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Shoreline Response to Three Submerged Offshore Breakwaters along Kerteh Bay Coast of Terengganu

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Abstract: This study will attempt to create a predictive empirical model exclusively for SBWs (submerged breakwaters) in terms of mode (erosion or accretion) and magnitude (size of salient) of formation. In the past, prediction of shoreline response to SBWs was done based on predictive empirical model for generalized offshore breakwaters (Submerged & Emerged). But majority of documented response of prototype submerged structures result in erosion rather than accretion in there lee. It is believed that these structures don't perform as expected because a generalized predictive empirical model is used to predict the shoreline response to these structures. A numerical model MIKE 21 CAM and aerial/satellite imagery will be adopted to deduce relationships between structural and environmental parameters, which will result in formation of a predictive empirical model. An ideal prototype of SBWs is available in Kerteh, Terengganu, Malaysia. This will serve as a study area and the results from the Numerical model and aerial/satellite images will be validated with results from the study area. The predictive empirical model will as well be tested on the study area. It is expected that a contribution will be made towards the understanding of the key parameters that governs the mode (i.e., erosion and accretion) and the magnitude (i.e., size of salient) of shoreline response to SBWs. It is also expected that a predictive empirical model will be established to accurately predict shoreline response in terms of mode and magnitude of SBWs.

Keywords: Aerial/satellite imagery, coastal erosion, numerical modeling, predictive model, submerged breakwater

INTRODUCTION

Coastal erosion is a global problem; at least 70% of sandy beaches around the world are recessional (Bird, 1985). Approximately 86% of U.S East Coast barrier beaches (excluding evolving spit areas) have experienced erosion during the past 100 years (Galgano *et al*., 2004). Widespread erosion is also well documented in California (Moore *et al*., 1999) and in the Gulf of Mexico (Morton and McKenna, 1999). This natural phenomenon is said to be reported in Asian and other countries along the ocean. Erosion has been reported in China (Bilan, 1993), also in Vietnam by Mazda *et al.* (1997).

India has not been spared either, this was reported by (Gopinath and Seralathan, 2005). Swan (1984) also reported such phenomenon in Sri Lanka. Indonesia and Thailand has also been reported to have such phenomenon, these were reported by Nurkin, (1994) and Thampanya *et al*. (2006) respectively.

Emergent coastal structures, such as groynes, detached offshore breakwaters and sea walls have been successfully adopted as coastal protection measures for many decades (Dean and Dalrymple, 2001; Silvester and Hsu, 1997; Seiji *et al.*, 1987). However, these types of highly intrusive and aesthetically unappealing engineering structures are becoming increasingly unpopular among the more environmentally aware modern communities. As a result, submerged breakwaters (SBWs), which do not impair beach amenity or aesthetics, are becoming a preferred option for coastal protection (Burcharth *et al*., 2007). However SBWs have rarely been adopted for coastal protection in the past and therefore, their efficacy remains largely unknown. Furthermore, enhanced shoreline erosion has been reported in the lee of the structure of several SBW project (Ranasinghe *et al*., 2006). Clearly, a better understanding of the characteristics of shoreline response to SBWs is required prior to routinely adopting SBWs for coastal protection.

While some investigations suggest that submerged breakwaters may results in larger salients than those that would results from emergent breakwater of similar size, other investigations indicate that submerged breakwaters may results in shoreline erosion in the lee of the structures. In contrast, shoreline erosion is almost never reported in the lee of emergent breakwaters. Therefore, it is likely that the characteristics of and processes governing shoreline response to submerged and emergent structures are fundamentally different. As result, the well

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established methods that are currently used to predict shoreline response to emergent structures (e.g., empirical relationships, one-line numerical models) may not be suitable to investigate shoreline response to submerged breakwaters (Ranasinghe *et al.*, 2006).

Problem statement:

- As submerged structures have only rarely been adopted for beach protection, the shoreline response to these structures is not well understood at present.
- Prototype data on the performance of submerged breakwater around the world are insufficient.
- From the available published data on prototype SBWs there are more of erosion than accretion reported at the lee of the structures.
- Results from Numerical and Physical modeling are conflicting with what is available from prototype data.
- Inconsistent and confusing observations from results of numerical and physical modeling of shoreline response of SBWs further illustrate the need for a focused and comprehensive investigation.

Objectives: Primarily the objective of this study is to study the shoreline response to three submerged breakwaters at Kerteh bay. Specifically, the study will attempt to:

- To identify key structural and environmental parameters governing the mode of salient formation (erosion or accretion).
- To identify key structural and environmental parameters governing the magnitude of salient formation (volumetric size).
- Develop a predictive empirical formula based on the finding of above objectives.
- Evaluate the performance of the SBWs at sites.

Scope: The study will be limited to the following:

- Uses of the Numerical model MIKE 21 CAM to study shoreline response to three submerged breakwater parallel to the shore. The structural parameters that will be investigated are; structure length, structure crest, distance from shoreline to structure and gaps in between structures. For validation, a beach profile survey will be carried out at Kerteh bay where three submerged breakwaters are available. Simulation of the structural parameters and environmental parameters available at the study area will also be carried out using the same numerical model. This will provide for correlation between the results from the beach profile survey and the simulation of the same structural and environmental parameters of the study area. Further correlation will be achieved with comparison of results with past studies.
- Aerial photographs/satellite images will be obtained for all of the documented sites with SBWs in different part of the world. Sites in Japan, Italy, US and Australia are chosen for this exercise. Ten sites with this type of mitigating structures are selected based on publication of the structural parameters availability. With the use of the GIS software ERDAS, the magnitude of salient formed after the construction of the structures will be extracted. The environmental and structural parameters that govern the magnitude of this formation will be identified. The environmental parameters will be obtained using MIKE 21 SW software this will be done by obtaining hindcast hydrodynamic parameters. Validation will be achieved by means of beach profile survey of the study area.

