AN EXPERIMENTAL FIELD STUDY USING A FLEXIBLE HIGH-STRENGH NET BREAKWATER FOR SHORE PROTECTION

Chyan-Deng Jan[1], Ta-Hsiung Peng[1], Shih-Jen Huang[2], and Hung-Chu Hsu[3]

Key words: coastal erosion, flexible device, high strength net, breakwater, shoreline protection.

ABSTRACT

Shorelines are subjected to severe erosion because of the action of perennial waves. Although traditional rigid structures have historically been constructed as coastline protection devices, they do not always work effectively, and certain coastal areas such as Shuang-Chun beach in Tainan, Taiwan, continue to experience serious erosion due to damaged and ineffective structures. The necessity of shore protection has been recognized in recent years, and alternative solutions are being sought. In this paper, we present a high-strength-net device that acts as a flexible breakwater to reduce wave energy, induce sediment deposition, and offer a more economic and innovative method for coastline protection. The device is composed of concrete posts, high-strength nets, and triangular gabions filled with stones and covered with recycled vehicle tires. Three high-strength-net breakwaters have been installed at Shuang-Chun beach since 2009 as an experimental field study to investigate both the effect of sediment deposition and the stability of the proposed breakwaters. Results show that these devices have the strength and stability to withstand the impact of severe wave action, and that they act effectively as sediment retainers, thereby preventing coastal erosion.

I. INTRODUCTION

Beaches become eroded when they lose more sediment along their length, or off the shore, than they receive from various sources. Coastal related disasters such as tsunamis, cyclones, and floods have increased in both frequency and intensity of their occurrence in recent years. The influence of sea level rise in relation to global warming is a major concern [23], and climate change has resulted in a significant increase in the probability of shoreline erosion [22]. Effective control measures are therefore needed to protect shorelines. Coastal structures such as rigid seawalls, detached breakwaters, submerged reefs, and groins have traditionally been used to reduce coastal erosion [1, 8, 9, 13, 19, 20]. These rigid protection structures are mainly constructed using concrete, and are now considered to be non-environmentally-friendly protection devices. The recent EU-funded DELOS project (www.delos-project.org) is based on extensive physical modeling and field experiments, and advocates the use of low-crested structures (LCS). Nowadays, an increasing interest in environmental concerns has provoked coastal managers to prefer the use of submerged breakwaters. These provide advantages such as enabling enhanced water circulation, delivering a reduced visual impact, and providing an environment for the existence of biodiversity [3, 10, 11,18].

The construction of rigid protection structures is usually expensive and time consuming, and such structures are not always effective in protecting the coast against extreme events such as typhoons. The demand for alternative solutions has therefore led to the development of innovative products [2, 4, 6, 12, 14]. One such product is the high-strength-net flexible breakwater described in this paper. It is used for erosion control, and is able to withstand the harsh conditions of extreme events, thereby providing coastal engineers with an alternative compliant solution, and enabling more effective, economic erosion control whilst maintaining a more user-friendly amenity.

The shoreline of Taiwan has a total length of approximately 1,100 km, and exhibits a various coastal geological features such as sand, rock, gravel, cliffs and reefs. [21]. Almost half of the shoreline suffers from erosion, and this has become increasingly serious in recent years, affecting recreational activities and tourism as well as agricultural and community life. As already stated, current protection is provided by hard and rigid structures. The rate of beach erosion depends mainly on the rate of long-shore sediment transport to the up-coast area, and on the rate of sediment supply from the associated river system.

Paper submitted 11/01/11 ; revised 01/06/14 ; accepted 02/06/14 . Author for correspondence: Chyan-Deng Jan (e-mail: cdjan@mail.ncku.edu.tw).

[1]*Department of Hydraulic and Ocean Engineering, National Cheng Kung University, Tainan, Taiwan, R.O.C.*

[2]*Department of Marine Environmental Informatics, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.*

[3]*Tainan Hydraulics Laboratory, National Cheng Kung University, Tainan, Taiwan, R.O.C.*

Shuang-Chun beach in Tainan County (Fig. 1) has suffered extensive shoreline erosion (Fig. 2). According to the summary report of a Shung-Chun field investigation by the Taiwan Water Resources Planning Institute [17], significant wave heights are 0.25–1.25 meters, and significant wave periods about 7.5–10.5 seconds. However, in the winters of 2002 and 2003 the main wave direction was WNW, significant wave heights were about 0.5–1.75 meters, and significant wave periods were about 5.0–8.0 seconds; in the summers of these years the main wave direction was WSW (these wave conditions do not include conditions during typhoons when conditions are more severe). Near the Shung-Chun coast study area there is a buoy station, located at Qigu (see Fig. 1 for location) that conducts wave measurements. Set-up and managed by the Coastal Ocean Monitoring Center, National Cheng Kung University, Taiwan, it is located near the southern part of Shuang-Chun beach at a latitude of 23.0956° N and longitude of 120.0083° E. During Typhoon Linfa in June 2009, the wave measurements recorded by the buoy station showed a significant wave height H_s of about 11.7 meters, a significant wave period T_s of about 10.6 s, and a main wave direction θ_m, at about 236°. During Typhoon Morakot in August 2009, the buoy station recorded H_s = 8.3 m, T_s = 8.2 s, and θ_m = 292°; during Typhoon Fanapi (September 2010), H_s = 6.5 m, T_s = 7.7 s and θ_m = 270°; and during Typhoon Nanmadol in August 2011 recorded H_s = 3.9 m, T_s = 7.0 s, and θ_m = 236°. Shuang-Chun beach has subjected to severe erosion because of the action of perennial waves.

