Performance Evaluation of Innovative Concrete Armor Unit for Coastal Protection Structure

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***Abstract*— Various local innovative armor units for coastal protection structure have been developed to mitigate and control serious coastal erosion problems. The armor units designed by researchers from several institutions in Malaysia include SAUH, SINE SLAB, L-Block and Labuan Block armor. These armor units were implemented to prevent critical erosion problems along various stretches of Malaysia's coastline. This paper discusses the site assessment that was conducted covering selected coastal protection projects along West Coast of Peninsular Malaysia to evaluate the` performance level and identify concerns regarding these armor units. Initial condition of the armor units and the site location were identified and documented as the base condition for the performance evaluation. Comparisons were later made with current observation and findings. The breakage, displacement and settlement of the armor units were noted and any sign of accretion and erosion were also taken into consideration. Most of the armor units remain intact in their initial position especially SAUH and SINE-SLAB armor units. Corrosion of reinforcement steel bars was observed in most of the armor units as evidenced from the presence of brownish color substance at the concrete surface. This was caused by intrusion of salt water in the concrete through minor fractures and gaps. No major failure on the armor unit was observed during the site assessment indicating good structural stability as expected in their design life. Overall, the implemented schemes were observed to be performing successfully with occurrence of accretion at most of the sites. The findings and result from this site assessment are important as guidance for future research and other initiative to improve the current innovations. The up-to-date assessment are also critical to estimate further maintenance works to prevent major failure due to prolong exposure to damage that may lead to potentially high maintenance costs to local authorities and nearby residences.**

Keywords-component; coastal protection; concrete armor unit; performance evaluation; West Coast of Malaysia

I. INTRODUCTION

A. Coastal Erosion and Mitigation Plan

Coastal areas contribute to the economy growth of a country especially in tourism sector. Besides, coastal areas have become a major contributor for food industry especially in supplying marine products as well as fisheries industry. Coastal zone has provided a suitable location for onshore facilities especially to oil and gas industry, ports and harbors. Coastal area or coastal zone is also defined as a stretch of area extended for 1 km from the shoreline [1].

The west coast of Peninsular Malaysia is exposed to the Malacca Straits with narrow fetch area. The ocean, which is sheltered by the Sumatra Region, has mild wave condition. Most part of west coast of Peninsular Malaysia is made of muddy beach and rich with diverse species of mangroves forest that promote growth of marine life and excellent in dissipating wave energy. Mangrove bands along the coastline used to dissipate the wave energy were destroyed and resulted into rapid coastal erosion. Mangrove requires minimum width to sustain their population and habitat. Construction of bunds along the coastline caused further depletion of mangroves fridges. Earth bunds block water exchange to mangroves areas which can result in unsuitable environment for the mangrove survival.

Earlier study revealed that about 29.4% of coastal areas in Malaysia have experienced erosion [2]. This alarming statistic has led to various mitigation plans to prevent more severe erosion which may result in loss of valuable land area. Generally erosion is due to man-related as well as natural phenomena [2, 3]. The erosion along the coastline in West Coast of Peninsular Malaysia is greatly accelerated by human interference in the natural process such as agriculture and aquaculture activities that involved construction of tidal gates, bunds and channel dredging. Constructions of earth bunds or dykes were used to prevent entrainment of seawater into the agriculture area [4]. The water discharged from the rivers or drains are diverted and controlled depending on the tidal flow. Besides, the discharge points are also altered to specific location. This has caused limitation in sediment supply and distribution of the sediment along the coastline. Thus, coastal area undergoes erosion due to unbalance net sediment transport.

Coastal erosion problem can be mitigated by using hard engineering approach either to reduce beach erosion by reducing the wave energy reaching the shoreline or totally stop erosion problem by covering or blocking the original beach material as discussed by [5]. Construction of hard structure to mitigate erosion problem may cause erosion problem downdrift [6], hence [7] has suggested that each affected area need to have sufficient sediment supply from the minimum width of

the beach itself or from nearshore and offshore coastal zone. There are various types of coastal erosion mitigation plans adopted to mitigate the erosion. The erosion in coastal area can be controlled either by soft or hard engineering approach. Common coastal engineering structures applied in Malaysia include breakwater, revetment, groin, seawall, and geo-tube. Revetments, which cover and prevent the earth material from eroded by wave action, are typically adopted in west coast of Peninsular Malaysia. Combination of geo-tube and breakwater are used as a first line of defense for mangrove replantation project, while breakwater is used in area with jetty and harbor. Breakwater and geo-tube have a primary function to provide sheltering effect, hence reduce the wave action behind the structure. Armor unit is one of major components in breakwater and revetment. Conventional breakwater and revetment have primary armor unit made by rock. The usage of concrete armor unit is necessary especially when the required size of rock is unavailable or not economically produced. Besides, the appropriate selection of concrete armor unit is able to reduce the overall size of structure, hence optimize the design and cost.