LITERATURE REVIEW

Study area: The study area is located within a town called Kerteh in the district of Kemamam in Southern Terengganu, Malaysia, about 30 km or 20 minutes' drive north of Chukai. Kerteh is the base of operations for Petronas in Terengganu, overseeing the oil platform operations off the state's coast. Kemamam is a district of 2,536 km^2 area with a population of 174,876. It geographical location is 4º 31′ 38″ N and 103º 28′ 9″ E. The stretch of the beach protected is approximately 2100 m. The study area is characterized with much of its coast to be a series of large and small hook-shaped bays, fully exposed to direct wave attack (especially during the NE-monsoon) from the South China Sea. The geomorphologic feature of Kerteh bay is such that its development is controlled by protruding headlands. Most of the bays along this region are considered to be in dynamic equilibrium; this is when constant supply of material from upcoast or within its embayment is passing through the bay and beyond the downcoast headland. The littoral drift rate, associated with the dynamically stable configuration of Kerteh Bay, has been computed to be some 210,000 m^3/yr of which more than 80% is transported during the NE-monsoon period.

The cause of the coastal erosion at the study area Kerteh bay, was studied by Tilmans *et al.* (1992). Some major causes were highlighted by the researchers. The beach platform at Kerteh bay is such that there exists a continual longshore sediment transport from upcoast to downcoast, disruption of this dynamic stability may easily occur when upcoast sediment supply is (partly) cut off which can result into erosion of the coast leading to a larger indentation of the bay configuration. If the entire upcoast sediment supply is cut off, the bay would become even more indented until littoral drift ceases. Another factor indentified is the cross-shore sediment transport, although it was reported that this factor doesn't have as much effect as the longshore sediment transport. The direction and intensity of this transport phenomenon are ruled by the wave steepness, geometry of the seabed slope and the size of the seabed particles. The beach will accrete at moderate wave conditions and recede under severe wave attack

The third factor is the supply of sand by S. Kerteh river discharge. Unlike the larger rivers in the region such as S. Terengganu, S. Dungun and S. Kemaman, it was found that S. Kerteh River only drains a very limited catchment and it is unlikely that its sediment yield will be of significance for beach stability. The last factor indentified to be affecting the stability of the coastal area within Kerteh Bay is considered to be the human activity such as removal of natural dune systems and vegetations.

An interesting phenomenon that affects the coastal erosion at Kerteh Bay is the upcoast sediment supply from Paka Bay which is largely transferred into Kerteh Bay through offshore bar bypassing at the northern end of the bay. The "supply point" on to the coast of Kerteh Bay is located immediately updrift from Rantau Petronas Complex, which makes this coastal stretch particularly vulnerable to any disruption of the equilibrium situation. This is reflected in the shoreline mapping from 1966 to 1987; the observed erosion over this period would indicate an average deficit in the upcoast sediment supply of some 40,000 m^3/yr. The causes and persistency of this deficit in unknown, but quite likely originate from S. Kerteh influence (disruptive of bar bypassing) and from shore developments within the upcoast Paka Bay, undertaken since the late sixties.

From the findings of the cause of coastal erosion at Kerteh Bay, Tilmans *et al*. (1992) proposed some mitigation measures. By careful examination of the geomorphologic situation of the Kerteh Bay and acknowledging the cause of erosion at the Rantau Petronas Complex, various defense schemes were proposed. An artificial supply of sand (beach nourishment, perched beaches), structures to prevent waves from reaching erodible materials such as bulkheads, seawalls, revetments and offshore breakwaters and the last being structures to slow down the rate of littoral transport such as groynes (trapping the sediment) or offshore breakwaters (reducing the wave energy in the coastal zone) were all among the methods proposed.

The beach nourishment and use of three offshore submerged breakwaters were adopted for the purpose of mitigating the coastal erosion at the affected area as it the time of the study carried out by Tilmans *et al*. (1992). Subsequently, after sometime erosion occurred at further north and south of the protected area.

No doubt the findings of Tilmans *et al.* (1992) have been of tremendous use for the mitigation of the coastal problem at a time. Their findings led to the construction of three submerged breakwaters with beach nourishment to mitigate the coastal problem at a specific time. The solution could be considered relatively effective considering the problem at that time but no monitory survey has been carried out since the installation to evaluate the performance of these structures but erosion has been noticed at the south and north of the protected area.

Shoreline response to submerged structures: Emergent coastal structures, such as groynes, detached offshore breakwaters and sea walls have been successfully adopted as coastal protection measures for many decades (Dean and Dalrymple, 2001). This type of breakwaters is common in the US and Europe (Dean and Dalrymple, 2001) and even more so in Japan, where Seiji *et al*. (1987) reported the completion of over 4000 emergent breakwaters by the mid-1980s. However, these types of highly intrusive and aesthetically unappealing engineering structures are becoming increasingly unpopular among the more environmentally aware modern communities. As a result, Submerged Breakwaters (SBWs), which do no impair amenity or aesthetics, are becoming a preferred option for coastal protection (Burcharth *et al*., 2007; Ranasinghe *et al.*, 2006; Lamberti and Mancinelli, 1996). However, SBWs have rarely been adopted for coastal protection in the past and therefore, their efficacy remains largely unknown. Furthermore, enhanced shoreline erosion has been reported in the lee of the structures at several SBW projects. (Ranasinghe and Turner, 2006) carried out a comprehensive review on documented projects of submerged breakwater in different parts of the world, unfortunately not many of these type of project are available, from the ten projects reviewed erosion were noticed at the lee of 7 of the projects. A detailed review of the projects is provided in the subsequent paragraphs.