Fig. 1. Field experiment site on Shuang-Chun beach, Tainan (indicated by an oval).

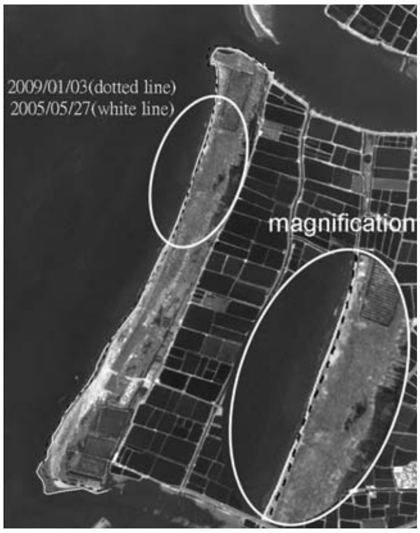

Fig. 2. Shoreline comparison based on satellite images taken on 2005/5/27(white line) and 2009/1/3(black-dotted line). We chose the same low tide conditions, and the satellite passed over the area at the same time.

Persistent erosion has caused the shoreline to recede to the seawall. Traditional rigid or compliant structures, such as offshore submerged breakwaters, seawalls, and artificial oyster booths were used to protect the shoreline, but failed to work effectively [16]. Previous researchers have proposed flexible devices as alternative beach protection methods to the traditional rigid or compliant structures, but unfortunately these have not yet effectively protected the shoreline. Hong et al. [5] showed that a flexible wire-net retaining device can reduce the moving energy of debris flow more effectively than traditional structures, and Hsu et al. [7] illustrated that sediment-laden water, or debris flow passing through a flexible wire-net device, will lose its momentum and result in sediment deposition. Therefore, to tackle the problem of coastal erosion, a high-strength-net flexible breakwater is proposed in this study to reduce wave energy and enable sediment deposition along the coast. Under a 3-year project supported by the National Science Council in Taiwan, three innovative high-strength-net flexible breakwater units (in total) were installed at Shuang-Chun beach as an experimental field study on coastal protection. The high-strength-net breakwaters consist predominantly of concrete posts, triangular gabions filled with stones, and flexible high-strength nets (such as wire net or nylon nets). Each high-strength-net breakwater unit is 50 m long and 2 m high. The first high-strength-net breakwater unit was installed in June 2009, and the other two breakwater units were installed in May 2010 and April 2011, respectively, and their total length is 150 m. They have now been subjected to several severe typhoons, and have demonstrated that they are strong and stable enough to remain intact even under extreme wave conditions. In addition, results show that these flexible breakwaters have effectively retained sediments and enabled deposition in the coastal zone. A comparison of the topographic measurements conducted before (May 17, 2009) and after (September 25, 2011) the installation of the breakwaters shows that the average deposition depth over this period was approximately 0.80 meters. This paper gives an outline of the contemporary design and specification of the flexible breakwaters, and presents the results of the three-year field experiment, in order to illustrate the performance of the innovative design. After the end of the 3-year project in 2011, these breakwaters have remained in existence and continue to work in the study area. Additional measurements of the beach elevation have also been conducted since the end of the project period to continuously check the performances of the installed three breakwaters.

II. FIELD STUDY AREA

Shuang-Chun beach (Latitude 23°19′16.86″ N; Longitude 120°06′53.79″ E), an area of outstanding natural beauty and home to a mangrove ecosystem preservation area, is located between the mouths of the Ba-Zhang River and the Zi-Shui River at the northern end of the Tainan coast. The beach is sandy, and according to the sampling analyses in this study, sediment in the study area has an average median diameter (d_{50}) of 0.23 mm (0.20 mm < d_{50} < 0.26 mm), average effective size (d_{10}) of 0.13 mm (0.10 mm < d_{10} < 0.16 mm), and average uniform coefficient ($C_u = d_{60}/d_{10}$) of 1.80 (0.16 < C_u < 0.20). This beach has suffered severe sediment erosion, and submerged breakwaters, beach nourishment and artificial oyster booths, which were installed to protect the shoreline from erosion, have not been effective in preventing beach erosion. According to Yang et al. [21], the shoreline had shifted onshore by more than 10 m between 1993 and 2002, causing the felling of a large number of beefwood trees.

Two satellite images (taken on 2005/5/27 and 2009/1/3) were used to compare and investigate the status of coastal erosion, as shown in Fig. 2. We chose the same low tide conditions, and the satellite passed over this area at the same time. The black-dotted line in this picture shows the shoreline on 2009/1/3, and the white line shows the shoreline on 2005/5/27. The most severe erosion is seen to have occurred on the northern shoreline, where the coast is seen to have retreated by up to 13.5 meters. An historical evaluation of coastal morphology revealed that one third of the northern section of the Shuang-Chun coastline had suffered shoreline retreat between 1993 and 2009. Based on data provided by a long-term field investigation of hydrodynamic characteristics, the Shuang-Chun coast can be classified as a moderate wave energy coast and has a micro-tidal condition [21]. However, significant wave heights along the coast can reach between 3 and 11 m during strong typhoons, as mentioned in the previous section, or due to freak waves (i.e. rogue waves). The Water Resources Agency in Taiwan permitted the use of hard structures (such as groins and offshore breakwaters), and of soft solutions (such as beach nourishment, geotextile sand containers, oyster booths, and porous cylinder groups) in the control of beach erosion, but unfortunately many of these have been damaged by storms and high waves, and can no longer retain sediments. We therefore introduce a high-strength-net breakwater as an alternative method and present the result of a three-year field experiment study for the control of beach erosion at the Shuang-Chun coast.