B. Background of Site Assessment

Four coastal protection structures with different primary armor units were assessed to evaluate the performance of the concrete armor unit and to identify their advantages and possible improvements. There are limited publications and review on performance and usage of these armor units. Most of these armor units were used in west coast of Peninsular Malaysia. SAUH revetment and segmented L-Block breakwaters are located at the coast of Sungai Haji Dorani in Selangor. Labuan Block System and Sine-Slab revetment have been applied at Pantai Kampung Padang Kemunting and Tanjung Kling in Melaka.

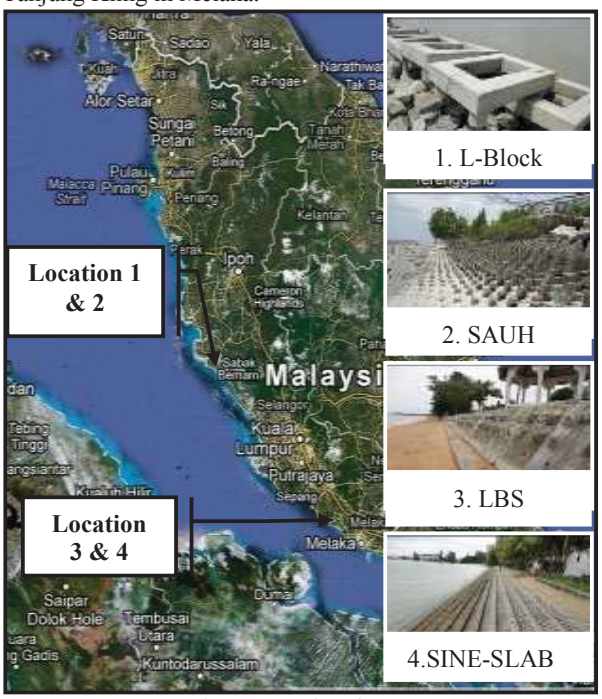

Figure 1. Location of Structures

The site assessment was carried out by direct observation of the individual armor unit and interviews with the local authority. A Rebound Hammer Test and sieve analysis were conducted as part of the assessment at Pantai Kampung Padang Kemunting and Tanjung Kling to obtain the concrete strength of the armor unit and the material deposited or origin at the particular areas. The locations of the structure are shown in the Fig. 1.

C. Local Armor Unit

1) Simplified Armor Unit-H (SAUH)

SAUH armor unit was designed by the Department of Irrigation and Drainage Malaysia. The armor unit has a twisted H section made by unreinforced concrete. The armor unit is a primary layer for revetment and can be found at Sungai Haji Dorani, Selangor [8]. The lightweight armor unit is suitable to be applied at muddy beach with low bearing capacity. Besides, the SAUH has shown significant performance in reducing erosion.

2) L-Block Armor Unit

L-Block was developed by researchers from University of Malaya (UM). The L-Block was designed with interlocking capability and lightweight characteristic. This L-Block unit has a rectangular frame and legs with different length at each corner. It was designed to geometrically fit into each neighboring units during placement and each unit can supports each other when subject to wave impact. The L-Block unit is capable of withstanding moderate wave energy and reducing the wave energy, [9]. The first breakwater project using L-Block unit as armor layer was implemented in Sungai Haji Dorani, Selangor. According to [10], the purpose was to protect the newly replanted mangrove from severe wave attack. The site was exposed to open sea and many young plants were often knocked down and washed out by storm waves and surges.

3) Labuan Block System (LBS)

The Labuan Block System (LBS) is another example of revetment protection. The LBS was designed by the Department of Irrigation and Drainage with the aim to prevent erosion especially when the source of granite rock is not available. It was designed to have sufficient weight to resist wave action. The massive weight helped to minimize the erosion at the shoreline by acting as a barrier to separate the land and water. The Labuan Block System consists of two sections, which are the toe and main block. The main block is equipped with weep holes to facilitate drainage and help in releasing pore pressure from fill materials. The two sections of LBS are installed in staggered manners to resist the wave action. It has the advantage of quick installation and suitable for emergency protection measure.