The performance monitoring of a single submerged breakwater which was expected to 'hold' an artificial sand deposit on the beach in Delware Bay, USA was reported by Douglas and Weggel (1987). The structure departed somewhat from a conventional shore-parallel submerged breakwater configuration in that the two ends of the breakwater were connected to the shore by oblique submerged groynes, creating a quadrilateral enclosed area adjacent to the shoreline. The breakwater was 300 m long and was placed 75 m offshore in approximately 1 m water depth. The crest of the structure was at Mean Low Water (MLW). The construction of the structure was accompanied by a beach nourishment program which pumped approximately 15,000 m^3 of coarse sand into the enclosure. The estimated net annual longshore transport rate in the study area was a negligible 2000 m^3/year (gross 10,000 m^3/year). The results of 4 years of periodic beach profile survey indicated initial formation of an asymmetric salient in the lee of the structure, immediately following the beach nourishment. However, the entire volume of beach nourishment had disappeared within the 4-year monitoring period. Douglas and Weggel (1987) attributed this erosion to the net longshore sediment transport resulting from oblique wave incidence. However, it is noted here that the estimated net longshore transport rate of 2000 m^3/year is small as far as nearshore processes are concerned.

The performance of an 80 m long, 20 m wide shore-parallel submerged breakwater at Keino-Matsubara Beach, Japan was reported by Deguchi and Sawarangi (1986). The structure was placed 85 m offshore in approximately 4 m water depth. The crest level was 2 m below MLW and the ambient beach slope in the shallower region (<2 m depth) was about 0.10, while that of the deeper region was about 0.03. A sand volume of 5000 m^3 was placed in the lee of the structure during the accompanying beach nourishment program. Surveys at the site indicated that about 50% of this sand volume was eroded within 2 months after project completion. Although the incident wave conditions or longshore sediment transport rates in the study area were not described by Deguchi and Sawarangi (1986), here too, it was implied that the erosion was due to obliquely incident high energy waves.

Monitoring of waves, currents and bed-level changes in the lee of a shore-parallel submerged breakwater at Niigata, Japan was reported by Funakoshi *et al.* (1994). The 540 m long submerged breakwater was located 400 m from the shoreline in about 8.5 m water depth and located immediately offshore of and between two shore-normal groynes. The two adjacent groynes were 200 m long, thus resulting in a semi-compartmentalisation of the area encompassed by the three structures. The crest of the submerged breakwater was 20 m wide and at a depth of 1.5 m below Mean Water Level (MWL). The ambient bed slope was 0.02. three months of wave and current data obtained near the structure were analysed by Funakoshi *et al*. (1994). Although the net longshore sediment transport rates in the study area were not described by the authors, the offshore wave records indicates that waves would most likely be obliquely incident at the shoreline, resulting in significant longshore sediment transport. Funakoshi *et al.* (1994) main findings were two-fold: first, storm events were accompanied by strong divergent currents in the less of the structure; and second, bed erosion of up to about 1 m was observed in the lee of the structure. No discussion was provided on the possible causative mechanisms for the observed rapid rate of erosion in the lee of the structure.

The contrasting shoreline response in the lee of two different submerged structures located along the Italian coastline in the vicinity of Rome (Lido di Osita), near the Tiber River entrance, were reported by Tomassicchio (1996). The net longshore sediment transport in the study area was estimated at about 50,000 m^3/year. The first structure was a 3000 m long, shore-parallel submerged breakwater with a crest width of 15 m and crest level of 1.5 m below Mean Sea Level (MSL). The structure was located about 100 m from the shoreline in approximately 4 m water depth. The ambient bed slope in the vicinity of the structure was about 0.05. The project included a major beach nourishment component were 502,000 m^3 of fine sand and 888,000 m^3 of a gravel and coarse sand mix was placed. The performance monitoring of this structure revealed shoreline erosion in the lee of structure 1 year after the structure was completed in 1991. analysis of aerial photographs before and after construction indicated that the submerged breakwater was providing no detectable benefit and that erosion rates in the vicinity of the structure remained unchanged. Tomassicchio (1996) attributed this negative shoreline response to the erosive processes first described by Dean *et al*. (1994), which are discussed in detail further. An annual sand supply of 15,000 m^3/km was estimated as the minimum requirement to counter the erosion attributed to the structure.

The second structure reported by Tomassicchio (1996) constructed 1 year later in 1992, was located along the neighbouring coastline. This structure was shore-parallel, 700 m long and consisted of a 15 m wide crest located 0.5 m below MSL. The structure was located about 50 m from the shoreline in approximately 3-4 m water depth. The ambient bed slope in the vicinity of the structure was about 0.10. This structure was not accompanied by a beach nourishment program. In constrast to the first and significantly larger structure, this second structure resulted in widening of the beach (15 m and 30 m) in the lee of the structure immediately after construction, Tomassicchio (1996) does not discuss the coastal processes that may have caused this constrasting shoreline response in the less of the two structures.