III. DESIGN OF THE FLEXIBLE BREAKWATER

The high-strength-net breakwater consists predominantly of concrete posts, triangular gabions filled with stones, and flexible high-strength nets, as mentioned earlier. The high-strength nets (such as wire/nylon nets) are used to reduce wave energy and to help sediment deposition in the coastal zone. These nets are placed in between two triangular gabions filled with used vehicle tires (with diameters of 0.58 m), which act to hold the flexible nets with the help of concrete posts (as illustrated in Fig. 3). A detailed drawing of the innovative breakwater device, including a top view of the upper part and the side view, is shown in Fig. 4. Each high-strength-net breakwater unit is approximately 50 m long and 2.2 m high. The total length of the three flexible breakwaters is 150 m. The

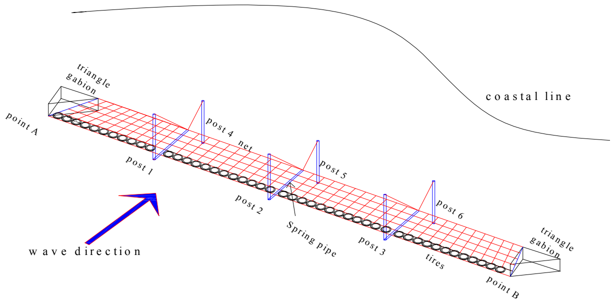

Fig. 3. Schematic diagram of a high-strength-net flexible breakwater.

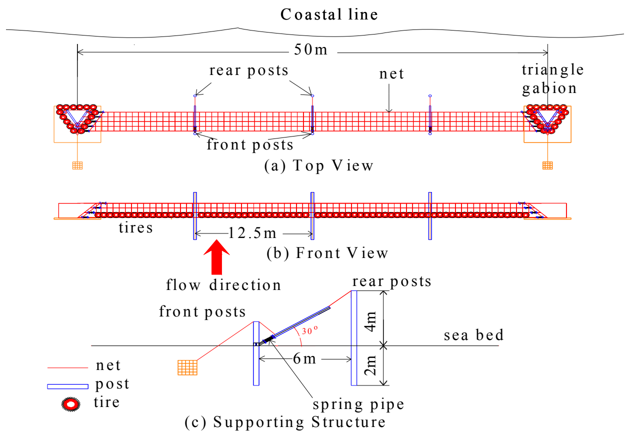

Fig. 4. Setup of the high-strength-net flexible breakwater used in the experimental field study.

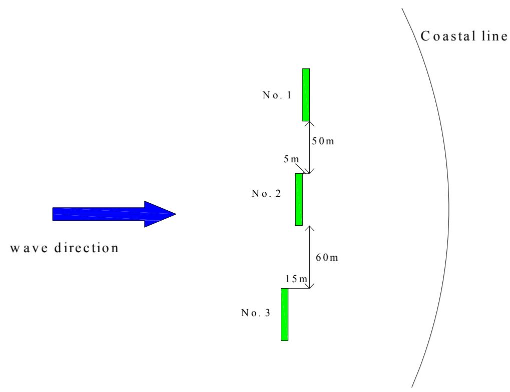

Fig. 5. Layout of three flexible devices: the second device was moved 5 m further into the sea than the first, and the third one moved 15 m.

layout of the tree breakwater devices is shown in Fig. 5.

1. Concrete posts with steel spring-pipes

Front and rear concrete posts with tilting spring-pipes are used to hold the flexible nets (shown in Fig. 6: assembling the posts). Each set of posts is comprised of two concrete posts and a tilting stainless steel spring-pipe, and the sets are situated 12.5 m apart. One end of the tilting spring-pipe is supported by a spring attached to the front post, and the other is attached to the rear post by a stainless steel wire. The spring-pipes are inclined at an angle of about 30°, at a height from the sea bed to the pipes of approximately 2.2 meters.

2. Triangular gabions

Each triangular gabion consists of three vertical columns composed of piles of used tires, and is supported by stainless steel pipes inside the tire columns. The rear of each column is joined to the front of the column behind by two stainless steel pipes inclined at an angle of 30°. Stainless steel wires are woven together around the three columns at regular intervals to hold the stones and boulders (which measure between 30 and 40 cm each). To reduce wave energy, the gabions are covered with used vehicle tires with wire fins on the surfaces to increase roughness. Although the used vehicle tires are chemically stable and will not pollute the environment, it is possible to replace them in the future with another available material, if required. A triangular gabion fully filled with boulders and covered uniformly with used vehicle tires is about 4 m long and 2 m high, which makes it heavy enough to hold the flexible breakwater. Two triangular gabions are then situated 50 m apart, holding the flexible breakwater between them.

3. Flexible high-strength net

A flexible wire net is strung between two triangular gabions and supported by the inclined stainless steel pipes. The No.1 breakwater measures 50 m long and 2.2 m high, and the grid size of each rectangular small net element is approximately 0.7 m long and 0.4 wide. The two-dimensional porosity of the net breakwater is approximately 0.67. One end of the steel pipe is joined to a spring to form a spring-pipe, which is then fixed on a fore post, and the other end of the pipe is joined to the rear post with wires. The spring-pipes are used to hold the flexible net. The net is therefore made flexible, and can adapt its position slightly when water passes through it. In addition to the tires (as mentioned in the above section), the wire net is also covered with a number of short fins to increase the roughness and reduce the energy of waves and currents passing through the flexible breakwater. The flexible permeable wire net is not only used to prevent coastal erosion by reducing wave energy, but it also allows the deposition of sediment around the breakwater (see Fig. 7).

