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REVIEW

Case Study of Coastal Erosion and Measures at Kezailiao Coast, Taiwan

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Abstract

This paper examines major factors of coastal erosion and measures against beach erosion at Kezailiao Coast, Taiwan. Typical examples of coastal erosion due to natural or man-made factors are reviewed. Case studies of countermeasure for beach erosion are addressed. We further analyze and discuss historical shoreline and coastal cliff recession as a result of the attack of storm surges and waves. The coastline mainly made up of cliffs (2–3 m high), made of soft, easily eroded boulder sand and clay. In total, 3 km of land have been lost since 1951, including villages and farm buildings. The most important impacts of beach erosion at the Kezailiao Coast include beach erosion, wave overtopping, coastal flooding, and damage to homes built on properties. This study investigates the impacts of coastal damage and examines various measures adopted in response to coastal erosion during the past 60 years at the Kezailiao Coast. We presented the prevention work through the hard soft solution against beach erosion based on their effectiveness in protecting life, property, and harmony with the adjacent environment. Key parameters for design and effectives of a submerged breakwater is in terms of different dimensionless terms are studied and discussed. Alternative defense solutions for the submerged breakwaters are suggested.

Keywords: Coastal cliffs, Coastal erosion, Measures against beach erosion, Submerged breakwater

1. Introduction

Coastal erosion and disaster are world globally problem because of various natural and human-made causes [1–4]. Natural influence leads to dynamic and continuously changes due to the interaction of the sea-level changes, tides, currents, wind, waves, storms, and extreme events. Human interventions are such as catchments of sand and from river and offshore, raising social, environmental and economic concerns in the long term. This variety of causes of erosion, especially in areas with rapidly rising coastal land value, have led to uncertainties on how to treat the coastal erosion. Typical examples of both factors resulting in coastal erosion and suitable measures to protections are referred to [5–11].

To protect life and property from the coastal disaster in the area, coastal protection structures have been designed and constructed since 1954 to resist waves and storm surges. Existing coastal defenses have been damaged by increasing erosion. For example, the seawalls and revetments have been severely damaged by erosion due to wave action. Breakwaters are widely constructed to minimize wave action in areas behind structures where wave action is reduced through reflection and dissipation of incoming wave energy [12]. Detached breakwaters were installed parallel to the shoreline in 1972 to protect the shore at Kezailiao Coast from

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waves [13]. For Taiwanese coastal measures, effectiveness of shore protection structures has mitigated the coastal damage and beach erosion rate than before [14,15]. However, these costly protection structures are hard structures, which are needed to repair and maintain repeatedly after extreme typhoon events.

A submerged breakwater is a kind of offshore structure with its top at or below sea water. This kind of breakwater is usually constructed parallel to the shoreline in shallow water. Submerged breakwaters are used globally as a means of preventing beach erosion. Investigators have reviewed the application of innovative submerged breakwater around the world. By reducing the height of the incident waves to smaller transmitted waves, breakwaters are the preferred measures for coastal protections because of their ability to dissipate wave energy, safety and habitat for marine life [16–19]. Na'im et al. [19] demonstrated the application of the innovative submerged breakwater globally and in Malaysia. Kawasaki [20] presents a numerical wave model for simulating wave breaking and energy due to submerged breakwaters. The spectrum of breaking properties and wave amplitudes is also examined for various incident wave conditions and breakwater configurations. Numerical results also show that the breaking wave induced circulating flow is formed on the shore side of the submerged breakwater.

Li et al. [21] studies the interaction of water waves with a set of underwater porous reef balls, which are hemispheres centered on a flat seabed. Wave forces acting on the reef ball in the direction of sway, swell and heave were calculated, as well as the surface elevation near the structure. In addition, the feasibility of underwater porous breakwaters consisting of a series of suitably arranged porous reef spheres was investigated.

In this paper, we present a case study of coastal erosion and measures to coastal prevention at Kezailiao Coast, Taiwan. The coast is located in the southwestern coast of Taiwan in Kaohsiung City, as shown in Fig. 1. We further analyze and discuss

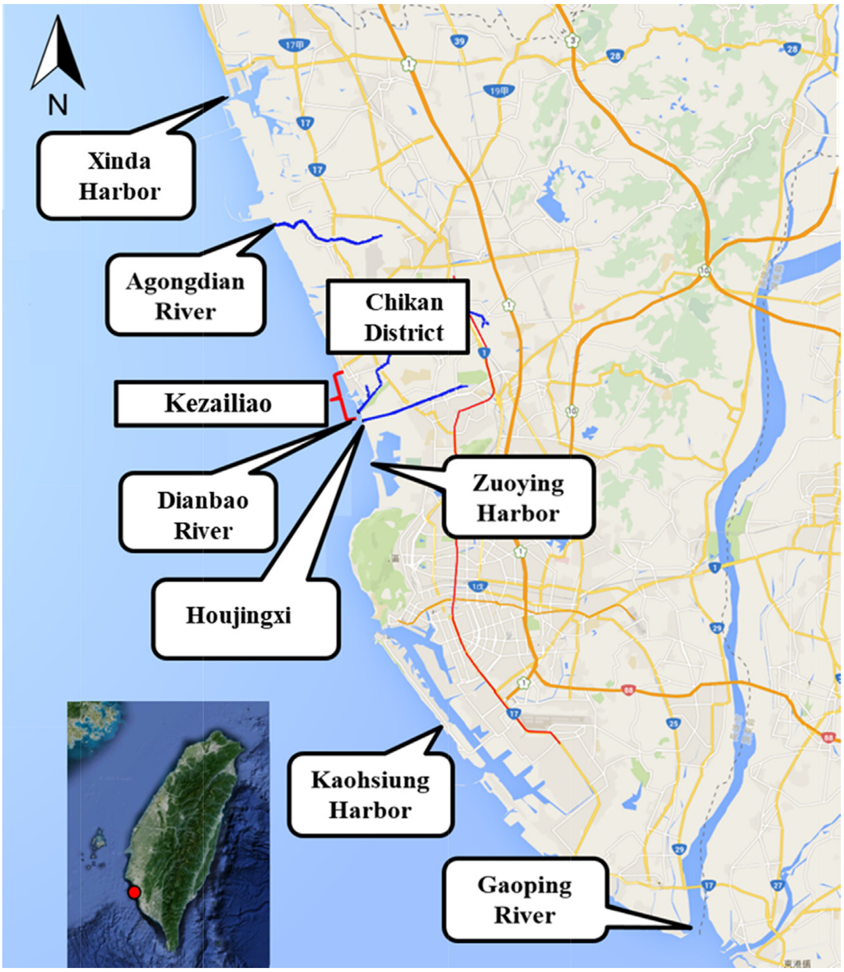

Fig. 1. Location of Kezailiao coast.

historical shoreline and coastal cliff recession as a result of the attack of storm surges and waves [5–8].

