Information of beach nourishments on Dongsha beach.

Nourishment	Time span	Sand volume (m^3)	Beach position
N1	9 Sep, 2016 - 13 Sep, 2016	~10000	Southern
N2	24 Sep, 2016	~1000	Southern
N3	29 Sep, 2016 - 30 Sep, 2016	~2000	Southern
N4	4 Oct, 2016 - 8 Oct, 2016	~5000	Southern
N5	31 Oct, 2016 - 10 Nov, 2016	~10000	Southern & Central
N6	5 Jan, 2017 - 13 Jan, 2017	~10000	Southern

N7	18 Jan, 2017 - 19 Jan,2017	~2000	Southern
N8	31 Jan, 2017 - 8 Feb, 2017	~10000	Southern
N9	18 Feb, 2017	~1000	Southern
N10	18 May, 2017	~1000	Southern

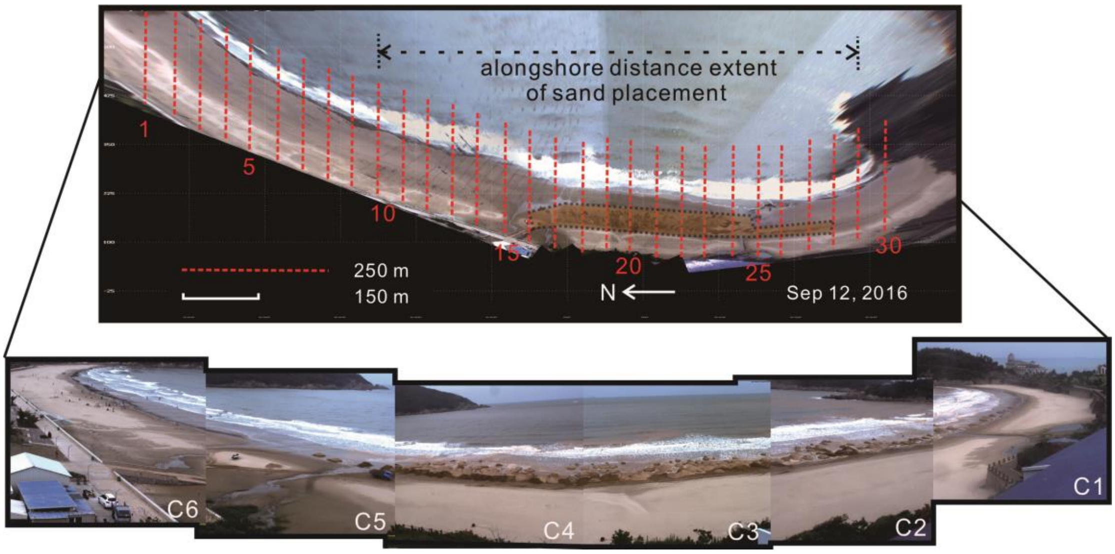

Fig. 2. Planview of Dongsha beach merged by snap images of six cameras (C1-C6) during N1 period (yellow shadow area shows the sand placement). 30 transects (red dotted lines) were set every 50 m on the beach surface from north to south (from y = 900 to y = -550), northward coordinates alongshore and eastward coordinates cross-shore with respect to Argus station are positive.

2.3. Identification of storm events

According to the method proposed by Boccotti (2000), storm events were identified when the significant wave height is greater than 1.5 times the annual average (0.82 m in this research) with duration ≥12 hours, which was based on the *in situ* data obtained by buoy. 19 storm events (S1-S19) were extracted during the study period from June 1, 2016 to July 1, 2017 (Fig. 3). Then, the wave energy storm peak E (m^2s)

was calculated as:

$$E = H_{max}^2 \cdot T_p \quad (1)$$

where H_{max} represents the maximum storm significant wave height, and T_p is the wave period at the storm peak (Archetti et al., 2016; Harley et al., 2014; Senechal et al., 2015). The storm power index P_s (m^2h) (Dolan and Davis, 1992) was also calculated:

$$P_s = H_{max}^2 \cdot D \quad (2)$$

where D is the duration of "storm conditions" in hours.

2.4. Beach morphological variation processing

Real-time and continuous imagery was extracted from the Argus video monitoring system, with a frequency of 2 Hz in 10-min bursts every daylight half hour, including Snapshot images, Timex images, and Variance images with a resolution of 2448×2048 pixels. To validate the accuracy of the beach morphology obtained by the Argus system, a field survey was carried out at Dongsha beach on May 4, 2016 using RTK GPS, and a total of 41 ground control points were measured. The results showed that the average vertical error is 0.145 m, and more details were introduced by Guo et al.(2019).