The initial performance of submerged breakwaters in the two Italian coastal regions of Emilia Romagna and Marche was reported by Lamberti and Mancinelli (1996). The net longshore sediment transport rates in both these areas were expected to be negligible. A shore-parallel, 770 m long submerged breakwater was constructed at Lido di Dante in the Emilia Romagna region to complement an existing series of emergent groynes which were reported to be ineffective at preventing erosion. The undisturbed shoreline in a water depth of approximately 3 m, with an ambient bed slope of 0.02. The crest width of the structure was 12 m while the crest level was 0.5 m below MSL. The construction of the structure was accompanied by a beach nourishment program. A maximum beach widening of 30 m was observed soon after the project was completed. However, long-term performance monitoring of the structure was not reported.

In the Mache region, submerged breakwaters were constructed along a number of beaches with existing groynes (e.g., Sirolo, Numana, Pesaro, Montemarciano, Ancona) since 1982. The structure were typically located between 100 and 200 m from the shoreline in approximately 3 m water depth. Beach nourishment programs accompanied the structures located in lower lying areas of this region. No nourishment was provided along rocky coasts. These structures were typically 3 m wide at the crest and the crest level was 0.9 m below MSL. The gap between breawters was about 30 m. However, several drawbacks, which included heavy erosion in the gaps between the breakwaters and high submergence during storms which led to insufficient wave energy dissipation, were noted for thes initial structures. In response they were replaced with modified strucuteres with increased crest widths of 10-12 m and slightly raised rest levels of 0.5 m below MSL. Beach nourishment was not included with these second-generation structures. Although Lamberti and Mancinelli (1996). The substitution of submerged breakwaters for preexisting emergent breakwaters at Senigallia was reported to have resulted in the disappearance of tombolos and a subsequent shoreline retrest of 20-30 m. Lamberti and Mancinelli (1996) do not discuss possible causative mechanisms for the observed shoreline responses.

The performance monitoring of a shore-parallel, 1260 m long submerged structure at Palm Beach, Florida (commonly known as the ‘PEP reef’) was reported by Dean *et al*. (1997). The structure comprised of 330 precast interlocking units. The individual units were 1.8 m high, 3.7 m long and 4.6 m wide at the crest. The structure was located about 70 m from undisturbed shoreline in about 3 m water depth (ambient bed slope ~ 0.04). The crest level of the breakwater was 0.7 m below Mean Low Low Water (MLLW). The net longshore sediment transport rate in the study area was estimated to be 100,000 m^3/year. The monitory indicated that the erosion which occurred in the lee of the structure was twice as much as the background erosion in the area. Dean *et al*. (1997) attributed the failure of the submerged PEP reef to insufficient wave attenuation (5-15%) over the structure due to the low crest level. This high degree of wave energy transmission was expected to have resulted in significant noshore flow over the reef, which then deflected in the nearshore, resulting in strong longshore currents. The observed beach erosion in the lee of the structure was attributed to these diverging longshore currents. The monitoring also indicated significant was found to have occurred during the first few months after construction.

Stauble *et al*. (2000) described the monitoring of a shore parallel, 915 m long segmented PEP reef, constructed of similar precast units, at Vero Beach, Florida, with similar results. The segments were constructed in a alternating inshore-offshore configuration with gaps in between. The structure consisted of 217 precast units and 11 segments. The inshore segments were at 2.1 m water depth, while the offshore segments were at a 2.7 m water depth. The crest levels of the inshore and offshore segments were 0.25 m above MLLW and 0.35 m below MLLW respectively. The entire structure was located about 85 m offshore. The ambient bed slope was 0.03. The net longshore sediment transport rate in the area was estimated to be approximately 30,000 m^3/year. The staggered configuration was expected to overcome the previously observed shortcomings of the Palm Beach PEP reef. However, similar to the Palm Beach experience, beach erosion in the lee of the structure was greater

Laboratory and numerical modeling studies of shoreline response to submerged structures undertaken to date imply that

- shoreline accretion is likely to occur in the lee of submerged structures located on coastlines with significant ambient longshore sediment ransport
- shoreline erosion is likely to occur in the lee of submerged structures located on coastlines with predominantly shore normal wave incidence (Ranasinghe *et al*., 2006).

However, field observations from documented prototype structures available contradict these implications. For example, shoreline erosion was in the lee of submerged structures located on coastlines with significant (>50,000 m^3/year) and moderate (20,000 - 50,000 m^3/year) longshore sediment transport (e.g., Lido di Ostia in Italy and Vero Beach in Florida, respectively). Also submerged structures located on coastlines with near shore normal wave incidence (i.e., negligible longshore sediment transport) have resulted in shoreline accretion (e.g., Lido di Dante, Italy). Such inconsistent and confusing observation further illustrate the need for a focused and comprehensive investigation of shoreline response to submerged structures.

The above project were monitored by field observation, other studies were carried out in both a physical and numerical model to study the change in shoreline as a result of submerged structures. Ranasinghe *et al*., (2006) also reviewed six studies that were carried out in a physical model, two of these studies involve the use of fixed bed, two mobile bed and two involved both fixed and mobile bed. Out of the six studies reviewed four indicated erosion at the lee of the submerged structures, one indicated accretion and one inconclusive. And, also three studies were carried out using numerical model two indicated erosion and one accretion.