2. Historical beach erosion at Kezailiao Coast

This coast has been suffering from the beach erosion for a long time. Beach material is transported southward to the beaches of Xinda Harbor. The coast is subject to the full force of the waves from Taiwan Straight with reduction in wave energy before they reach the cliff line. The sea is continually able to reach the base of the cliff, leading to liquefaction and scouring of the foundations. The boulder sand and clay are also prone to mass movement in the form of landslides and rotational slumps when the cliff footing becomes saturated. In addition, improper human activities and sea level rise due to climate change have also resulted in fast coastal erosion [12–15]. Kuo's study indicated that the heavy erosion at Kezailiao Coast is the most serious of any region in Taiwan. The administrative division map and topographic map produced by the Japanese government in 1903 and 1904, respectively, were scanned, digitalized and superimposed on Google Maps to calculate t the temporal and spatial evolution of the coastline along the Kezailiao coast. The scales of the Japanese maps in 1903 and 1904 are 1:1000, respectively. Ou et al. [14] point out the major factor is primarily caused by the improper coastal protection constructions and storm wave conditions induced by typhoon events. The location of Kezailiao Coast is about 1.5 km south of Xinda Harbor and 15 km north of Kaohsiung Harbor, as shown in Fig. 1.

The satellite image for every sublittoral cell was also used to check the equilibrium condition and estimate the predominant wave direction as the shoreline orientation sediment circulation patterns. The north boundary of Kezailiao Coast is the Mituo Coast (Fig. 2) and south boundary is the Dianbao River which is 25 km long with a stream area of 107.1 km2. Two rivers, the Agongdian River, that is 38 km long with a stream area of 105 km2 and the Houjingxi, which is 13 km long with a stream area of 74 km2, also run into the coast. These areas supply some sediment transport to the Kezailiao Coast. Fig. 2 shows the Kezailiao Coast, which is 3 km long and consists of five segments: (1) Chikan Cliff Coast (610 m), (2) Chikan Village Coast (810 m), (3) Kezailiao Village Coast (800 m), (4) Kezailiao Harbor (160 m), and (5) Dianbao Coast (620 m).

According to the record of the Central Weather Bureau (CWB) of Taiwan, the first coastal damage was caused by Typhoon Iris, which brought about coastal damage along 2.5 km of the coast in 1951. There were 107 houses destroyed, 740 people injured and 300 m of wide beach disappeared in this event. Subsequently, Typhoon Bess struck Kezailiao Coast Taiwan in 1952, and Typhoon Viola struck southern Taiwan in 1969 leading to waves

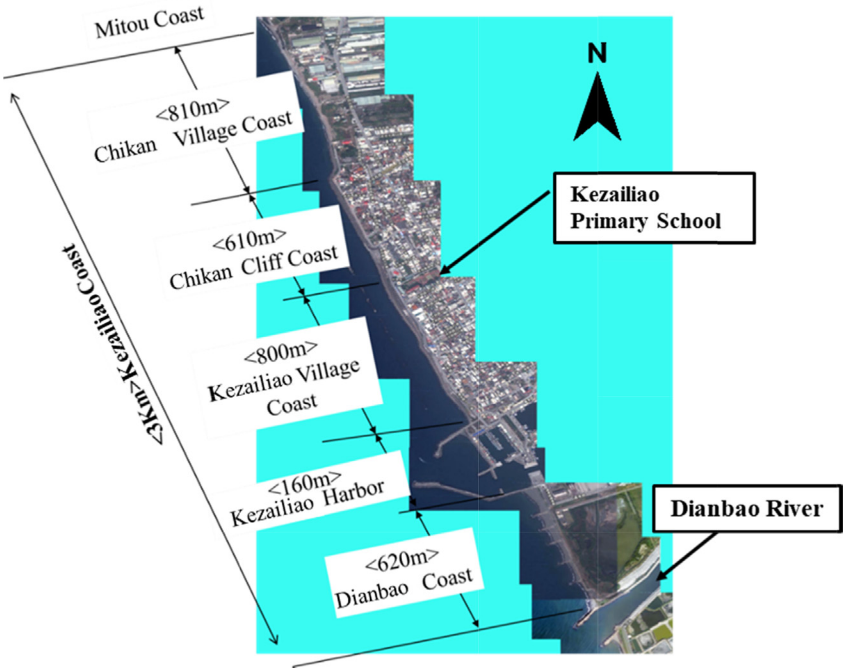

Fig. 2. Five segments of Kezailiao coast.

undermining the revetments and seawalls, damaging about 1145 m of the protected structures, destroying 78 houses and leaving 538 people homeless along the Kezailiao Coast. It also caused 141 ha of rice farms and ponds to be flooded in the Kezailiao district. A previous study provided details of these coastal disasters [4].

The present prevention structures of revetments and seawalls, which span 2540 m, consist of dissipating stones and armored blocks built very close to the residential areas to protect people and properties from waves. At present, many settlements and buildings built in at risk areas on low value land are threatened by worsening erosion that is increasing the loss of infrastructure. Buildings on cliff tops have increased runoff that may be making the cliffs more unstable. Powerful destructive waves brought by typhoons have long fetch, allowing them to build up high energy before they strike the coast. The coast also faces the dominant wind and wave direction from the SW with the most powerful waves in summer season. Few obstructions exist to reduce and dissipate the energy of strong waves before they erode the cliffs. In cases of storm surges and high tides, wave run-up and overtopping over the revetments cause frequent coastal damage [12].