The images from June 2016 to July 2017 were selected from the image dataset for beach nourishment evolution analysis. All images of the months when the storm events and sand nourishments were concentrated (September 1, 2016 - February 28, 2017) were selected, and only partial images of the rest months were selected. Based on the merged images of Argus cameras, 30 transects were set every 50 m on the beach from north to south (from y = 900 to y = -550, Fig. 2). Then unit width volume change and shoreline position of each transect were calculated in Argus Intertidal Bathymetry Mapper module (Aarninkhof et al., 2003).

Dry beach width (*DBW*) can be calculated by shoreline position (Harley et al., 2014) as follows:

$$DBW_i = X_{shoreline,i} - X_{seawall,i} \tag{3}$$

where $X_{shoreline,i}$ is the position of shoreline obtained from Argus at transect i, and $X_{seawall,i}$ represents the position of the seawall at transect i.

The alongshore-averaged dry beach width ($\overline{DBW}$, Harley et al., 2014) for the beach was also calculated:

$$\overline{DBW} = \frac{1}{N}\sum_{i=1}^{N} DBW_i \tag{5}$$

where the number of transects N is 30.

Dry beach area (*DBA*) is an important parameter for the beach management, which determines the space available for beach tourists. *DBA* can be approximately calculated according to Harley et al. (2014) as:

$$DBA \approx \Delta S \sum_{i=1}^{N} DBW_i \tag{6}$$

where ΔS represents alongshore spacing between transects (ΔS=50 m).

Changes in shoreline position are often in response to sediment supply, sea level rise, climate change, and human intervention (Karunarathna et al., 2018). In order to describe the response of Dongsha beach over the study period, the mean distance Δx (distance between shoreline of Jun 1, 2016 and later days in cross-shore direction during the study period) was calculated according to Archetti et al. (2016) as:

$$\Delta x = \frac{\Sigma_i d_i}{n} \tag{7}$$

where i is the transect (i=1-30), d_i is the distance between shorelines in cross-shore direction at each transect and n is the transect number (n=30. The previous field investigation in Dongsha beach showed that 30 transects could represent the whole beach in this study).

Shoreline variability is additionally influenced by beach rotation on embayed beaches (Short and Masselink, 1999), and beach rotation is a key process for understanding the morphodynamic of embayed beaches (Ojeda and Guillén, 2008). Beach orientation and rotation were calculated according to Ojeda and Guillén (2008) in this study, positive (negative) rotation value corresponds to a more clockwise (counter-clockwise) orientation. A degree change in beach orientation means a 26 m shoreline change of the two extremities in Dongsha beach.

Based on the morphological variation of the beach, the longevity of each nourishment could be calculated. The longevity in this study represents the lasting duration of borrowed sediments, it is the time duration when the mean unit width volume is larger than that before the nourishment.

3. Results

3.1. Storm characteristics

A total of 19 storm events (S1-S19) were extracted during the study period from June 1, 2016 to July 1, 2017 (Fig. 3). H_{max} and T_p, D, storm direction θ_p (wave direction at the storm peak with respect to north), E and P_s were summarized for all the storm events. The strongest storm event (S3) occurred in September 2016 with a P_s of 1157.76 m^2h, which is identified as significant severity ($P_s > 500$ m^2h) according to Mendoza et al. (2011). Overall, four storm events over the study period were categorized as significant, and three as moderate ($251< P_s \leq 500$ m^2h), with the remaining 12 events recognized as calm ($P_s \leq 250$ m^2h) (Fig. 3c). As shown in Fig. 3, storm events were predominantly intensive in autumn (September - November), with a minority of calm events occurring within the winter months (December - February). It can be seen that peak direction of these storm events mainly distribute between north and east, with a small number of storm events having a south direction.