4) SINE-SLAB

Sine-Slab is an innovative armor unit designed by researchers from Universiti Teknologi Malaysia (UTM). It was designed with sinusoidal shape that inspired by the shape of surface wave [11]. Sine-Slab was developed for revetment application by using concrete grade 40 with reinforcement steel inside the armor unit. The armor unit has a smooth surface with drainage gaps to provide voids and help in reducing pore

pressure. In addition, [11] has mentioned that the Sine-Slab has a Stability Coefficient, K_D of 40, which is superior as compared to other established armor units in the market.

II. Site Assessment

A. LBS at Kampung Padang Kemunting

Kampung Padang Kemunting beach is a continuation of Tanjung Bidara beach and it was surrounded by villages and chalets. Most of the local community work as fisherman, farmers and chalet operators. The beach is adjacent to the power generation plant and a berthing port for small ships and boats. The Labuan Block was implemented as a revetment to protect the beach from wave action. LBS were installed along the beach approximately for 1.5 km in length. The sandy beach is exposed to the mild wave action from Strait of Melaka without any protection from islands or hard structures. The wave climate at the site is affected by the South-West Monsoon and the storms usually limited by the effective fetch length. Most of the sandy beaches have higher bearing capacity compared to muddy beaches, therefore LBS is suitable to be applied at Kampung Padang Kemunting beach.

The Labuan Block System was installed along the dry beach area to prevent erosion of inland area. The LBS was situated approximately 6 meters from nearby chalets along the beaches. A rigid wall was constructed behind the LBS to separate the fill material that consisted of rock with angular shapes and LBS. A concrete cap was also provided behind the LBS to prevent scouring from overtopping wave. Besides, the concrete cap was used as pedestrian walk to give access to the beach and add on the function value of the structure. Weep holes were provided at the structure to allow better drainage and reduce the pore pressure behind the structure. The cross-section of LBS installed at the beach is as shown in Fig. 2 below.

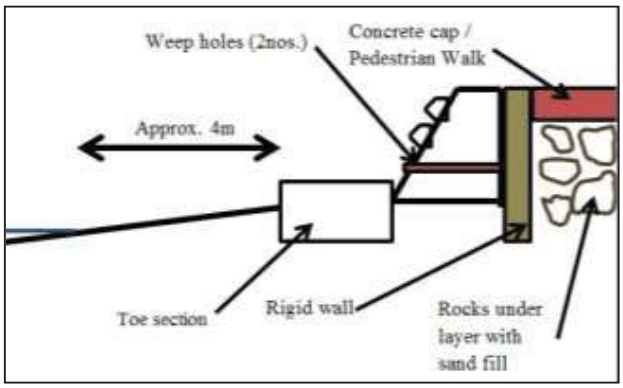

Figure 2. Typical Cross section of Labuan Block System

Sediment accumulation was observed during the site assessment especially on top of toe section and in front of LBS reaching to the weep holes level. This implied the ability of the LBS to dissipate wave which then allowed accumulation of sediment at the structure. It also indicated the toe section was submerged during high tides and promoted sediment to settle at the structure. Sediment accumulated at the structure is categorized as poorly graded sand material according to ASTM D 2487 standard based on the sample's sieve analysis with median grain size ranged between 0.97 mm to 1.11 mm. Some of the units were also observed to experience settlement with certain toe sections displaced in vertical direction. Wave reflection at the structure would have been the possible main cause for the scouring at the toe section of the LBS. The rigid and flat shape of toe section resulted into high possibility of reflection when the wave hit the structure.

Most of the main section of LBS had experienced abrasion due to friction between the sediment particles and LBS surface especially at the edge and corner of the LBS. The Rebound Hammer test showed that the surface strength of LBS installed is nearly 40 N/mm^2. Hence, it met the requirement mentioned by [12] for unreinforced armor units. No excessive cracks were observed during the assessment and most of the LBS have minor cracks at the concrete surface. Scouring of crest and behind of the LBS was also observed. This was caused by the overtopping wave, where the high volume of water bodies overtopped the structure and eroded the crest portion. Cracks and breakage of concrete caps with width of 1.2 m were observed but no under-layers were extracted from the crest section.