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Design of submerged waters to reduce the wave loading and low cost is proposed by [8]. Broad-crested submerged breakwaters became widely used in Japan [4]. Development of alternative sand–filled gestures as a core of such breakwaters is implemented [14]. In some salient formation cases, submerged breakwaters may form greater formation than detached breakwaters. This paper first examines the coastal protection response options for the seriously eroded Kezailiao Coast. Coastal protection effectiveness for protection structures along the coast was reviewed within hazardous regions. More attention was focused on what can be done to protect the threatened areas and possibly restore the Kezailiao beach.

The protection of coastal erosion requires an understanding of influence factors that cause the resulting retreat of shoreline. The major factors bringing about heavy beach erosion at Kezailiao Coast include (1) coastal cliff erosion; (2) improper coastal structures and defenses constructed on the beach; and (3) a shortage of sediment supply from rivers to the shore. The administrative division map and topographic map produced by the Japanese government in 1903 and 1904, respectively, were scanned, digitalized and superimposed on Google Maps to calculate the temporal and spatial evolution of the coastline along the Kezailiao coast. The scales of the Japanese maps in 1903 and 1904 are 1:1000, respectively.

The shoreline has retreated noticeable distances varying from 100 to 321 m. The shoreline variation in each segment of the coast ranged from 221 m–275 m, 100 m–147 m, 190 m–241 m and 297 m–321 m at Chikan Village Coast, Chikan Cliff Coast, Kezailiao Village Coast, and Dianbao Coast, representively. The serious beach erosion is the combined effect of the above mentioned 3 major reasons. Table 1 presents lost land from 1961–2009 registered by the administrative district. We found that land loss reached 54 ha in 1961, and up to 75 ha in 2009. The amounts of lost coastal areas in hectares which have been fully and partially recorded are 65 and 376, respectively.

Fig. 4(a) shows coastal cliff areas at the Chikan Cliff Coast. The cliff is composed of mudstone, shale, sandstone, fine sand, gravel and loam covering on the surface. The base of the cliff is filled with debris which has fallen from the cliff. The total

Table 1. Coast area lost at Kezailiao coast (1961−2009).

Year	Non-registered area (hectare)	Registered area (hectare)	Total area (hectare)	Numbers of lost registered area		
				Location	Partially registered	registered
1961	23	31	54			
2009	23	52	75	Chikan Cliff Coast	33	82
				Chikan Village Coast	15	36
				Kezailiao Village Coast	17	258
				total	**65**	**376**

length of the coastal cliff is 610 m with the height ranging from 2 m to 6 m. Details coastal cliff erosion are demonstrated in Fig. 4(b). The erosion of coastal cliff takes the form of abrupt large-scale land sliding or the more continuous failure of small portions of the cliff face. The recession of the cliff is caused by liquefaction of sea water induced by infra-gravity waves, direct heavy rain wash, and large waves in typhoon events. Waves travelling on the high sea level act at the base of the cliff to remove the accumulated talus and lead to cliff erosion and shoreline retreat.

Based on the analysis of administrative district and topographic maps, the shoreline with a narrow beach was almost parallel to the cliff at a distance ranging from 51 m to 72 m in 1903, as shown in Fig. 5. From Fig. 3, it is clear to see that the shoreline retreat has ranged from 100 m to 275 m at Chikan Cliff Coast. The maximum shoreline recession was 275 m from 1904 to 2015 (see Fig. 3). By comparing the positions of the coastal cliff between 1903 and 2002, as shown in Fig. 5, it is evident that the shoreline continuously retreat distances varying from 18 m to 66 m in the period from 1975 to 1982.

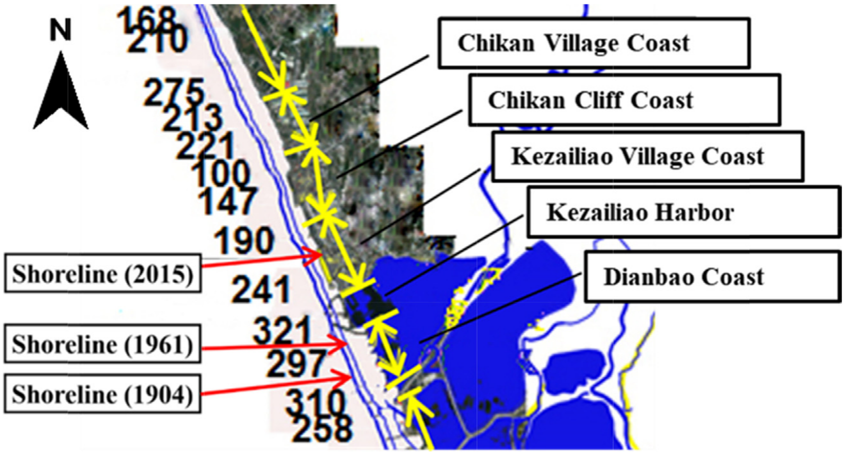


Fig. 3. Shoreline changes at Kezailiao coast over 111 years from 1904 to 2015.

(a) (b)

Fig. 4. Coastal cliff at Chikan cliff coast: (a) side view; (b) close view.

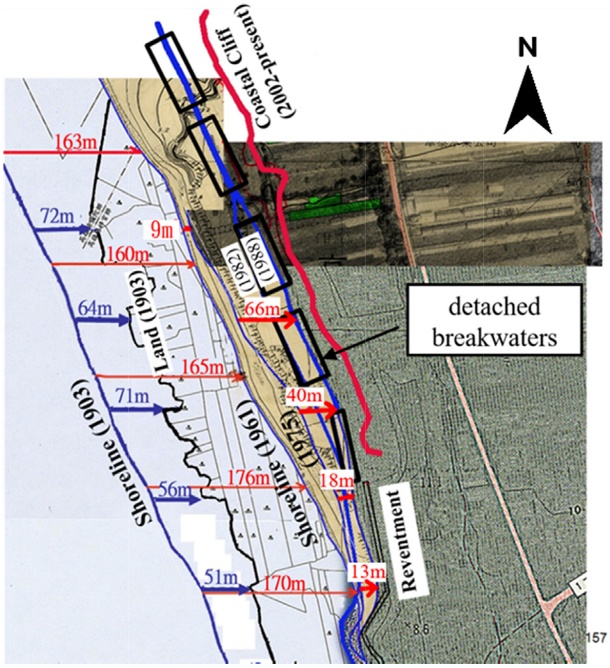


Fig. 5. Analysis of shoreline changes (1903–2002) using district maps of Chikan cliff.