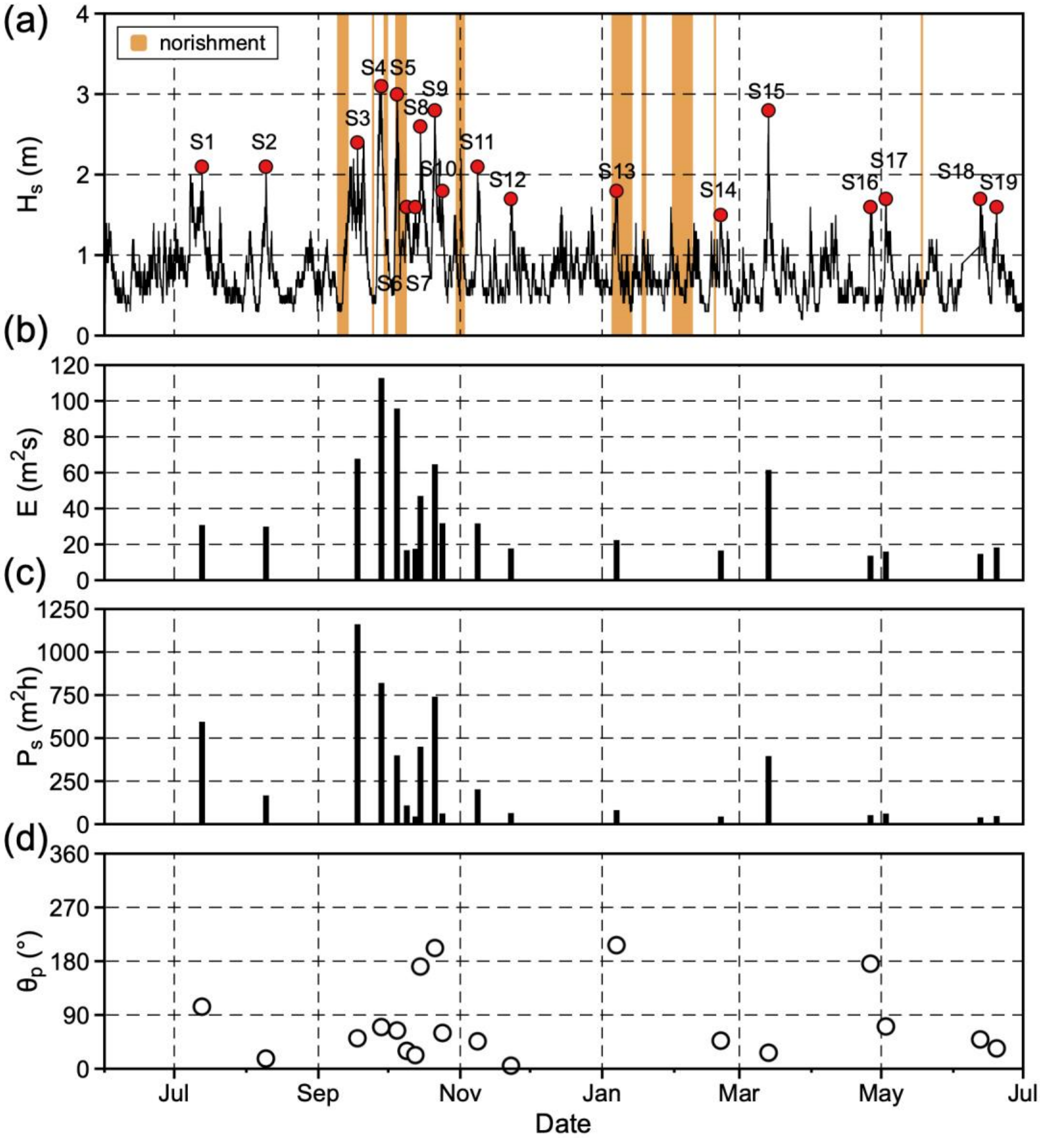

Fig. 3. Significant wave height (H_s) over the study period (**a**), storm energy E (**b**), storm power index P_s (**c**) and the peak direction θ_p (**d**) of each storm event. Red circles represent the peak significant wave heights during storm events, while the dark yellow shadow areas show the time span of each nourishment project.

3.2. Morphological variation of Dongsha beach

Averaged *DBW* at each transect was quantified for the beach over the study period as shown in Fig. 4. Since some transects (1-10 and 27-30) are not perpendicular to the shoreline (Fig.2), calibrations of *DBW* at those transects were done (Fig. 4). Generally, the northern part of the beach had the narrowest *DBW* while the middle part of the beach had the widest *DBW* over the study period. *DBW* of Dongsha beach ranges from 76 m (transect 8) to 138 m (transect 17). It is worth noting that the beach tourism facilities are located on the area with larger *DBW* than the average (area between transect 13 and transect 23), which is also the tourist-dense area.