B. SINE-SLAB at Tanjung Kling

Tanjung Kling which is located 20 km north of Melaka town is significantly important for tourist attraction. New developments especially for tourism purposes sprung rapidly along the coastal area. Many chalets and hotels were constructed along shoreline, thus affected the morphological processes at the shoreline. According to the pilot study done by [11], the coastline has retreated more than a meter per year and this was supported by [2] which classified this as critical erosion area. Subsequently, a collaborative effort between Universiti Teknologi Malaysia (UTM) and Department of Irrigation and Drainage Malaysia (DID) has led to the first Sine-Slab application in front of Shah Beach Resort in Tanjung Kling to mitigate the erosion problem.

Initially a 120 m stretch of coastline was lined with Sine Slab revetment with slope of 1:3 as reported by [11]. Later, an extension of 500 m was done in 2006 reaching Sekolah Menengah Lereh. The crest width of the structure was approximately 2 m with a sea wall to prevent splashing of overtopping wave. A geotextile was provided before placing the armor unit in order to separate the in-situ material and fill material. A toe made of rock was provided to stabilize the slope and helped to slow down the incoming wave. Besides, the toe is important to prevent scouring at the bottom section that may result in sliding failure and movement of Sine-Slab. The typical cross section of the revetment is as shown in Fig. 3.

Sedimentation was observed at site, where the sediments were accumulated at the structure's face. The sediments was also observed at the crest, thus indicated that the wave reached the crest and transported the sediment there. Generally the sediment can be categorized as poorly graded sand with median grain size ranged between 1.05 mm to 1.19 mm. Almost no displacement of the armor units were identified during the assessment, a small gap was identified at the turning section of the stretch. The gap was intentionally done during

the construction of the structure due to the rigid placement of the armor units, thus it does not perfectly fit at particular section. Presence of vegetation was detected especially at dry area and between gaps of the armor unit.

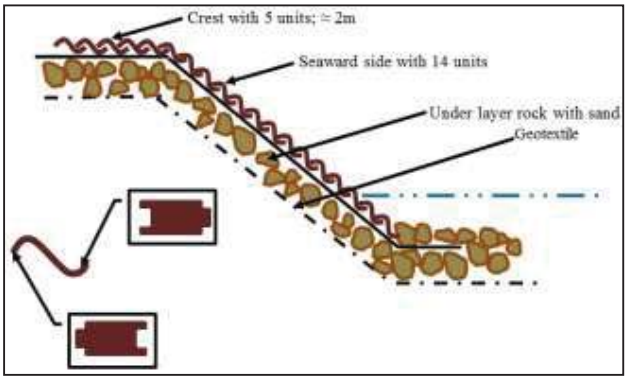

Figure 3. Cross section of Sine-Slab Revetment

The Rebound Hammer Test showed that the Sine-Slab has concrete surface strength of 41 N/mm^2 and this met the typical mix specification by [12] for reinforced concrete armor unit. Breakage and crack armor units were observed and eroded reinforcement bars were identified based on visible brownish color on the concrete surface. Some of the armor units' reinforcement steel was already exposed caused by the breakage. The eroded reinforcement was caused by reaction of salt water with steel reinforcement thus lead to expansion of the steel and result into breakage of armor unit. This problem was expected in every concrete armor unit with reinforcement as highlighted by [13] and [14]. Hence, [15] suggested that reinforcement with sufficient cover depth must be provided to minimize the effect of salt water entrainment into the concrete. This is also supported by [12], where a minimum cover of 40 mm must be provided when the armor unit is constantly in contact with sea water.

C. SAUH at Sungai Haji Dorani

SAUH is an innovative armor unit produced by the Department of Irrigation and Drainage. The armor unit has high interlocking capability to minimize the concrete consumption and reduce dependency on weight to obtain stability. SAUH has been successfully implemented at Sungai Haji Dorani, Selangor to minimize erosion at the coastline. The coastal area consisted of muddy beach with weak soil condition while fluid muds were observed especially during high tide as reported by [8] and [10].

Earth bunds were constructed along the coastline to prevent intrusion of sea water to agriculture land during high tide and monsoon season. This result into diversion of freshwater and sediment input to the coastline and caused partial starvation of sediment to the coastline. This issue has been discussed in many studies done by [1], [2] and [16]. Deforestation of mangrove fridges for agriculture activities and tourism reported by [4] had also accelerated the erosion rate. This finding was supported by [17] which underlined the importance of the mangrove fridges in reducing wave action and shelter the beach from direct wave action.