From the above studies carried at different location, monitored through the beach survey exercise, studied through the use of both numerical and physical model, it is obvious that a better understanding of the characteristics of shoreline response to SBWs is required prior to routinely adopting SBWs for coastal protection.

Past studies on the effect of offshore breakwaters in shore protection: In the past a much generalized study has been carried out by different researchers to study shoreline response to offshore breakwaters (submerged and emerged). These studies were quite comprehensive and have been validated using field study, numerical model and/or physical modeling. The results for these studies have been consistent with numerous offshore breakwaters (emerged) prototype constructed in the past. With reference to emerged breakwaters their has been more success stories than unsuccessful stories. The following paragraphs highlight some of the studies that have been carried out in this respect.

Dally and Pope (1986) presents several techniques for controlling shoreline response to a single or segmented offshore breakwater project. They recommended the following limits for the structure length-distance offshore ratio (B/X) (and gap (G) distance (X) for segmented systems) based on the type of beach planform desired and length of beach to be protected. For tombolo development,

B/X = 1.5 to 2 (single breakwater)
B/X = 1.5, $L \leq G \leq B$ (segmented breakwaters)

where, L is the wave length at the structure for salient formation,

B/X = 1.5 or 0.67 (single and segmented breakwaters)

Nir (1982) developed based on the prototype data (the Israel Mediterranean Shore) the following relationship between the distance offshore to the breakwater length ration (*X/B*) and average tombolo sand layer thickness (d_s):

$$d_s = 1.78 - 0,809\ X/B$$

Pope and Dean (1986) defined based on the prototype a shoreline classification scheme that included five types of beach response; tombolos, salient and no sinuosity. A relationship was developed that gives the beach response classification scheme as a function of the ratios of segment length to gap length B/G and effective distance offshore to the average water depth at the structure X_e/d_s Harris and Herbich (1986) explained based on prototype and field data the following relationship between the amount of sand accumulation in the sheltered area (Q_b) and the distance of the breakwater from the shoreline (X):

$$Q_b/xBd = \exp(0.315-1.922\ X/B)$$

Silvester and Hsu (1997) developed based on the prototype data and laboratory results, the following relationship between the ratio and salient distance to breakwater length (X_s/B):

$$X_s/B = -0.1626 + 0.8439(X/B)^2$$

Hanson and Kraus (1990) carried out an experimental study for offshore breakwaters. They have some criteria of shoreline change behind the breakwater. Tombolos and salient formed when,

$B/L \leq 48\ (1-K_T)H_0/d$ (salient)
$B/L \leq 48\ (1-K_T)H_0/d$ (tombolo)

where, B is the breakwater length, L is wave length on the breakwater, H_0 is deep sea wave height, d is depth of water in front of the breakwater and K_T is coefficient of breakwater permeability.

McCormick (1993) gave based on experimental data the following relationship for the prediction of salient and tombolo forming:

$$0.38 < \varepsilon_0 < 0.83 - \varepsilon_0 = \frac{H0/_{L0}}{m} \text{ (tombolo)}$$

X/B<0.6 (*tombolo*)

X/B >0.6 (*salient*)
$15 < \propto_0 < 60$ (*salient*)
$\propto_0 = 45^o$ (tombolo)

Wen-Juinn and Ching-Ton (1995) showed based on laboratory results the following relationships between Q_b and $^X/_B$:

$$\frac{Q_b}{H_0^2 G} = 28{,}46\left(\frac{X}{B}\right)^{3.67} \exp\left(-\left(\frac{X}{B}\right)^{2.1}\right)$$

$$\frac{Q_b}{H_0^2 G} = 1.13\left(\frac{X}{B}\right)^{0.6} \exp\left(-\left(\frac{X}{B}\right)^{6.1}\right)$$

where, (Q_b) is the amount of sand accumulated in the sheltered area, X is the distance of the breakwater from the shoreline, B is the breakwater length and G is the gap between breakwaters, d is the water depth of breakwater.

Hakeem *et al.* (2010) carried out a study that involve the modeling of the effect of nearshore detached breakwaters on sand macro-tidal coasts. The use of two numerical model were used, MIKE 21 CAM and PISCES. They came up with some findings which include; for a given breakwater location in the surf zone (X/Xb), the salient length (S/X) increases as the dimensionless breakwater length (Ls/X) increases.

In summary the following *B/S* ratios have been proposed.

B/S<0.5 Non-depositional conditions (NIR, 1982)
B/S = 0.5-1.0 Salient formation (Anonymous, 1984)
B/S>0.67 Tombolo formation, (Gourlay, 1981)

Table 1: Shoreline response behind offshore breakwaters

Formation	B/S range	Average B/S value
Tombolo	>0.67-2.5	>1.5
Salient	0.4-1.5	0.8
None	≤0.125-0.5	<0.25

The ratios define limiting parameters for salient and tombolo formations disregarding external factors such as sediment input, wave hydrodynamics and beach properties. An overlap has been identified in the literature for B/S ratios defining the salient and tombolo division. Generally, tombolo formations are expected to develop when:

The Coastal Engineering Manual (CEM), published by the US Army Corps of Engineers, presents numerous theories on the prediction of shoreline response behind nearshore breakwaters (U.S. Army Corps of Engineers (2006). The different theories present a wide range of structure width (B) to offshore distance (S) ratios for salient and tombolo formation. The ratios are summarized in Table 1. The methods presented in the CEM are not specific to submerged structures and are typically used for predicting the response to emergent breakwaters. The CEM methods offer only qualitative predictions and do not attempt to predict the size or shape of the response.