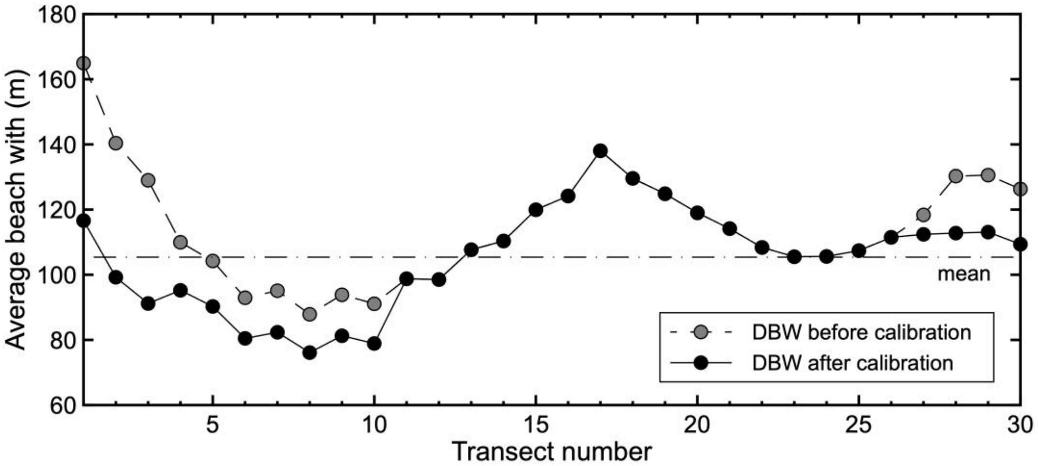

Fig. 4. Averaged dry beach width at each transect over the study period.

The majority of Δx values range generally between -25 and 20 m over the 13 months (Fig. 5a). There were a few higher positive values (from 20 to 49 m) came after nourishments, and a few lower values occurred commonly in the storm-intensive period. The largest shoreline retreat (-42.6 m) came after the last storm event during the storm-intensive period, while the largest advance (49 m) occurred in the latter part of study period without storm event. Temporal distribution of Δx values over the whole study period suggests that shorelines retreated during autumn and winter while advanced in spring and summer. It is worth noting that a lot of peak values occurred after nourishment projects.

Temporal evolution of *DBA* has the similar pattern with *Δx* (Fig. 5b). *DBA* values range from 108,848 m^2 to 241,216 m^2, with an average of 163,635 m^2 over the whole study period. Dry beach area values smaller than the average also mainly occurred in autumn and winter when storm events were intensive.

The variation pattern of beach orientation is shown temporally in Fig. 5c. Generally, abrupt variations in the beach orientation (caused by storm events or nourishments) were always followed by gradual recoveries to 19.5° (the average beach orientation). Beach rotation varied between a minimum value of -2.63° and a maximum of 0.67°. Clear rotation was identified as counter-clockwise after March, 2017 when storm events were sparse.

The unit width volumetric change highly depends on the alongshore position with an average of -60.4 m^3/m and various patterns are present at the northern (transect 1-10), middle (transect 11-20) and southern (transect 21-30) beach (Fig. 5d). It is shown that the largest positive volumetric change occurred on transect 29 (488 m^3/m) and the largest negative on transect 9 (-460 m^3/m). The overall variation of unit width volume indicates a transition from erosion in the north to accretion in the south under calm conditions, while the erosion of northern beach is more severe than the southern beach after storm events. Averaged unit width volumetric changes are 14.4 m^3/m, -59.71 m^3/m, -0.23 m^3/m, and 139.97 m^3/m in summer, autumn, winter and spring, respectively, suggesting an seasonal variation pattern: slight accretion-severe erosion-slight erosion-strong accretion. Most of the obvious accretion (erosion) peak values commonly correspond to nourishments (storm events). In addition, the borrowed sediments were mainly placed between transect 16-28 (Fig. 2), while the distribution of obvious accretion peaks commonly ranged from transect 15-30, indicating the nourishment impact on beach.