The flexible wire nets placed between two triangular gabions have 4 rows of wire nets. In the construction of the first flexible breakwater, the upper 3 rows of nets were attached with soft wire blades to reduce wave energy. The bottom row of the wire net, which is attached to the used tires, was used to stabilize the wire net and to trap sediment. When the waves and sediment-laden currents passed through this breakwater device, the energy of the waves and currents was reduced, and sediment was deposited. It was found, however, that sediment was deposited not only behind, but also in front of the breakwater device.

Fig. 6. Assembling the concrete posts with spring-pipes.

Fig. 7. The No.1 flexible device and appearance of the beach after a typhoon on 2009/07/04, one month after the device was set-up. Rich sediment is deposited around the device. The bottom row of the flexible net (attached with tires) was buried by sediment.

The second and third flexible breakwaters (Nos. 2 and 3) were set up as similar structures beside the first one, with a distance between them of 50 or 60 m, following the coast. No. 1, No. 2 and No. 3 breakwater devices were positioned at sea levels of -0.5, -0.8, and -1.2 meters, respectively. The longitudinal directions of the three breakwater devices are roughly parallel to the coastal line, as shown in Fig. 5. The devices are designed to be soft and protecting, and to nourish the beach. No. 2 was designed to improve the shortcomings of No. 1, and was installed in May 2010 on the southern side at a distance of about 50 meters from the first one, and 5 meters further forward into the sea. No. 3 was installed in April 2011 on the southern side, about 60 m away from No. 2 and a further 10 meters in front. As No. 3 is situated in deeper water, the original design needed to be improved and adjusted, and this was achieved with an increase in the heights of the posts.

4. Device improvement

The first wire-net breakwater was constructed to evaluate design performance, and results from field tests showed that the soft wire blades used to reduce wave and current energy were easily damaged by large waves. The original design was then improved in four ways. Firstly, the strength of the support and materials was improved; the original stainless steel wire material, SUS304, was replaced with SUS316. Secondly, the material used for the wire net was improved. The stainless steel wires were replaced with high-strength woven nylon ropes, and the attached blades on nets were replaced with stainless steel short wire fins measuring 20 cm in length. Thirdly, the height of the posts was decreased to improve the appearance of the landscape. Lastly, in No. 2 device short stainless wire fins were used to replace the wire blades, and were fixed to the tires on the triangular gabion. Fig. 8 shows the use of the wire fins attached to the flexible wire-net. These improvements in the device design increased its overall performance. For ease of working and assemblage in deeper water depth, in No. 3 device we replaced the triangular gabions with a set of concrete posts, which considerably reduced the number of vehicle tires used.

IV. RESULTS AND DISCUSSION

1. Wave reduction

In order to understand the effect of the high-strength-net flexible breakwater on wave reduction, wave-level measurements in the front and rear of the high-strength-net flexible breakwater were conducted using a telescope to view the level on rulers attached to the concrete posts (as shown in Fig. 9). When waves are transported through the concrete posts, the level of waves above the sea bed at the front and rear posts are measured and denoted as $\eta 1$ and $\eta 2$, respectively. The wave reduction rate is estimated by the ratio defined as $(\eta 1 - \eta 2)/\eta 1$. Table 1 shows measurements of wave levels at the front and rear of the flexible breakwater, and also shows that the estimated wave reduction rate provided by the flexible breakwater was about 15 %.

2. Evaluation of No. 1 device

The function of No. 1 device (installed since June 2009) has now been tested by the action of typhoons, such as Typhoon Linfa (June 19–22, 2009), Morakot (August 6–10, 2009), Fanapi (September 17–20, 2010), Megi (October 21–23, 2010) and Nanmadol (August 27–31, 2011). Results show that the flexible breakwater device effectively traps sediments and allows their deposition on the coast. Coastal bed elevation measurements H1, H2, H3, H4 and H5 were taken on 2009/5/17 (before the set-up of the device), on 2009/7/26 (after Typhoon Linfa), 2009/8/15 (after Typhoon Morakot), 2010/10/5 (after Typhoon Fanapi) and 2011/9/25 (after Typhoon Nanmadol), respectively. The deposition depth (ΔH) around the breakwater device two years after its set up was between 1.17 and 1.36 m (as shown in Table 2). Fig. 10 shows the temporal variations of beach deposition, measured around

Table 1. Measuments of wave level above sea bed taken at the front and rear of the high-strength-net flexible breakwater.

No.	η1 (m)	η2 (m)	(η1-η2)/η1
1	1.00	0.85	15.0%
2	1.10	0.95	13.6%
3	0.95	0.80	15.8%
4	0.90	0.75	16.7%
5	1.05	0.90	14.3%
Average reduction rate			15.1%

Fig. 8. Short wire fins attached to the wire nets of No. 2 flexible breakwater.

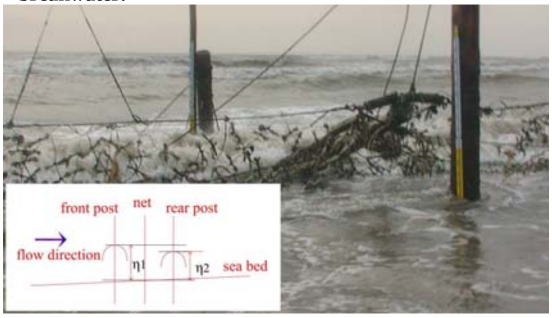

Fig. 9. Wave-level measurements taken at the front and rear of the flexible breakwater are conducted using rulers attached to the concrete posts.