A total of 1.5 km of coastline was protected by SAUH revetment at Sungai Haji Dorani and the project was constructed in 1991 by the Department of Irrigation and Drainage, Malaysia [8]. SAUH has impressive interlocking, the slender members of SAUH provide interlocking with adjacent units. It was observed that breakage of the armor units occurred at the joints and center section. This may cause by high force concentration at the corner of the units. This was supported by [18], where [19] suggested that features such as chamfering and fillet need to be provided at the members. In addition, SAUH does not have any reinforcement steel thus the breakage is also contributed by tension force from the wave action. This is in line with finding by [20] during their study on performance of Dolos under wave action.

Accumulation of sediments especially shells was observed at the structure. Assessment by [10] also mentioned that SAUH was able to reduce the wave action at the coastal bank and was subsequently result in sediment accumulation at the structure. Some settlements of the structure were identified due to poor soil condition. Soft clay has low bearing capacity, where it cannot sustain heavy loads or pressure [9]. Therefore, some settlement at SAUH revetment is expected to occur because of the soft nature of ground of the area.

A. L-Block at Sungai Haji Dorani

Sungai Haji Dorani is located in Sabak Bernam district where the economy is mainly contributed by agricultural activities and fisheries. The beaches along this area were consisted of soft clay and muds deposited by nearby rivers. Mangroves fridges were also observed along the coastline thus helped in dissipating the wave's forces. The wave climate according to [2] is reasonably mild with wave height less than 1.50 m in normal condition and 2 to 3 m during severe storm. Developments at coastline that led to deforestation of mangroves have caused erosion hence raised initiatives by government agencies to mitigate the erosion problems as reported by [8] and [1]. Collaboration between University of Malaya and FRIM resulted into innovation and implementation of L-Block breakwater in Sungai Haji Dorani, which was constructed in front of SAUH revetment.

L-Block is a concrete armor unit with rectangular frame equipped with four legs to provide interlocking between the neighboring units. The armor unit as mentioned by [4] was implemented in series of segmented emerged breakwaters to protect a mangroves rehabilitation project behind the structure. Settlements of the structures were expected and a bamboo mat was used to provide an equally distributed force and resulted into even settlement [21]. Besides, the bamboo mats were also helped to minimize the settlement, [21]. The L-Block units were placed in a single layer and overlapped with each other. The uneven length of the legs helped in enhancing the interlocking and ease in placement process. The cross section of the breakwater is shown in Fig. 4 and Fig. 5.

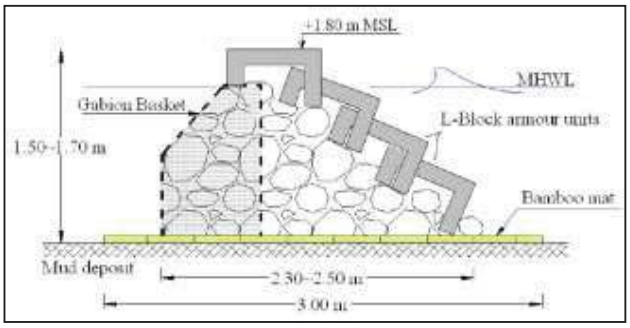

Figure 4. Cross section of L-Block Revetment by [4]

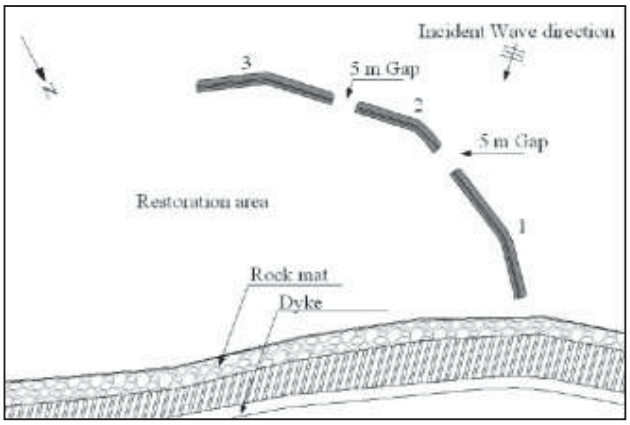

Figure 5. Location of Segmented L-Block Breakwaters by [4]

L-Block armor unit has reinforcement bars to improve the armor unit strength and help in resisting tension force. Corrosion of the reinforce bars were observed in most of the armor units caused by intrusion of seawater through the cracks. Visible brownish substance of Fe^{+3} appeared at the concrete surface. Besides, the gabion basket holding the under layer and core materials for lee section were also found to be eroded. In addition, displacement of the armor units occurred at the crest and lee side level caused by overtopping wave focused at the crest especially during high tide. The opening provided at the frame section of L-Block is used to dissipate wave energy and this has positively resulted in the accumulation of sediments behind the structure.