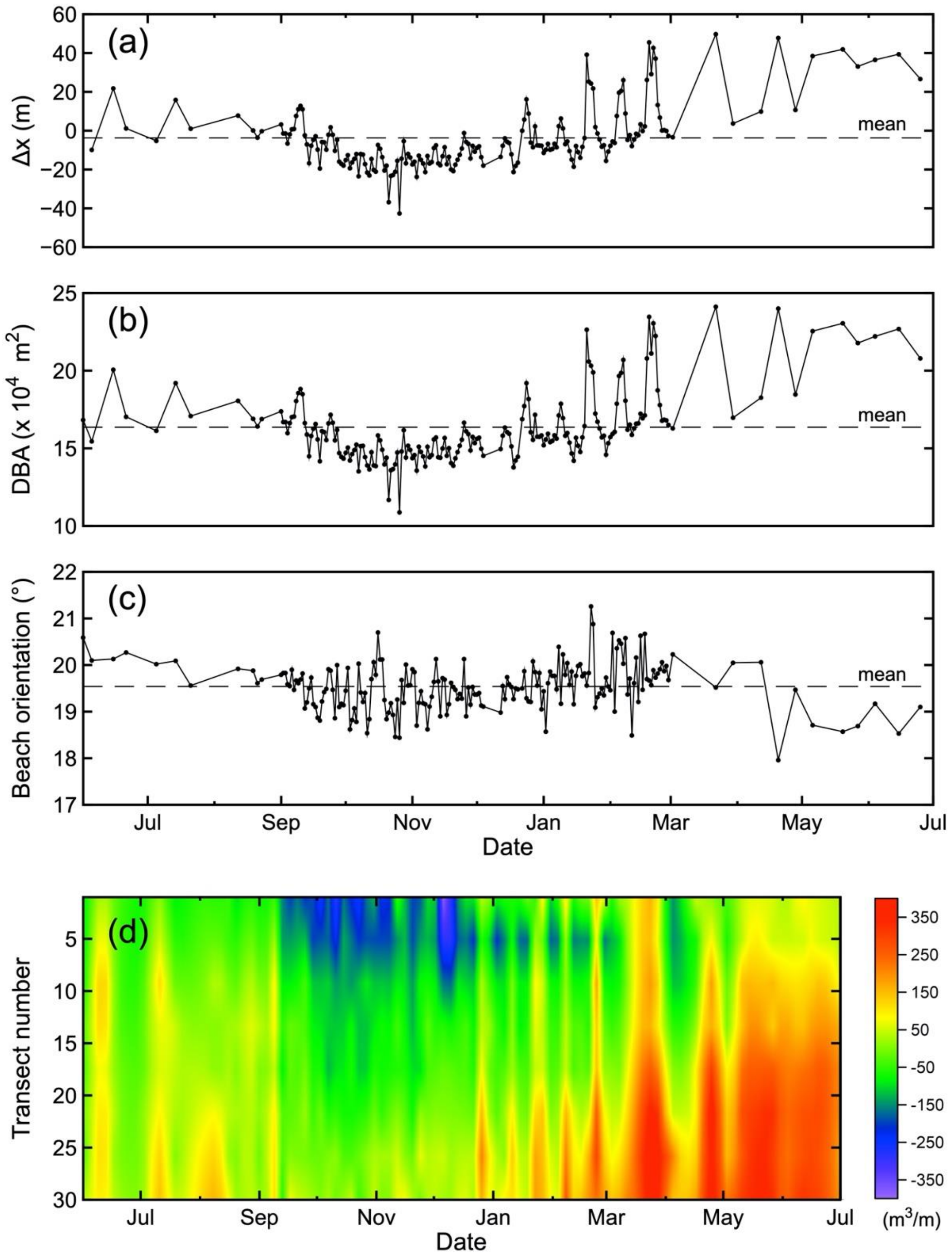

Fig. 5. Distribution of shoreline displacement (Δx) (**a**), dry beach area (*DBA*) (**b**), beach orientation (**c**) and unit width volumetric change (ΔV) **(d)** of Dongsha beach over the study period.

3.3. Beach responses to individual storm events

There were 19 storm events over the study period with various impacts on Dongsha beach. Table 2 shows the Δx, change in dry beach area (ΔDBA), unit width volumetric change (ΔV), and beach rotation during each storm event. Since most of the storm events occurred along with beach nourishments, beach responses to individual storm events are different and complex. According to the relationship between the occurrence time of the storm events and nourishments, we divided beach responses (to individual storm events) into five cases (Table 2). In Table 2, we chose the nourishment event with the nearest occurrence time in depicting the occurrence time of each storm event. E.g., if S3 occurred in 1 day after N1 and 4 days before N2, then the occurrence time of S3 in Table 2 would be recognized as 1 day after N1.

Case1: Without nourishment

Case1 includes the storm events occurred before the beginning of nourishment projects (S1 and S2). The two storm events with moderate H_s in Case1 produced none erosion but advances in shoreline (Table 2). In the meanwhile, beach rotation is not significant in this case.