Ranasinghe (2006) reported that some investigation suggest that submerged breakwaters may result in larger salient than those that would result from an emergent breakwater of similar size, other investigations indicate that submerged breakwaters may result in shoreline erosion in the lee of the structure. In contrast, shoreline erosion is almost never reported in the lee of emergent breakwaters. Therefore, it is likely that the characteristics of and processes governing shoreline response to submerged and emergent structures are fundamentally different. As such, the well established methods that are currently used to predict shoreline response to emergent structures (e.g., empirical relationships, one-line numerical models) may not be suitable to investigate shoreline response to submerged breakwaters. Therefore, prior to the wider adoption of submerged structures for beach protection, it is imperative that an extensive study be undertaken to rigorously investigate characteristics of and process governing shoreline response to submerged structures.

Past studies on shoreline response to submerged structures: Although, Ranasinghe *et al.* (2006) stated that the key environmental and structural parameters governing the mode (erosion or accretion) and the magnitude (i.e., size of salient) of shoreline response to submerged structures are yet to be identified, some studies have been carried out to investigate the effect of some structural parameters and environmental parameters of breakwaters to change in shoreline. Ranasinghe *et al.* (2006) still feels and pointed out clearly that to date, very few studies have systematically investigated shoreline response to SBWs. The following paragraphs highlight the studies that have been conducted to investigate shoreline responses to SBWs.

In the first of such study is the study by Black and Andrews (2001) in which they drew parallels between submerged structures and natural reefs and investigated shorelines in the lee of natural reefs along the coastlines of south eastern Australia and New Zealand. They quantified the shape and dimensions of salient and tombolos formed in the lee of natural reefs by visually inspecting a large number of aerial photographs and predicted salient formation when $LB/XB<2$, where LB is the alongshore length of the reef/structure and XB is the distance to the reef/structure from the undisturbed shoreline. Black and Andrews (2001) also made counter-intiutive suggestion that, all other parameters (e.g., length, distance from shoreline to reef/structure and wave climate) being equal, a larger salient would develop in the lee of a submerged reef/structure than in the lee of a comparable emergent structure. A subsequent review of the methods adopted by Black and Andrews (2001), however, concluded that the critical length-scales of natural reefs obtained from aerial photographs may not be entirely accurate (Ranasinghe *et al*., 2001). This raises some concern about the conclusion drawn by Black and Andrews (2001).

Ranasinghe *et al.* (2006) investigated shoreline response to the specific case of V-shaped multifunctional surfing reefs, based on numerical and physical modeling results. They proposed a relationship between Y/LB and XB/XBR (where Y is the magnitude of shoreline response (positive Y= shoreline accretion and negative Y= erosion) and XBR is the natural surf zone width) to predict shoreline response to submerged structures. Ranasinghe *et al*. (2006) results indicated that shoreline accretion can be expected when $XB/XBR>1.5$, while shoreline erosion can be expected when $XB/XBR<1$, regardless of the direction of wave incidence. This study only investigated the dependence of shoreline response on three variables, i.e., distance between the structure and shoreline, wave incidence angle and structure crest level. However the characteristics of shoreline response to submerged structures can depend on vast number of variables (Hanson and Kraus, 1990).

Ranasinghe and Sato (2007) used results of a small-scale physical model experiment to investigate shoreline response to submerged breakwaters under obliquely incident waves. Their results indicate no shoreline erosion in the lee of the structure for any combination of design parameters. However, field observations have shown that is certainly not the case: unlike emergent breakwaters, SBWs can result in shoreline erosion as well as shoreline accretion in their lee (Ranasinghe *et al*., 2006). This inconsistency maybe due to the way in which the 'effectiveness' of the structure is defined using only one parameter by Ranasinghe and Sato (2007). Complexities associated with scaling, particularly of grain size, are also likely to render Ranasinghe and Sato (2007) results not directly applicable to prototype scale SBWs in natural environments.

Ranasinghe *et al.* (2006) carried out a study to investigate the structural and environmental conditions that govern the mode of shoreline response (i.e., shoreline erosion vs shoreline accretion) to SBWs. The use of theoretical analysis and numerical modeling were adopted to study the response to a single shore-parallel submerged breakwater. Using physical considerations, a theoretical response-function model is derived under several simplifying assumptions including parallel depth contours, linear wave theory, shore normal waves and no wave-current interaction. In total 92 coupled wave-current simulations were undertaken in the MIKE 21 CAM software. Results from the study indicate that irrespective of the angle of wave incidence, the mode of shoreline response to a SBW primarily depends on the relative magnitudes of the two non-dimensional parameters. However, it was stated that the above dependency cannot be comprehensively tested due to insufficient quantity and quality of relevant prototype data currently available for single shore parallel SBWs. Also stated is that the crest width does not affect the mode of shoreline response when the crest is deeper and the absence of strong tidal currents, tides appear to have negligible impact on the net mode of shoreline response to SBWs. For this study a parameter that was not studied is the shoreline response to gap between break waters. In addition to other parameters, this study will study the shoreline response to three submerged breakwaters and the impact of gap between the breakwaters.

The above discussion indicates that although some important initial advances have recently been made, the characteristics of shoreline response to SBWs are not yet fully understood. Due to the limited reported data on prototype SBWs, such an understanding will necessarily need to be based on numerical and/or physical modeling. Assess to a prototype SBWs is an essential steps in understanding the exact characteristics of shoreline response to SBWs. This study will make great use of the availability of typical SBWs at the study area. The three submerged breakwaters available at the study area is a great advantage for the study, it will provide a great opportunity to understand the characteristics of shoreline response to SBWs. It will also serve as a good validating tool for the numerical and other tools that will be adopted in the study.