III. DISCUSSION

Most armor units invented by Malaysian researchers are suitable to be applied as revetment based on the armor unit characteristics. One of these is Sine-Slab developed by Universiti Teknologi Malaysia which is made of concrete slab with sine shape and designed to be applied as armor layer on revetment slope [11]. The Sine-Slab has considerably high interlocking capability. The porosity provided by the gap between the units enabled vegetation to grow and sediment to be accumulated at the unit's surface.

Labuan Block System (LBS) is an attractive protection structure with the advantage of fast and easy installation. Thus, LBS are convenient alternative as emergency protection structure when erosion started to endanger local community and infrastructures near the coastal area. LBS are more suitable for sandy beaches with high soil strength because of the massive weight of the units which may impose in excessive settlement.

L-Block and SAUH have outstanding performance in muddy beaches due to their lightweight characteristic and highly interlocking feature. The usage of bamboo mattress in L-Block segmented breakwaters are also a brilliant idea where the mattress helped in spreading the structure load evenly to the ground, thus preventing uneven settlement from occurring.

The summary of the geometric details and design parameters and beach characteristic of the assessed sites can be referred to Table I and Table II respectively.

TABLE I. SUMMARY OF GEOMETRY DETAILS

Structure	Type	Front Slope	Height (m)	Crest Width (m)	Length (km)
SAUH	Revetment	1:2	3.00	-	1.50
L-Block	Breakwater	1:1.5	1.70	0.40	0.80
LBS	Revetment	-	1.50	0.50	1.50
SINE-SLAB	Revetment	1:3	1.00	2.00	0.62

TABLE II. SUMMARY OF DESIGN PARAMETERS AND BEACH CHARACTERISTIC

Structure	Strength (N/mm^2)	Under-layer size (m)	Beach material (mm)	Dominant Wave	
				Height (m)	*Direction*
SAUH	40	-	0.002-0.05	1.50	SW & WNW
L-Block	35	0.2-0.3	0.002-0.05	1.50	SW & WNW
LBS	40	0.4-0.6	0.97-1.11	2.00	SW & WNW
SINE-SLAB	40	0.1-0.15	1.05-1.19	2.00	SW & WNW

While Sine-Slab is probably more attractive for recreational beaches, usage of SAUH armor unit would be very practical in most part of the muddy rural areas especially where access to the beach is not important. In addition, usage of reinforcement bars in concrete armor unit must be properly designed and with sufficient depth of cover to avoid failure of the armor unit due to corrosion of steel bars. As it can be observed in most of reinforced concrete armor units assessed at site, breakage problem occurred in unreinforced concrete armor unit where the wave load concentrated at the corners and joints. Hence, extra cover may reduce the possibility of breakage.

Gabion made by steel wires that contained the under-layer material for L-Block has the tendency to be corroded. Once damaged, the instability of the back side of the breakwater will be affected. Failure may occur during high tides and severe storm that can lead to dislodgment of under-layer material and instability of armor unit at crest. Affected part of the crest and back section were already visible during site assessment.

Several neighboring armor units at crest were noticeably displaced from original location especially at sections where the underlying gabions were damaged.

CONCLUSION

The site assessments have revealed current status and possible gaps in design and application of various concrete armor units along West Coast of Peninsular Malaysia. Improvements and modifications of the armor units are possible to enhance their performance.

Coastal erosion especially in mudflats areas remains challenging and still requiring serious attention as it may potentially lead to severe damage. Usage of armor unit with interlocking capability and lightweight characteristic is useful to reduce failure due to excessive settlement. Reinforce concrete has great benefit in reducing tendency of breakage and a precaution of corrosion must be taken into consideration by providing sufficient concrete cover. Aesthetic value of protection structure is also important consideration especially at holiday beaches. Summary of assessment on the armor unit's performance is tabulated in Table III.

TABLE III. SUMMARY OF STRUCTURE PERFORMANCE

Structure	Advantages	Disadvantages
SAUH	High interlocking capability	Difficult to access the beach
	Lightweight	Weak in tension
	Promote settlement	Potential breakage at joints
L-Block	High porosity for dissipation	Weak interlocking at lee side
	High interlocking with neighboring units	Breakage due to corrosion
LBS	Fast construction process	High possibility for reflection
	Excellent for emergency protection measure	Massive weight
	Promote settlement	Unsuitable for mudflats
SINE-SLAB	Give access to beach	High run-up
	Promote settlement	Rigid placement
	Good esthetic value	

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