Case2: Nourishment occurred before storm event

Case2 consists of the storm events occurred after nourishments (S3, S4, S6, S7, S8, S9 S12, S14 and S15). S3 has the longest duration with the highest P_s of 1157.76 m^2h, but did not cause the most severe erosion. While S4 with the second higher P_s, induced the severest beach erosion of 79.16 m^3/m and 15.83 m retreat in shoreline (Fig. 3 and Table 2). Different beach responses to S3, S4, S9 and S14 may correlate with sand volume scale of nourishment projects. S3 and S9 occurred after two large sand nourishments (~10000 m^3 and ~5000 m^3, respectively), while S4 and S14 occurred after two small sand nourishments (~1000 m^3). Although nourishments implemented before storm events can compensate for the sediment loss, the beach still lost a lot of sediments after those four storm events. However, storm events identified as calm (S6, S7, S8, S12, S15) occurred after nourishments did not cause erosion. The results of this case show that nourishments before storm events can be effective only when the storm energy is low. Beach rotation varied significantly in this case without regular pattern. In the meanwhile, consecutive storm events did not show cumulative erosion in this case.

Case3: Nourishment occurred at the same time with storm event

There were two pairs of storm events and nourishments happened at the same time: N5 and S11, N6 and S13. The two storm events in this case showed no erosion but accretion with the same volume (~5000 m^3) nourishments (Table 2). The different Δx corresponds well to the different storm energy in this case: the higher the storm energy is, the larger the shoreline displacement is.

Case4: Nourishment occurred after storm event

Three storm events (S5, S10, S17) in this case did not cause any erosion (Table 2). Especially, S5 with a H_{max} of 3 m did not cause shoreline retreat, which might due to the compensation of N5. The result shows that nourishments in this case compensated the sediment loss effectively.

Case5: Long interval between storm event and nourishment

S18 and S19 occurred at the end of study period. S18 made no erosion but a 0.64° counter-clockwise beach rotation, while S19 caused a 12.75 m retreat in shoreline with a 0.57° clockwise beach rotation. Although the two storm events in this case had the similar E and P_s (Fig. 3), the impacts vary. Furthermore, the calm storm S19 caused significant erosion of the beach, and its erosion degree even exceeded S3, S9 and S14, indicating that the borrowing sediments before the storm event has compensated for the beach loss during those storm events. When there is no borrowed sediment to make up for the loss, a calm storm event like S19 can cause a shoreline retreat of more than 10 m.

Comparing the above five cases, we could get the results that the storm erosion can be fully compensated by sand nourishment no matter when the nourishment project occurred for storm events identified as calm ($P_s \leq 250$ m^{2}h). Regarding moderate ($251 < P_s \leq 500$ m^{2}h) and significant ($P_s > 500$ m^{2}h) severity storm events, borrowing sediments timely after the storm event is the most effective way to maintain Dongsha beach. Although the beach did not show significant erosion when the storm events and nourishments occurred simultaneously, the nourishment effect was not so significant as in Case 4. Nourishments in Case1, Case2, Case3 and Case4 all have compensated for the storm erosion. However, the sediment loss caused by storm erosion cannot be compensated in Case5 due to the long interval between storm events and nourishments, which made the calm storm (e.g. S19) cause severe erosion.

Table 2

Morphological variations of Dongsha beach after individual storm events during the study period.

Case	Storm	H_{max} (m)	Occurrence Time (refer to Fig. 3)	ΔV (m^3/m)	Δx (m)	ΔDBA (m^2)	Rotation (°)	Recovery period (day)
1	S1	2.10	without nourishment	105.16	21.03	30704	0.07	/
1	S2	2.10	without nourishment	33.80	6.76	9862	0.37	/
2	S3	2.40	1 day after N1	-36.85	-7.37	-10839	0.42	no recovery
2	S4	3.10	2 days after N2	-79.16	-15.83	-23113	-0.33	no recovery
2	S6	1.60	1 day after N4	9.66	1.93	3812	-1.49	/
2	S7	1.60	4 days after N4	34.79	6.96	8455	1.16	/
2	S8	2.60	6 days after N4	26.28	5.26	7704	0.42	/
2	S9	2.80	14 days after N4	-37.82	-7.56	-9455	-1.66	no recovery
2	S12	1.70	7 days after N5	41.53	8.31	11988	-0.19	/
2	S14	1.50	2 days after N9	-41.78	-8.36	-12327	0.06	32
2	S15	2.80	21 days after N9	265.49	53.10	78313	-0.71	/
3	S11	2.10	at the same time with N5	3.65	0.73	909	0.14	/
3	S13	1.80	at the same time with N6	58.82	11.76	16375	0.63	/
4	S5	3.00	1 day before N4	2.98	0.60	1928	-1.17	/
4	S10	1.80	7 days before N5	36.71	7.34	10651	0.33	>13
4	S17	1.7	14 days before N10	138.85	27.77	40807	-0.76	/
5	S16	1.6	60 days after N9	-185.52	-37.1	-55230	1.51	24
5	S18	1.60	27 days after N10	14.54	2.91	4811	-0.64	/
5	S19	1.70	31 days after N10	-63.75	-12.75	-19046	0.57	>7