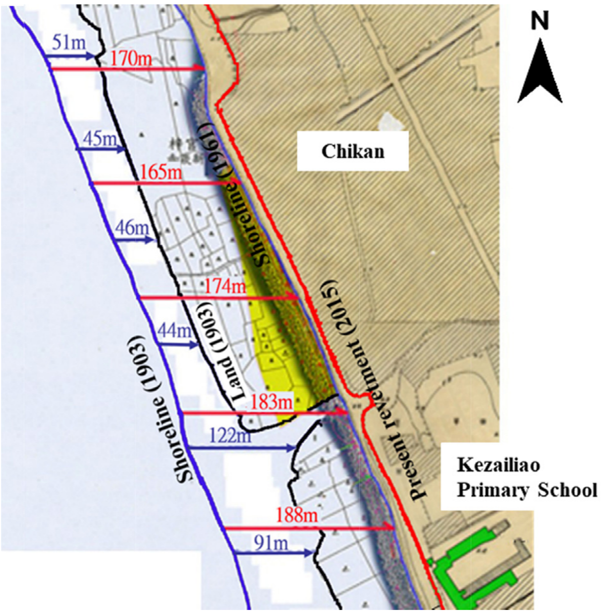


Fig. 6. Analysis of shoreline changes (1903–1961) using district maps of Chikan village coast.

Up to now, the shoreline has reached the toe of the coastal cliff. Continuous erosion has occurred for almost a hundred years according to the analysis from overlapped maps. Average beach erosion in the Chikan Coast was around 2.8 m per year during the 111 year period. Coastal cliff recession slowed down after the completion of 5 units of detached breakwaters built from 1981 to 1983 (see Fig. 5).

Fig. 6 shows temporal and spatial shoreline changes at Chikan Village Coast. Note that the distance between the shoreline and land varied in the range of 44 m–122 m in 1903. The shoreline recession varied significantly from 165 m to 188 m from 1903 to 1961. To prevent serious beach erosion, a stockpile of armored blocks was installed in front of the revetment. It is interesting to note that the shoreline is approaching the revetment because of the defense of the armor units. Therefore, no significant shoreline change has occurred since 1961.

Temporal and spatial shoreline evolution at Kezailiao Village Coast is depicted in Fig. 7. The distance of the shoreline in 1903 to the land varied from 48 m to 110 m. The shoreline retreat varied in the range from 172 m to 198 m from 1903 to 1961, but the recession slowed down to intervals of 18 m–72 m from 1961 to 1972. The shoreline has not changed since 1972 because it is approaching to the large amount of armored blocks for built for coastal prevention.

The construction of breakwaters can interrupt the longshore sediment movement and reduce the

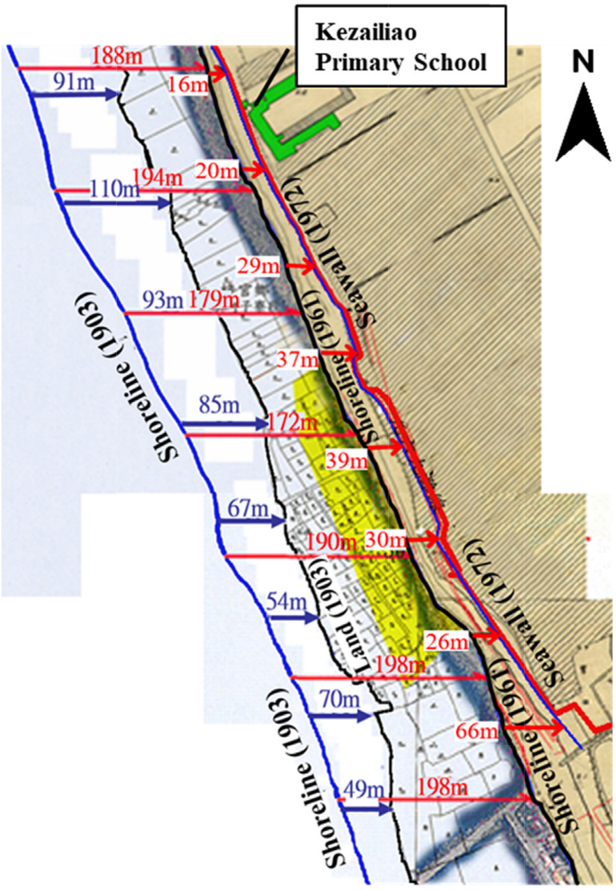


Fig. 7. Analysis shoreline changes (1903–1972) using administrative district maps at Kezailiao coast.

longshore sediments to the down drift beaches. Blockage of littoral drift by breakwaters due to the completion of Kaohsiung Harbor in 1958, Zuoying Harbor in 1948, Xinda Harbor in 1973, and Kezailiao fishing Harbor in 1978 produced destructive erosion. Fig. 8 presents the massive shoreline recession due to breakwater construction of the abovementioned harbors down drift to Kezailiao Coast, resulting in massive shoreline recession with shoreline retreat ranging from 172 m to 198 mt. It is also noted that the shoreline retreat estimated from satellite image (Fig. 3) is about 300 m over the 111 years (1903−2015) following breakwater completion. The coast was eroded to the road behind which lay houses and properties built on the land. The installation of revetments covered by armor units was conducted down drift from the breakwater. This shifted the region of maximum erosion farther to the north, but beach erosion still continues.

Sand, gravel and cobble delivered from rivers are the most important resources to form a variety of accretional sandy beaches. Based on the recorded data of WRA, there has been extensive beach erosion along Kezailiao Coast largely due to the river renovations of Agongdian River, Houjingxi, Dianbao River, and Gaoping River block barriers and concrete embankments built along these rivers. It has decreased essentially all sediment supply to the coast. The resulting shoreline retreat has been significant near the Dianbao Coast. Fig. 8 shows the temporal and spatial variation of the shoreline evolution for Dianbao Coast traced from 1903 to 1982 from administrative district maps as well as topographic maps. The overlapping of maps illustrates that remarkable beach erosion occurred along the river mouth and the whole coast.