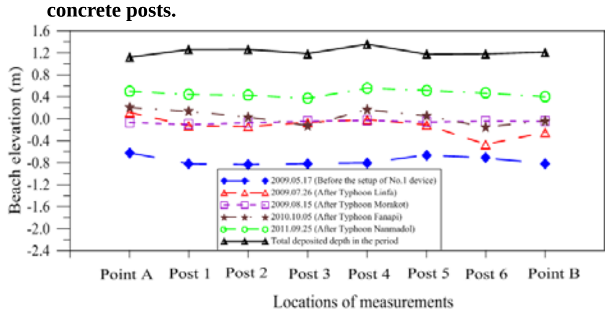

Fig. 10. Temporal variations in beach elevation measured around the No. 1 flexible breakwater, before and after device set-up.

Fig. 11. Beach appearance on 2011/10/04, approximately 2 yrs after the set-up of device No.1. Rich sedimentation can be seen around the breakwater.

Table 2. Temporal variations in beach elevation measured around No.1 flexible breakwater before and after the set-up of the device, using measurements recorded after typhoons. (Unit: meters).

Location	Point A	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Point B
Before set-up, H1 (2009/5/17)	-0.62	-0.82	-0.84	-0.82	-0.80	-0.66	-0.72	-0.82
After Typhoon Linfa, H2 (2009/7/26)	0.12	-0.12	-0.14	-0.06	-0.01	-0.11	-0.47	-0.25
After Typhoon Morakot, H3 (2009/8/15)	-0.07	-0.10	-0.07	-0.04	-0.03	-0.06	-0.04	-0.05
After Typhoon Fanapi, H4 (2010/10/05)	0.20	0.13	0.03	-0.12	0.17	0.05	-0.15	-0.04
After Typhoon Nanmadol, H5 (2011/09/25)	0.50	0.44	0.43	0.37	0.56	0.51	0.47	0.40
Difference ΔH	1.12	1.26	1.27	1.19	1.36	1.17	1.18	1.22

Note: Elevation difference ΔH = H5 – H1. The location of each post is referred to Figure 3.

Table 3. Temporal variations in beach elevation around No.2 device before and after set-up, using measurements recorded after typhoons. (Unit: meters).

Locations	Point A	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Point B
Before set-up, H1 (2010/04/17)	-0.54	-0.75	-0.65	-0.88	-0.56	-0.65	-0.64	-0.56
Before Typhoon Fanapi, H2 (2010/08/09)	-0.52	-0.75	-0.78	-0.77	-0.66	-0.63	-0.64	-0.59
After Typhoon Fanapi, H3 (2010/10/05)	0.04	-0.03	-0.06	-0.14	0.07	0.06	-0.01	-0.11
After Typhoon Nanmadol H4 (2011/09/25)	0.32	0.20	0.17	0.10	0.32	0.30	0.28	0.20
Difference ΔH	0.86	0.95	0.82	0.98	0.88	0.95	0.92	0.76

Note: Elevation difference ΔH = H4 – H1. The location of each post is referred to Figure 3.

Table 4. Temporal variations in beach elevation around No.3 device before and after set-up, using measurements recorded after Typhoon Nanmadol. (Unit: meters).

Locations	Point A	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Point B
Before set-up, H1 (2011/04/20)	-0.85	-1.14	-1.12	-1.10	-0.71	-0.80	-0.83	-0.85
After Typhoon Nanmadol H2 (2011/09/25)	-0.05	-0.18	-0.18	-0.26	0.04	-0.07	-0.07	-0.11
Difference ΔH	0.80	0.96	0.94	0.84	0.75	0.73	0.76	0.74

Note: Elevation difference ΔH = H2 – H1. The location of each post is referred to Figure 3.

No.1 breakwater before and after its set-up (locations of measurements taken are referred to in Fig. 3). The blue-dashed line indicates the elevation before set-up, the red-dashed line indicates the condition after Typhoon Linfa, the purple-dashed line after Typhoon Morakot, the brown-dashed dotted line after Typhoon Fanapi, and the green-dashed dotted line after the Typhoon Nanmadol. The solid black line shows the total amount of sediment deposition recorded between 2009/5/17 to 2011/9/25, and it highlights the sediment deposition on the beach after the set-up of No.1, showing an average deposition depth of 1.22 m. Figure 11 shows the beach and the appearance of sediment deposition after the set-up of No.1 device, using a photograph taken on 2011/10/04, which provides further evidence of the deposition of sand on the foreshore area that has resulted in the shoreline shifting forwards towards the sea; thus avoiding beach erosion.

3. Evaluation of No. 2 device

After its set-up in May 2010, No. 2 breakwater was challenged by severe waves from Typhoons Fanapi (September 17–20, 2010), Megi (October 21–23, 2010) and Nanmadol (August 27–31, 2011), respectively. The depths of sediment deposition (ΔH) around the breakwater between 2010 and 2011 were between 0.76 and 0.98 m, as shown in Table 3. This indicates that the device can effectively trap sediments and allow deposition on the beach around it. The average deposition depth was approximately 0.89 m, which provides evidence that No. 2 breakwater performs very well as a beach protection device. The shoreline was very close to the forest windbreak in 2009 and many *Casuarina equisetifolia* trees were lost due to erosion. However, field observations made in 2012 after the set-up of the device found that the shoreline had subsequently been moved over 20 m away from the windbreak.

Fig. 12 shows the temporal variations in the beach appearance around No. 2 device after its set-up. The photograph taken on 2010/05/29 shows the device surrounded by sea water (Fig. 12a); the photograph taken on 2010/09/07 shows the device buried by sediments up to about half its height (Fig. 12b); the photograph (Fig. 12c) taken on 2011/10/30 shows the triangular gabion and the flexible net almost fully buried by sediment. These photographs show that there has been significant improvement in terms of beach nourishment since the set-up of the device.