However, the large number of structural and environmental variables that govern shoreline response to SBWs requires that a large number of simulations be undertaken to address this knowledge gap. As it is virtually impossible to undertake a large number of physical model tests due to the associated prohibitive cost, numerical modeling is a feasible option. From the past studies on SBWs, more emphasis were laid on single structures that doesn't involve the effect of gaps between the structures. This study will among other structural parameters study the effect of gap in between three submerged breakwaters. Other structural parameters that will be studied are distance from shoreline to structure, freeboard, structural length and crest width and for the environmental parameters will include wave height, wave period and wave direction.

Various methods of detecting shoreline change: Being able to monitor and predict the shoreline response to the three submerged breakwater is of great importance. Past researchers have used satellite imagery, physical model and numerical modeling to carry out this task. For this study the use of aerial/satellite imagery and numerical model will be adopted. Field observation in form of beach profile survey will be used to validate results from both aerial/satellite imagery and numerical model.

Satellite imagery: Application of remote sensing images for the analysis of coastline changes have been carried out in an area close to the present study area. The coastline changes along 4 km of Terengganu coastline, Peninsular Malaysia, have been detected by simple application of satellite images and the changes were related computationally to the environmental factors. The coastline stretch, near Sungai Besut, is formed by a fairly straight shoreline but it was found to be interrupted along 400 m by a, river mouth. For the study four high-resolution (2.5 m) satellite images were explored to detect the erosion or accretion rate along the shoreline. Hourly tide levels were also taken into account to adjust the apparent waterline before the sediment volume of the coastline change was extracted from the overlaid images. To verify the result from the satellite images the longshore sediment transport was estimated using empirical CERC formula. Comparison of the estimation from these two methods was made. It was shown that the analysis of the images backed by preliminary field data provides for a reliable detection of the past trends of coastline changes. The finding showed that the technique could project the changes into near-to-intermediate future as a safe estimation method for conceptual design purposes.

Nowadays the usage of satellite images and the application of GIS techniques have been so popular since it able to supplement to the existing empirical and numerical tools to predict the long-term coastline changes. Satellite images are simple to interpret and easily available from the government agencies for study purposes. Absorption of infrared wavelength region by water and its strong reflectance make the images an ideal combination for mapping the spatial distribution of land and water (DeWitt and Weiwen Feng, 2002).

Numerical modeling: Numerical modeling software has also been adopted in the past to study/detect the changes in shoreline by other researchers. Some of the studies deviate a bit from the image-related studies to detecting the changes in shoreline by determining the littoral drift before and after installation of mitigating structures such as revetment, groyne and breakwaters. Nguyen *et al.* (2007) used the LITPACK numerical model to study the shoreline changes in Cat Hai Island, Hai Phong City, Veitman. LITPACK is a numerical model in MIKE software package, developed by Danish Hydraulic Institute (DHI), for simulating non-cohesive sediment transport in wave and currents, littoral drift, coastline evolution and profile development along quasi-uniform beaches. Based on the analysis of hydrodynamic-lithologic conditions in this area, a coast protected structure system has been proposed, consisting of revetments, groynes, submerged breakwaters and emerged breakwaters. Results derived from LITPACK model show that they are reliable enough and suitable for use as remedial protecting measures. Although for this particular study area the structures have been installed, so this study will investigate the effect on the protected area, north of the protected area and also south of the protected area. The littoral drift before the structures were installed and after installation will be calculated for the three areas.

Hanson and Kraus (1990) described the application of the one-line model GENESIS to investigate, amongst other factors, the effect of wave transmissitivity on salient growth. In this simulation the shoreline response to a single shore-parallel breakwater was investigated on a beach with initially straight bottom contours. The alongshore uniform bed slope was 0.01. The structure was 200 m long and located 250 m offshore. The model was forced with shore-normal monochromatic waves with H=1.5 m and T=6 s. The simulations were run for 180 h. results indicated the size of salient decreased as the wave transmissivity increased. An improved version of the GENESIS model, which allows a variable wave transmissitivity, was described by Wamsley *et al*. (2002).

Lesser *et al*. (2003) described the application of the Delft3D model to a number of idealized submerged breakwater r configurations. The underlying bathymetry consisted of parallel depth contours and the cross-shore profile was representative of Cortellazzo Beach, Italy. The nearshore slope (<2 m depth) was about 0.02, while the bed slope further offshore was about 0.003. The breakwater configuration tested were; a single 1150 m breakwater, two 410 m long segmented breakwaters with a gap of 320 m, three 260 m long breakwaters with 180 gaps and 215 m gaps and a single 1150 m long breakwater with 3 shore-normal groynes at 550 m spacing. The wave conditions used were those at Cortellazzo Beach and consisted of wave heights of 0.54 to 1.58 m and periods of 3.3 and 5.6 s. The mean wave direction was always oblique to the north-south alignment of the shoreline in the site. The longshore sediment transport in the area was estimated at 60,000 - 100,000 m^3/year. The crest width of the breakwaters was 25 m and two crest levels of 1 and 1.5 m below MSL were tested. The breakwaters were located either 315 or 460 m from the shoreline for the various configurations. Two sets of simulations were undertaken for durations of 1 year and 5 years.