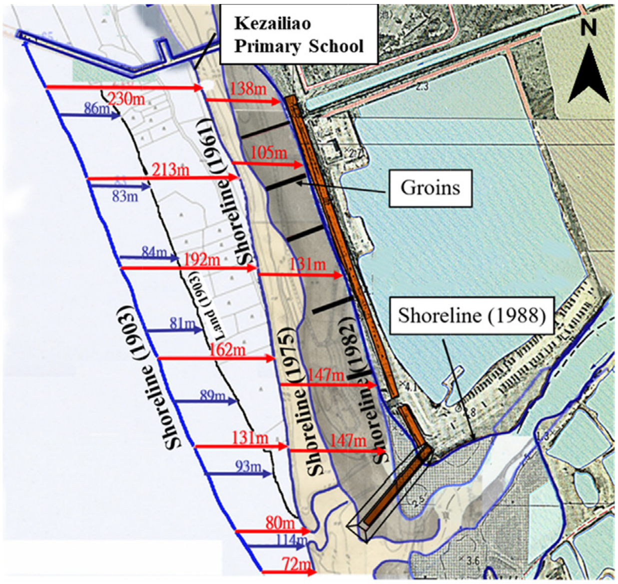


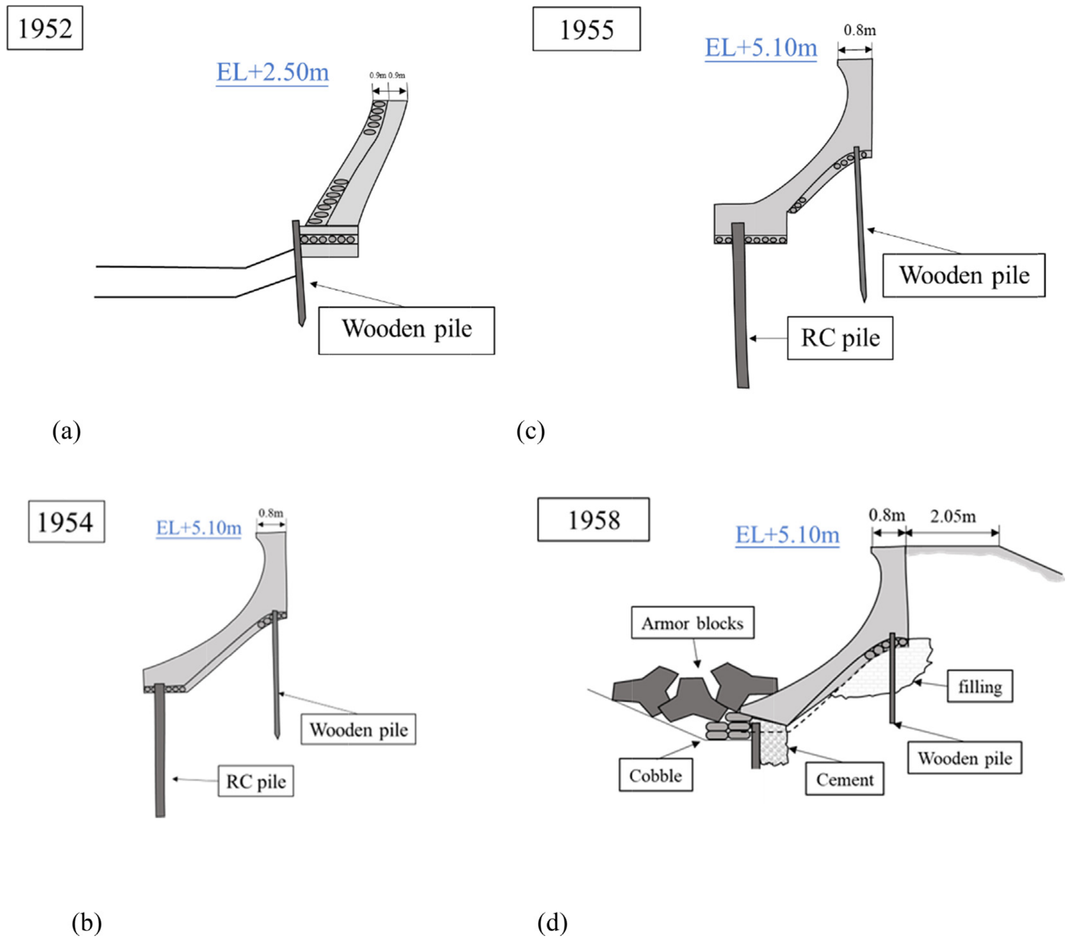
Fig. 8. Analysis of shoreline changes (1903−1988) using administrative district maps at Dianbao coast.

3. Review of measures against beach erosion

The seriousness of beach erosion at Kezailiao Coast has received much attention since the 1960s. Detection of the major factors for beach erosion is the first priority for solving such a heavy beach erosion problem. However, it is difficult to clarify the causes over a short period by theoretical analyses, laboratory experiments and field measurements. Beach erosion could bring about inundation and subsequent displacement of buffer zones, wetlands and lowlands. Therefore, the hard solution of building stabilization structures is usually implemented primarily to protect human life and property from the erosive action of storm surges and waves.

Fig. 9 depicts different types of revetments which were constructed at a distance from or very close but parallel to the shoreline. Note that the revetment began as a nearly vertical concrete wall in which the core was filled with sand mined from the beach (Fig. 9(a)). Then the revetment was modified into a concave and inclined shape with a thin concrete face, as shown in Fig. 9(b). The front face was designed as concave-type to decrease wave run-up and overtopping. Fig. 9(c) demonstrates that the toe protection was added and reinforced using a rubble mound design. More recently use of combined concave and inclined shapes with armored blocks was utilized to reduce wave run-up and deflect the wave swash upward for preventing water from running over the wall (Fig. 9(d)).

Revetments were first built in 1953 with vertical concrete surfaces covered by armored blocks in front of the toe in response to Typhoon Viola. The revetment has provided effective protection over the years by protecting Kezailiao Coast from a number of potentially destructive typhoons. In 1969 and 1977, Typhoon Viola and Thelma, respectively, brought great storm surges and struck the Kezailiao Coast for long durations. Revetments were repaired and improved with concave concrete faces to reduce wave overtopping during the storm surges and waves. After then, the components of a riprap revetment were built with core stone and filter cloth and a cover layer of armored blocks. It is recognized that revetment structures have a limited life time due to their design and frequent storms. Maintenance has been needed periodically to add new armor blocks, especially after 36 extreme typhoons have struck Kezailiao Coast. Table 2 outlines the



(a) (c) (b) (d)

Fig. 9. Different types of revetments at Kezailiao Coast. (a) nearly vertical shape; (b) concaved and inclined shape; (c) concave inclined shape with rubber mound; (d) concaved and inclined shape with armored blocks.

investment of more than 3 million USD each year by WRA for protection of life and properties.