4. Discussion

4.1. Evaluation of beach nourishments

The effectiveness of sand nourishments in this study has been evaluated in terms of their abilities to meet the project goals, which were to prevent storm erosion and widen the recreational beach. As for preventing storm erosion, 12 storm events with none erosion and 3 storm events recovered within several days were observed (Table 2). However, seawall constructed on the beach and the intensive storm events resulted in long-term erosion. Guo et al. (2018) found that Dongsha beach didn't recover from a storm event during 2014 and 2015 without sand nourishment, suggesting that the nourishment projects in this study are successful in preventing storm erosion. In terms of widening the recreational beach, all the nourishment projects recorded increases in $\overline{DBW}$ and DBA. The maximum increases in $\overline{DBW}$ and DBA observed over the 10 nourishment periods are 50.18 m and 74755 m^2, respectively (Table 3). The relatively short duration of this study limited the assessment of longer-term benefits of the nourishments, the results only suggest that nourishments on Dongsha beach were successful in achieving these two goals over a year video monitoring.

Although nourishment on this beach have met the project goal, beach nourishments can often cause large-scale nearshore disturbances that affect the balance of alongshore and cross-shore sediment transport (Dean, 1983). In general, the sediment transport on the beach without human intervention is mainly controlled by the hydrodynamic processes(Wiggins et al., 2019) and beach characteristics (Oliveira et al., 2017). Sediment transport on the beach can be more complex with human activities

(Duvat et al., 2019; Luo et al., 2016). Cheng et al.(2014) found that significant erosion in summer and accretion in winter were the main seasonal variation pattern of Dongsha beach without nourishment, while the beach accreted in summer months with nourishment in this study. In addition, the distribution of erosion/ accretion on Dongsha beach also varies with and without nourishments. The beach used to be eroded in the southern beach (Cheng et al., 2014), while significant accretion can be seen on the southern beach with nourishment. The change of seasonal variation pattern and erosion/accretion distribution on this beach may be related to the nourishment impacts, and further study on sediment transport needs the support of sediment information.

Besides, longevities of the borrowed sediments in this study can only be considered short compared with beach nourishments in Europe countries (Hamm et al., 2002; Hanson et al., 2002) and the USA (Leonard et al., 1989). Generally, the larger scale of volume produced the better effectiveness on both morphological variation and longevity of borrowed sediments (Table 3). In the meanwhile, beach nourishment with the largest volume did not always cause the largest increase in $\overline{DBW}/DBA$ and the longest longevity due to the intensive storm events. For example, N1 with about 10000 m^3 borrowed sediments but only has a 3-day longevity. Although the borrowed sediments limited in the tourist-dense area (Fig. 6) could meet the recreational need, counter-clockwise rotation was identified after 9 nourishment projects. The advances in southern shoreline resulting from the limited sand placement of borrowed sediments might have contributed to the counter-clockwise rotation in this study. Long-term erosion rates and its spatial gradient is a design guide for the beach nourishment project (Kaczkowski et al., 2018), which the spatial location of borrowed sediments should depend on. Limited alongshore position of sand placement and the implement timing when storm events were intensive are the main causes of those inefficiencies in the nourishments in this study.

Table 3

Beach nourishment longevity and morphological variations of Dongsha beach.

Nourishment	Sand volume (m^3)	Longevity (days)	$\Delta\overline{DBW}_{max}$ (m)	ΔDBA_{max} (m^2)	Beach rotation(°)
N1	~10000	3	5.20	7631	-0.18
N2	~1000	1	3.83	5551	-1.06
N3	~2000	2	3.32	3484	-0.47
N4	~5000	7	7.31	10198	0.09
N5	~10000	59	32.96	47496	-1.39
N6	~10000	8	16.07	24680	-0.27
N7	~2000	11	50.18	74755	-0.26
N8	~10000	18	41.56	61124	-0.98
N9	~1000	7	43.25	63539	-0.61
N10	~1000	3	3.45	5010	-0.15

Note: $\Delta\overline{DBW}_{max}$ is the max change in $\overline{DBW}$; ΔDBA_{max} is the max change in DBA.