(a) No. 2 device on 2010/05/29

(b) No. 2 device on 2010/09/07

(c) No. 2 device on 2011/10/30

Fig. 12. Temporal variation in beach appearance around No. 2 breakwater device.

4. Evaluation of No. 3 device

Installation of No. 3 breakwater was completed in April 2011, in the third-year of the field study. Table 4 shows the deposition depths of sediments around the device as being between 0.73 and 0.96 m after the action of Typhoon Nanmadol, and this reveals the ability of the flexible breakwater to effectively trap sediment and allow its deposition along the coast. The beach surface elevations around the device, measured on 2011/04/20 (before the device was set up, blue-dashed line), and on 2011/09/25 (after Typhoon Nanmadol, red-dashed line), are also shown in Fig. 13. The solid black line shows the overall depth of sediment deposition, with an overall average of 0.81 meters. This provides further evidence that the improved No. 3 device performs well, and that it also has the ability to deposit the sediment on the foreshore area, which has resulted in shoreline protection. Fig. 14 illustrates the condition of the device and the beach on 2011/05/02, and on 2011/09/26 after Typhoon Nanmadol. These figures show that the newly developed flexible device is strong enough to withstand waves that accompany severe typhoons, in addition to enabling sediment deposition.

5. Overall performance of the flexible breakwaters

The installation of three high-strength-net breakwaters commenced in June 2009 and was completed in April 2011. These devices were challenged by the impact of severe waves from typhoons between June 2009 and September 2011. Several post-typhoon beach topographic surveys were carried out around the devices after their set-up to investigate the temporal changes in beach elevation. Fig. 15 shows the beach contours measured on 2010/04/17 after the set-up of No. 1 device (left-hand drawing), and on 2011/04/10 after the set-up of No. 1 and No. 2 devices (central drawing). The difference seen in the beach contour between 2010/04/17 and 2011/04/10 illustrates the variation in deposition depth during this period (right-hand drawing), and indicates that sand has significantly accumulated around the two devices. The gradient of the foreshore area has also become gentler since the deposition of sediment. These changes are also illustrated in the surveys of the beach contour taken pre- and post-construction. Fig. 16 compares the beach contours measured on 2009/05/17 and 2011/09/25, before and after the set-up of the three devices, respectively. Sedimentation is evident on the beach after the set-up of the flexible breakwaters, and the average deposition depth in the surveyed area was about 0.8 m during the above-mentioned period. Additional measurements of beach elevation were also conducted

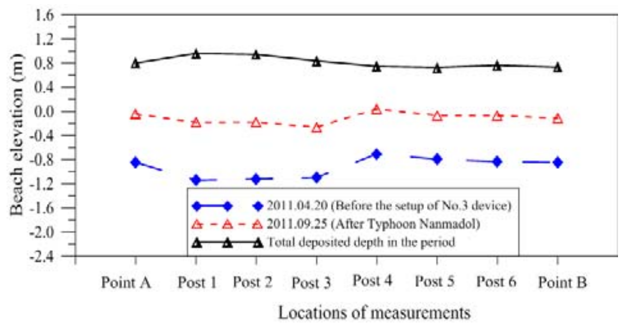

Fig. 13. Temporal and spatial variations in beach elevation around No. 3 flexible breakwater.

(a) No. 3 device under wave action on 2011/05/02

(b) Beach appearance around No. 3 device on 2011/09/26

Fig. 14. Appearances of wave action and beach sedimentation after set-up of No. 3 device.

in 2012 and 2013, and the results were compared to further evaluate the effectiveness of the installed breakwater (Fig. 17). The area protected by the three devices has evidently experienced significant sediment deposition, but the area outside the protection zone continues to suffer erosion (Fig. 17).

To understand the distribution of sediment deposition, we transversely sliced the field-study area into 7 profile lines (as shown in Fig. 18), from profile line 1, located about 25 m to the north of No. 1 device, to profile line 7, located about 25 m south of No. 3 device. Profile line 2 is located transversely along the center line of No. 1 device; profile line 3 is located transversely along the middle between No. 1 and No. 2 devices; profile line 4 is located transversely along the center of No. 2 device; profile line 5 is located transversely along the middle between No. 2 and No. 3 devices; profile line 6 is located transversely along the center of No. 3 device; and profile line 7 is located about 25 m south of No. 3 device. Fig. 19 gives an example of the variation in temporal beach-elevation along profile line 2. The study of beach profiles can aid in understanding the temporal and spatial variations in the beach elevation around these three breakwaters. The results shows that: (a) significant sediment deposition occurred in the first year after the device set up; (b) according to beach elevation profiles measured on 2009/08/15, this area was ever suffered severe erosion during Typhoon Morakot; (c) a comparison of the beach contours measured on August 9, 2010 and January 16, 2013 shows that the beach around the three breakwaters has accumulated sediment, but the southern part of the beach (about 50 m away from No. 3 flexible breakwater), where the area is out of breakwater protection, continued to suffer sediment erosion.

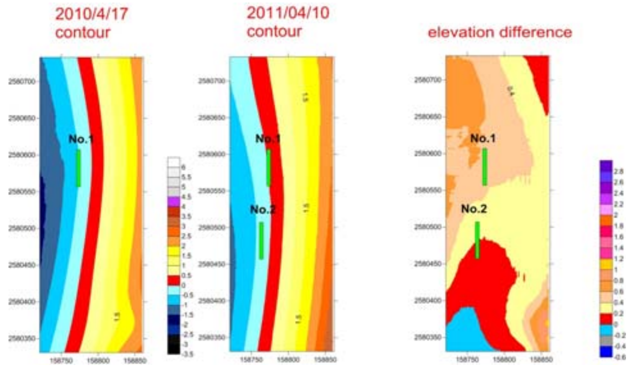

Fig. 15. Comparison of beach contours measured on 2010/04/17 (left-hand drawing) and 2011/04/10 (central drawing), and the difference between them (right-hand drawing) after the set-up of the first two devices (Unit: m).