According to the survey of WRA, concrete walls with rigid structures and vertical or concave faces reflect wave energy back to sea, leading to standing waves with higher energy accumulated in front of the base at Kezailiao Coast. This could cause soil fluidization and failures of the structures. The well-known Kezailiao Coast is called "Golden Coast" because a stockpile of armored blocks have been built to protect life and properties during typhoon events. Fig. 10 depicts the typical protection design of revetments with a riprap of a large amount of armor units at Kezailiao Coast. It is worth noting that the water depth is about 5 m in front of the base of the revetment due to wave reflection induced scouring. A number of studies from field surveys have indicated that scouring tends to develop at the toe of revetments, causing failures of constructions [9,18]. Based on the analysis and the later discussion

Table 2. Revetments and detached breakwaters (DBs) built to protect against coastal erosion at Kezailiao Coast.

Locations and Structures	Length (m)	Protection period	Cost (USD million)	Armor blocks (number)
Chikan Village Coast (revetments)	810	1952–2002	2.75	11,011
Chikan Cliff Coast (revetment and detached breakwaters)	610; 130 × 3(DBs)	1983–1995	5.08	11,054
Kezailiao Village Coast (revetment, groins and detached breakwaters)	800; 130 × 5(DBs)	1952–2002; 2004–2013	18.83	87,393
Dianbao Coast (groins and revetment)	620	1998	0.82	1353
Total	3750	1952–2013	27.48	110,811

Fig. 10. Coastal prevention work using a stockpile of armored blocks causing water depth the be deeper in front of revetments at Kezailiao Coast.

by [8], the presence of a seawall or revetment tends to withhold sediment from the littoral system when erosion occurs. This results in the rapid erosion of adjacent unprotected coasts. The accumulation of reflected and incoming waves in front of vertical seawalls or revetments brings about erosion that causes beaches to progressively decrease with distance from the structures. Ou et al. [13] concluded that improper design of seawalls and revetments that are built too close to the shoreline could resulting in accelerating disappearance of sandy beach and excess erosion of unprotected adjacent properties.

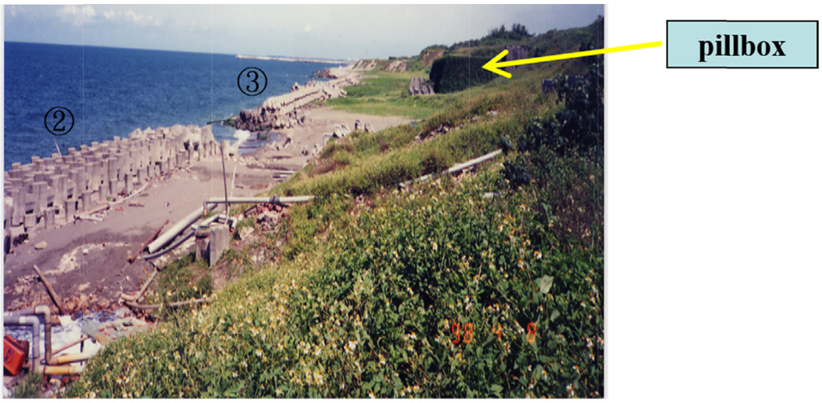
Five units of groin systems were installed approximately perpendicular to the shore nearby the Kezailiao Fishing Harbor to trap sand and build up a buffering beach in 1998. The design is shown in Fig. 8. They were built using small stones in the core and covered with a surface layer of armor units. The length of each groin is 80 m with a spacing of 80~120 m between two adjacent groins. It is known that groins have the effect of damming the longshore sediment transports and thus building up new beach along the up drift side, but causing erosion in the down drift stream. Field observations by [1] reported that the predominant direction of incident waves is almost normal to the coast. This could create a rip current adjacent to the groins that can move away the impounded sand and transport it offshore. On the other hand, cell circulations may lead to scouring in the tip or lee of groins and cause the failure of groins to meet their objective of trapping sand. At present, all the groins have been destroyed by storm surges and waves and are submerged in water.

Detached breakwaters were constructed and aligned offshore and approximately parallel to the local shoreline. Six units of detached breakwaters were built at Chikan Cliff Coast near the shoreline to protect storms and waves from reaching the eroded cliff from 1981 to 1983. Fig. 11 presents an alignment of detached breakwaters installed at Chikan Cliff Coast. Each segment of the detached breakwaters is 80 m long, 3 m wide, and 1 m above mean sea level, with a 30 m gap distance between two breakwaters. This prevention work has been shown to mitigate the serious erosion of the coastal cliff [8]. The grasses have grown back and the army pillboxes still exist after the construction of detached breakwaters in front of the naked cliff.

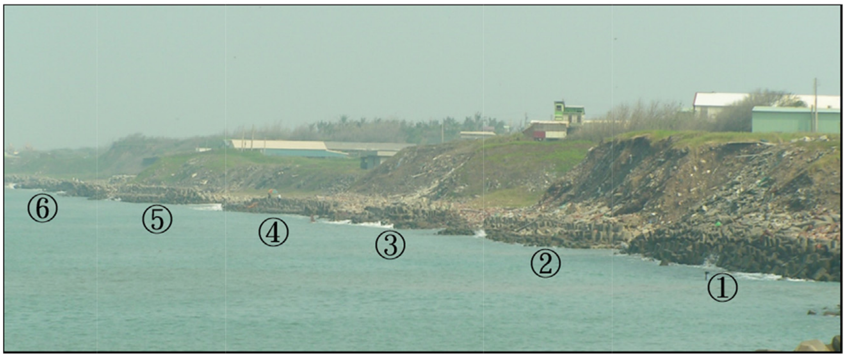
As a result, 8 units of detached breakwaters were constructed from 2005 to 2014 along the Chikan Cliff Coast and Kezailiao Coast. Fig. 12 shows the alignment of detached breakwaters which were built at about 5 m water depth and an offshore distance of 150 m. Each segment has the following dimensions: 130 m long, 9 m wide, and 0.5 m high, with a 45 m gap distance. The geometry of the structures is designed as a trapezoid shape with a slope of 1:3 on the front side and 1:2 on the black side. Wave refraction occurs at the tip of the breakwater to reduce wave energy and cause sand deposition in the shadow zone. Detached breakwaters have been shown to decrease coastal erosion in the lee of breakwaters, but without producing a salient or tombolo behind the breakwaters. Notably detached breakwaters are constructed by accumulating 3−4 layers of armor units on a foundation of filter cloth and gravel ingredients which are easy to slide, roll or collapse in storm wave conditions. To maintain the coasts, the amount of armor units has increased with the increased number of typhoons. According to [8], a recent prevention work in Japan replaced old detached breakwaters with submerged breakwaters or artificial reefs to maintain the landscape and ecology. Coastal prevention work of detached breakwaters should include alternatives based on safety, landscape, ecology, attraction to water and budget.