Fig.6. A snap image taken by the Argus video monitoring system of sand being placed on the beach (Image date: 12/09/2016 08:00 GMT).

4.2. Factors affecting nourishment longevity

The majority of nourishment projects have a longevity of several years in USA (Leonard et al., 1989) and Europe countries (Hamm et al., 2002; Hanson et al., 2002). However, in this study, the longevity of borrowed sediments can only last for several days to tens of days (Table 3), which correlates well with the wave regime of the study area. Frequent storms with high significant wave heights make the sediments difficult to preserve (Table 2).

Besides, characteristic of the borrowed sediment can influence the longevity. The larger volume scale of the borrowed sediments can often causes the longer nourishment longevity (Cooke et al., 2012; Hamm et al., 2002; Hanson et al., 2002; Leonard et al., 1989), and the different beach responses to individual storm events in Case2 showed the similar result. Previous studies also showed that grain size distribution (Chiva et al., 2018; Pranzini et al., 2018; Stauble, 2007), mineral component (Pagán et al., 2018) and spatial location (Karambas and Samaras, 2014) can affect the nourishment longevity, which could not be obtained in this study due to the data limitation.

It is worth noting that different occurrence time of nourishments is also a significant factor affecting the longevity. Generally, nourishments occurred timely after storm events have longer longevity in this study (Table 3). Storm events with high significant wave heights can take away a great number of sediments on the beach (Coco et al., 2014; Harley et al., 2014; Qi et al., 2010; Scott et al., 2016; Senechal et al., 2015), and borrowed sediments might lose more easily than the native sediments during storm events (Seymour et al., 2005). Nourishments implemented timely after storm events can not only avoid strong hydrodynamic conditions, but also quickly compensate for losses caused by storm erosion. Thus, occurrence time can have significant impacts on the longevity of nourishment implemented on this beach.

4.3. Implications of nourishment management

Serious beach erosion is observed globally due to the climate change with sea level rise and more frequent and severe storms (Castelle et al., 2007; Houston and Dean, 2014; Qi et al., 2010; Scott et al., 2016; Smith et al., 2014). Under this circumstance, there are growing numbers of beach nourishments to meet increasing public requirements (Kuang et al., 2011). This kind of nourishment coupled with the consideration of nourishment occurrence time can be an effective way to restore the beach exposed to frequent storms. Also, placing borrowed sediments should consider the erosion distribution pattern to achieve better efficiency. Since the nourishment projects were implemented with the same operations and cross-shore position in this study, we can only suggest that placing the borrowed sediments on the erosion area alongshore but not the limited easy-access area might cause better efficiency. Many studies have predicted the evolution of different kinds of sand nourishments by numerical simulation (Kuang et al., 2011; Pan, 2011), which may make the sand nourishment more effective. Although the applicability of this work may be limited, our results can provide a reference for beach management since this kind of nourishment is common in the local area. Besides, this research can also provide a case study for protecting eroded beaches around the world, but the implementation on other beaches needs to consider their respective characteristics and local storm condition.

5. Conclusions

Due to the increasing storm erosion of beaches, beach nourishment has become a wide-used measure. Argus video monitoring system is an effective means to monitor continuous storm-induced erosion of beaches and corresponding nourishment effectiveness. In this case study of Dongsha beach, video-derived morphological parameters of the beach were analyzed over a year, and the following main conclusions are obtained.

Seasonal morphological variation related to storm-intensive period existed on this beach. Shorelines retreated during autumn and winter when storms were intensive, while advanced in spring and summer, with a lot of bulges occurred after nourishment projects. Abrupt variations in the beach orientation were always followed by gradual recoveries to the average, while continuous counter-clockwise rotation occurred after March, 2017 when storm events were sparse.

The implementation of nourishment to prevent storm erosion on embayed beaches should consider the occurrence time, borrowing sediments timely after the storm event is the most effective way to compensate for storm erosion in this study. Unsuitable timing and alongshore position of these nourishments might cause short longevity and beach rotation. This study can provide a reference for sand nourishments on eroded beaches, enabling beach management decisions to be implemented reasonably.

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Declaration of interest

The authors report no conflicts of interest.

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