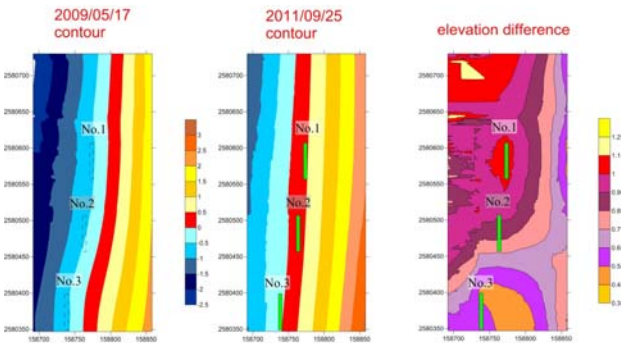

Fig. 16. Comparison of the beach contours measured on 2009/05/17 (left-hand drawing) and 2011/09/25 (central drawing), and the difference between them (right-hand drawing) after the set-up of the three devices (Unit: m).

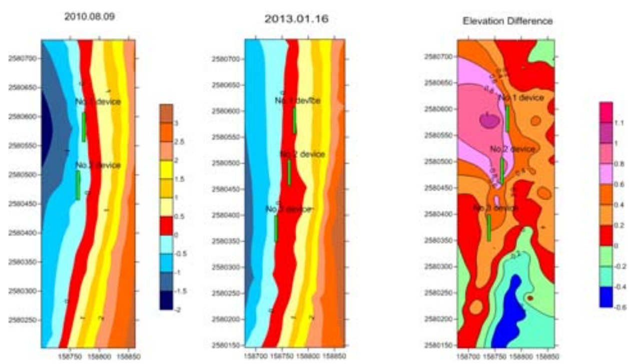

Fig. 17. Comparison of beach elevation contours measured on Aug. 9, 2010 and Jan. 16, 2013. The beach around these three breakwaters has sediment accumulation, but the south part about 50 meters away from No. 3 breakwater (out of breakwater protection) still suffers sediment erosion.

V. CONCLUSIONS

Coastal environments are exposed to the impact of severe

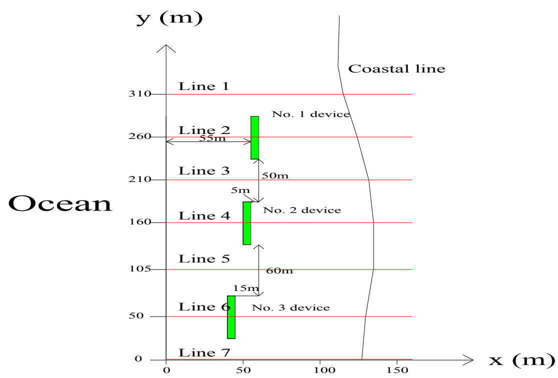

Fig. 18. Assigned profile lines for studying temporal and spatial variations in beach elevation.

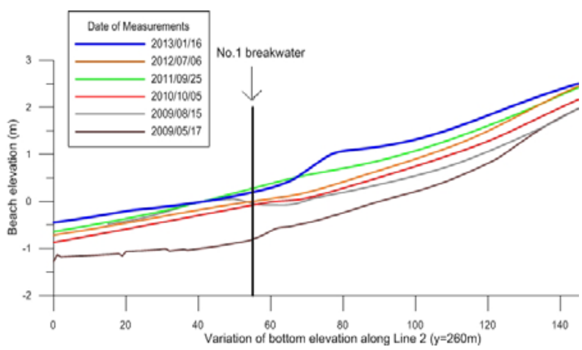

Fig. 19. Temporal variation of beach elevation along profile line 2. Three additional measurements in 2012 and 2013 are also indicated in this figure.

waves and storms. Therefore, effective structural and non-structural engineering countermeasures are needed to protect coasts from erosion. Coastal protection has become a topic of international importance because of recent extreme-weather events. Concerns related to the effects of climate change and associated sea level rise have prompted the search for innovative coastal protection systems. Under a 3-year pioneering project supported by the National Science Council in Taiwan (between 2008 and 2011), we conducted the installation of three high-strength-net flexible breakwaters at Shung-Chun beach, to evaluate their use in coastal protection against sediment erosion. After the set-up of the devices, a series of topographical surveys indicated that significant quantities of sand had accumulated on the beach, and that the shoreline had subsequently been moved seawards.

This 3-year field experimental indicated that the flexible breakwaters effectively reduced wave energy, trapped sediments, and allowed deposition along the coast. The devices are still in existence, and are working effectively in the study area. In 2012 and 2013 we conducted additional measurements of the beach elevation, to be used as comparisons to evaluate the effectiveness of the breakwaters. It is considered that these breakwaters are capable of ameliorating the problem of beach erosion, and are strong enough to withstand severe typhoons, and that therefore they should be applied as devices for beach protection.

Although this field experiment has demonstrated that our device can improve sediment deposition, thereby decreasing erosion, the field study did not investigate the effects of net porosity, or the effect of the inclined angle and spacing of the alignment on the results. We therefore cannot confirm whether the present design of the device is at its optimum, and further laboratory and field experiments are required to fully understand the sedimentary processes that occur under varying wave conditions, in relation to the new device. Further study is also required to investigate the most efficient design and alignment on these flexible breakwaters, to enable optimum beach protection. In addition, we need to evaluate the most appropriate depth of water required, and the orientation of the device, as within this study they are subjective and empirical, and further study is also required to evaluate the limitations of the device's applications.