4. Demonstration site of new measures against beach erosion

More recently, four key elements including safety, environment, sea view, and water attraction for natural coastal prevention work has intensively developed. Along this line, we take a typical study of measures for Kezailiao coast (Fig. 12) by using submerged breakwater combined with beach nourishment. The crown of 8 units of the detached breakwater is cut down below the mean sea level and added their width as a series of submerged



(a) Close view



(b) Far view

Fig. 11. Grass regrown after construction of detached breakwaters at Chikan Cliff Coast.

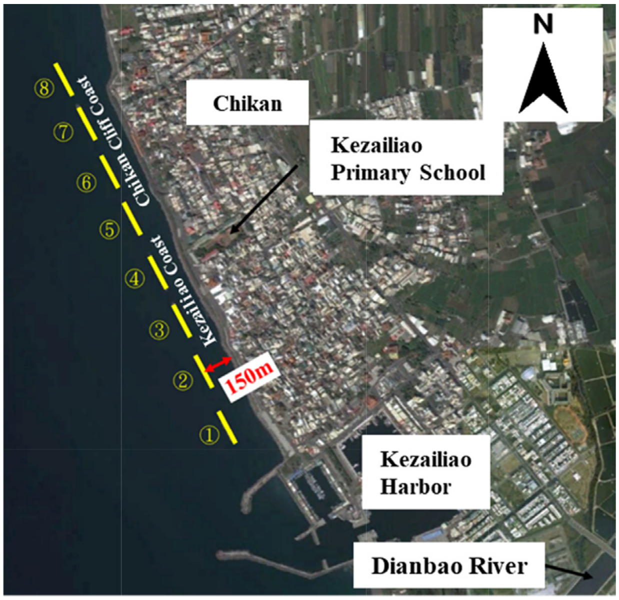


Fig. 12. Eight units of detached breakwaters at Kezailiao Coast.

breakwaters. Beach nourishment combined with submerged breakwaters and plant cover on the back sides of seawalls and revetments are the alternative measure for restoration Kezailiao Coast. A large quantity of sand or gravel in the littoral zone or fine sand dredged from Kaohsiung Harbor, Xinda Harbor or Kezailiao Harbor can be placed behind the submerged breakwaters.

Submerged breakwaters have been widely used as coastal protections for recreational and residential coastal areas due to their reduced environmental and visual impact. They are less subjected to wave action and consequently not exposed to severe wave breaking because they are built underwater. Many successful cases have shown that submerged breakwaters may also cause beach restoration by trapping natural sediments or providing beach nourishment. Lower construction cost compared with other kinds of detached breakwaters is another advantage. The advantages of submerged breakwaters over conventional structures make them more attractive with respect to safety, landscape, ecology and water solubility for protecting natural and developed beaches. Basically, a successful application of submerged breakwaters strongly depends on its accuracy and the effectiveness of its design [22]. Seawalls, revetments, groins, detached breakwaters and a number of concrete armor units have already been built in the eroded area. Proper measures against beach erosion which are harmonious with the environment are required to prevent the coast from future deterioration.

Beach nourishment combined with submerged breakwaters and plant cover on the back sides of seawalls and revetments are the alternative measure for restoration Kezailiao Coast. A large quantity of sand or gravel in the littoral zone or fine sand dredged from Kaohsiung Harbor, Xinda Harbor or Kezailiao Harbor can be placed behind the submerged breakwaters.

The advantage of a submerged breakwater is quite similar to that of a detached breakwater, but it is not visible and thus does not disturb the view of the sea. This measure has been implemented on one section of Kezailiao Coast where submerged breakwaters were designed by cutting the crown 2 m high and moving armor units into the water to expand the length from 100 m to 150 m.

The key parameters for the design and effectiveness of a breakwater are expressed by different dimensionless terms: (1) the relative water depth h/L, the relative structure height = d/h and the relative freeboard to water depth ratio = $h\text{-}d/h$, which indicates the relative height of the breakwater compared to the water depth. This parameter is used to determine the wave shoaling, refraction and magnitude of the wave, the current forces on the breakwater and the effectiveness of the structure in attenuating wave energy, where h the mean water depth, and d is the height of the structure. (2) The offshore distance X/L_b, dimensionless width B/L_b, and length of gap between breakwaters in a segmented breakwater G/L_b represent the distance of the surf zone, width of wave dissipation and pattern of the nearshore circulation. (3) Another important dimensionless parameter used for determining the interaction between the waves and a breakwater structure is the freeboard divided by the wave height, $h\text{-}d/H$, where H is the wave height, indicating the wave attenuation of the breakwater. The parameters used in the present numerical simulation are the relative water depth, $h/L = 1/16$, $d/h = 0.8$, $h\text{-}d/d = 0.25$, $G/L_b = 0.4$, and $W/L_b = 1/50$, where $h = 5$ m is where the breakwater is located, $L = 80$ m is the local wavelength, $G = 40$ m is the width of the gap, $L_b = 150$ m is the length of the breakwater and $B = 3$ m, $X/L_b = 0.7$ and $h\text{-}d/H = 0.8$ match the criterion of wave breaking at the top surface of the breakwater.

Numerical simulation for wave transformations and dissipation after the installation of submerged breakwater was conducted. The input wave height and period are 1.5 m and 6sec, and the prevailing wave direction is SW, respectively. Figs. 13 and 14 present a comparison of wave energy reduction between before and after the construction of submerged breakwaters. We note that submerged breakwaters are able to reduce the intensity of wave action in inshore waters by reflection, diffraction and breaking, and thereby provide safe shelter water areas. This implies that a local pair of symmetric vortexes would be developed resulting in impoundment of sand behind the structure.