ACKNOWLEDGEMENTS

The three-year financial support from the National Science Council in Taiwan (NSC 97-2622-E-006-024-CC1, NSC 98-2622-E-006-001-CC1 and NSC 99-2622-E-006 -001-CC1) for this study is highly acknowledged. The authors also thank Mr. J. A. Chuang for his help in the first-year field observation and sediment analysis.

REFERENCES

1. Bruun, P., "Rationalities of coastal erosion and protection: an example from Hilton Head Island, South Carolina," *Journal of Coastal Research*, Vol. 4, No.1, pp. 129-138 (1988).
2. Chu, J., Yan, S. W., and Li, W., "Innovative methods for dike construction - An overview," *Geotextiles and Geomembranes*, Vol. 30, pp. 35-42 (2011).
3. Geeraerts, J., Troch, P., De Rouck, J., Verhaeghe, H., and Bouma, J.J., "Wave overtopping at coastal structures: prediction tools and related hazard analysis," *Journal of Cleaner Production*, Vol. 15, No. 16, pp. 1514-1521 (2007).
4. Hanson, H., Brampton, A. Capobinco, M., Dette, H.H., Hamm, L., Laustrup, C., Lechga, A., and Spanhoff, R., "Beach nourishment projects, practices and objectives - a European overview," *Coastal Engineering*, Vol. 47, No. 2, pp. 81-111 (2002).
5. Hong, T. H., Lin, G. Y., Peng, T. H., and Jan, C. D., "Flexible retaining structure for evaluation of debris-flow hazards mitigation," (in Chinese), *Proceedings of the 12th conference on current researches in geotechnical engineering in Taiwan*, Chi-Tou Taiwan, pp. D2-13-001– D2-13-010 (2007).
6. Hornsey, W. P., Carley, J. T., Coghlan, I. R., and Cox, R.J., "Geotextile sand container shoreline protection systems: Design and application," *Geotextiles and Geomembranes*, Vol. 29, pp. 425-439 (2011).
7. Hsu, D. S., Wu, C. C., and Pong, D. H., "Improvement of Pre-cast Element for Grid-Type Dam," *Proceedings of the 11th East Asia-Pacific Conference on Structural Engineering and Construction*, Taipei, Taiwan, pp. P1-P9 (2008).
8. Jan, C. D. and Yen, C. L., "Sand Bed Configurations Under 2-D Standing Waves," *Journal of the Chinese Institute of Engineers*, Vol. 15, No. 3, pp. 255-263 (1992).
9. Jan, C.D. and Lin, M. C., "Bedforms Generated on a Sandy Bottom by Oblique Standing Waves," *Journal of Waterway, Port, Coastal and Ocean Engineering*, ASCE, Vol. 124, No. 6, pp. 295-302 (1998).
10. Johnson, H., "Wave modelling in the vicinity of submerged breakwaters," *Coastal Engineering*, Vol. 53, pp. 39-48 (2006).
11. Johnson, H.K., Karambas, T.V., Avgeris, I., Zanuttigh, B., Gonzalez-Marco, D., and Caceres, I, "Modelling of waves and currents around submerged breakwaters," *Coastal Engineering*, Vol. 52, pp. 949–969 (2005).
12. Lee, E. C. and Douglas, R. S., "Geotextile tubes as submerged dykes for shoreline management in Malaysia," *Geotextiles and Geomembranes*, Vol. 30, pp. 8-15 (2012).
13. Mimura, N. and Nunn, P. D., "Trends of beach erosion and shoreline protection in rural Fiji," *Journal of Coastal Research*, Vol. 14, No. 1, pp. 37-46 (1998).
14. Silvester, R. and Hsu, J. R. C., *Costal Stabilization: Innovative Concepts*, Prentice Hall, New Jersey, (1993).
15. Smith, S. E. and Abdel-Kader, A., "Coastal erosion along the Egyptian delta," *Journal of Coastal Research*, Vol. 4, No. 2, pp. 245-255 (1988)..
16. Tainan Hydraulics Laboratory, *The research of new shore protection technology*, (in Chinese), Technical Report, National Cheng Kung University, Bulletin No. 312 (2004).
17. Taiwan Water Resources Planning Institute, *In situ investigation on tide, wave, current and sediment from the Au-Gu coast to the Tseng-Wen coast*, (in Chinese), Summary Report (2005).
18. Ting, C.L., Lin, M.C., and Cheng, C.Y., "Porosity effects on non-breaking surface waves over permeable submerged breakwaters," *Coastal Engineering*, Vol. 50, pp. 213–224 (2004).
19. US Army Corps of Engineers, *Shore Protection Manual*, Dept. of the Army, Waterways Experiment Station, Corps of Engineers, Coastal Engineering Research Center, Vicksburg, Miss. (1984).
20. van Rijn, L. C., "Coastal erosion and control," *Ocean & Coastal Management*, Vol. 54, pp. 867-887 (2011).
21. Yang, R. R., Wu, Y.C., Hwung, H.H., Liou, J.Y., and Shugan, I.V., "Current countermeasure of beach erosion control and its application in Taiwan," *Ocean & Coastal Management*, Vol. 53, pp. 552-561 (2010).
22. Yoshida, J., Udo, K., Takeda, Y., and Mano, A., "Potential impact of climate change at five Japanese beaches," *Journal of Coastal Research.* Vol. 65, pp. 2185-2190 (2013).
23. Zhang, K., Douglas, B.C., and Leatherman, S. P., "Global warming and coastal erosion," *Climatic Change*, Vol. 64, No. 1-2, pp. 41-58 (2004).