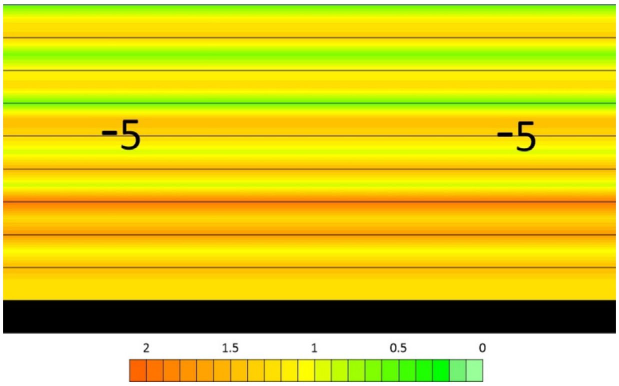


Fig. 13. Wave height distribution at the front of the sea wall.

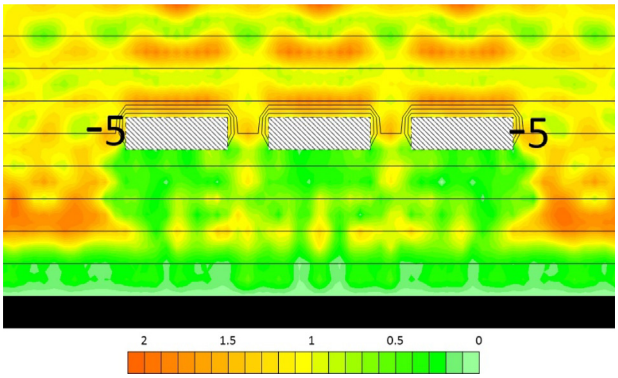


Fig. 14. Wave height distribution after construction of 3 units of submerged breakwaters.

Beach nourishment is also conducted by putting sand in sandbags to create a buffer zone against storm surges and erosion. Moreover, a larger beach could protect coastal settlements, maintains a view of the ocean and space for leisure, and prevent obstruction or destruction of the natural environment for those organisms that rely on sandy spaces for habitat or reproduction. The addition of sand has been linked to high property values and increased tourism. The total volume of the supplementary sand is 56,250 m^3 which was calculated by the offshore distance of the sloping shelter areas from the submerged breakwaters. Fig. 15 shows a series of salient formed behind the 3 units of breakwaters. Notably, beach nourishment combined with a

Fig. 15. New innovative submerged breakwaters combined with an artificial beach.

submerged breakwater system could provide a reservoir of sand during times of low wave energy, which is resource that could eroded during a storm. We also focus on a coastal landscape design along a section of coastal line that has distinguishable features at Kezailiao Coast. Trees that provide sightseeing and a promenade have been planted on the sandy beach at the waterfront of the coast. This measure is a combination of beach nourishment, submerged breakwaters and landscape design that provides a typical example of soft beach erosion control with more attractive coastal water regions.

5. Summary

This study first addresses the most serious beach erosion at Kezailiao Coast spanning 3 km and the large budget invested for coastal pretention. The major factors causing beach erosion, coastal cliff and subsequent shoreline recession were studied and discussed. Different countermeasures for protecting beach erosion and destruction of life and properties built on the land were reviewed and examined. Effectiveness or failure of various measures of hard solutions, including constructing seawalls, revetments, groins, and detached breakwaters covered by a stockpile of armored blocks in their concrete face and base, for dissipating wave energy in response to extreme conditions were investigated.

The analysis of coastal erosion from satellite image analysis indicated that the maximum shoreline retreat is 221 m at Chikan Coast; 275 m at Chikan Village Coast; 190 m at Kezailiao Coast; and 321 m at Dianbao Coast from 1903 to 2015. The total lost land and beach is 376 ha. The average shoreline retreat along the 3 km long Kezailiao Coast is about 300 m. Based on the administrative and topographic maps, the maximum coastal cliff recoil is in the range of 164 m–232 m. Detailed shoreline recession is given in the present investigation. The rate of beach erosion has been slowed down after implementations of hard prevention measures such as detached breakwaters. The sports field of Kezailiao primary school has disappeared and is submerged 5 m deep. This implies that the beach erosion is severe and critical at Kezailiao Coast. We also found that hard structures designed for coastal protection always fail during typhoon events that bring storm surges and waves attacking the coast. When even section of beach erosion has been controlled and protected by seawalls or revetments, the adjacent beach has been eroded and shoreline retreat has occurred. Moreover, waves at Kezailiao Coast reflected in front of the structures cause accelerating beach loss, deeper surf zones and scouring at the base, resulting in the destruction of seawalls and revetments. Maintenance cost is also an important factor of coastal protection design.

We proposed an innovative measure for protecting Kezailiao Coast that combines beach nourishment with alignment of submerged breakwaters and vegetation behind the present revetment. we conduct typical study of measures for Kezailiao coast (Fig. 12) by using submerged breakwater combined with beach nourishment. The crown of 8 units of the detached breakwater is cut down below the mean sea level and added their width as a series of submerged breakwaters. Beach nourishment combined with submerged breakwaters and plant cover on the back sides of seawalls and revetments are the alternative measure for restoration Kezailiao Coast.

Wave energy is dissipated due to shallow water depth. Numerical simulations show that diffraction and reflection could reduce the wave energy behind the structures. Sand deposition occurs in the shadow zone at times of low energy waves. Beach nourishment combined with submerged breakwaters provides a reservoir of sand that can serves as a buffer zone and can be eroded under storm conditions. The measure fits the coastal management requirements of safety, landscape, ecology and attraction to water.

Author contributions

Conceptualization, T.-W H. and J.-Y.C.; methodology, T.-W H.; formal analysis, T.-W H. and Y.-T. T.; investigation, resources, T.-W H.; data curation, Y.-T. T.; writing—original draft preparation, T.-W H.; writing—review and editing, T.-W H. and J.-Y.C.; visualization, Y.-T. T.; supervision, T.-W H. All authors have read and agreed to the published version of the manuscript."

Conflict of interest

There is no conflict of interest.

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