MIKE 21 CAM is a numerical modeling software, it was used by a group of researchers to investigate the effect of breakwaters to the shoreline Hakeem *et al.* (2010). MIKE 21 CAM (developed by DHI, Denmark) combines standard MIKE 21 modules for waves, flow and sand transport, as well as a bed level update scheme, into an automated system for the simulation of spatial and temporal change in nearshore morphology. Execution of the modules is controlled by a shell, which also ensures a flow of information among the components of the modeling system. This software has been used successfully to simulate the morphological evoluation (bed level changes) in the vicinity of breakwaters in the field. Past researchers describe the validation of the model against the morphological evolution in the vicinity of a breakwater on the Jumerah coast of Dubai, UAE, over a period of 21 months. The results showed very good agreeent between the measured and simulated changes to the beach profiles in the lee of the breakwater (accretion) and in the middle of the breakwater bay (erosion). Zyserman *et al*. (1999) used MIKE 21 CAMS to illustrate the dependence of far-field erosion near edges of a detached breakwater scheme on the freeboard of the coastal protection structures.

The numerical modeling software chosen for this study is MIKE 21 CAM based on the it's functionality and its abilities.

METHODOLOGY

Past studies on shoreline response to SBWs have been carried out using numerical model, physical model and other available tools. One hindrance to these studies is the lack of prototype data to validate results from these studies. This study will have a rare opportunity of having its entire results validated using field of an ideal prototype of submerged breakwaters. The methodology that will be adopted for this study is as follows (Fig. 1):

Data collection: Satellites/Aerial images from ten documented SBWs (Ranasinghe *et al*., 2006) will be collected. Structural and environmental parameters for

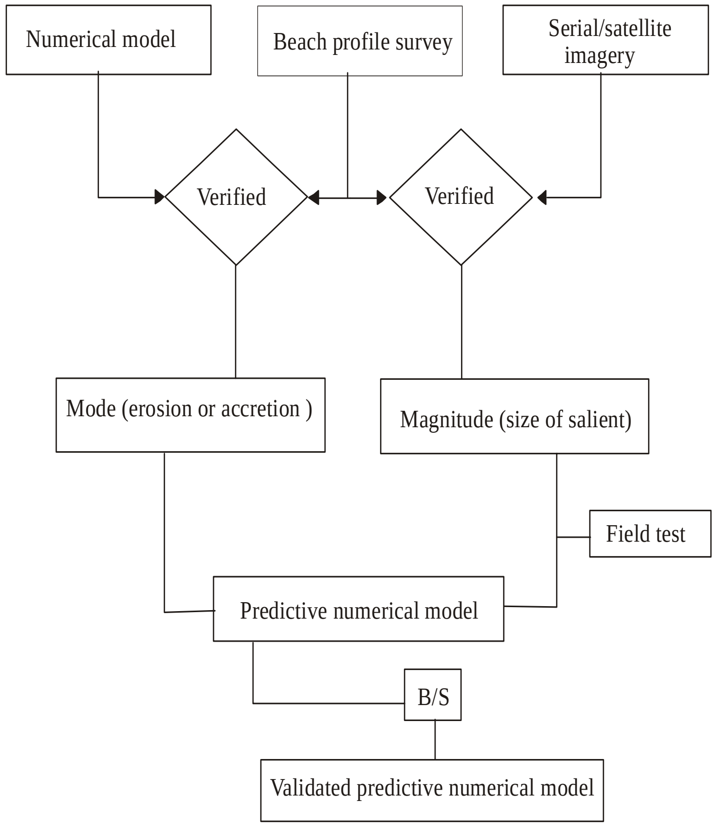

Fig. 1: Proposed research methodology process

these projects will be obtained as well. Structural parameters will be obtained from various publication of each of the projects and environmental parameters in terms of wave characteristic will be obtained using MIKE 21 SW to provide hindcast data for these wave characteristics. Aerial photographs will be obtained from JUPEM for the study area Kerteh, Terrengannu and also hindcast and forecast wave characteristics will be obtained for the study area as well. This will be obtained from the nearest meteorological centre to the study area.

Numerical modeling: MIKE 21 CAM will be used to simulate response (morphology) to some forcing parameters. Various non-dimensional structural parameters such as distance from shoreline, crest submergence, gap between SBWs, crest width and structure length will be simulated under different environmental parameters such as wave heights, wave period, wave direction, tidal range, bathymetry and currents.

Field study: A beach profile survey of the study area, Kerteh, Terengganu will be carried out for all of the monsoon seasons for a period of two years. The total station method of surveying will be applied using the Topcon 7000i equipment.

Predictive empirical model: Non-dimensional parameters that were compared by Silvester and Hsu (1997) and Black and Andrews (2001) for both emergent breakwaters and natural reefs respectively will serve as baseline for this study. An empirical predictive model using the same non-dimensional parameters will be used to create an empirical model exclusively for submerged breakwaters. This empirical model will be based on results or deduction from the analysis of the both the numerical modeling results and aerial photographs.

Validation: With the availability of an ideal prototype/study area of multiple SBWs system, quite a number of validations will be carried out. The results from the simulation of the same structural parameter available at Kerteh under different environmental parameter at Kerteh will be validated with the results from the field study. Also, the predictive empirical model obtained from the aerial photographs will be used to predict the response to the shoreline at Kerteh.

EXPECTED RESULTS

In the past predictions of shoreline response to submerged breakwaters have been based on empirical

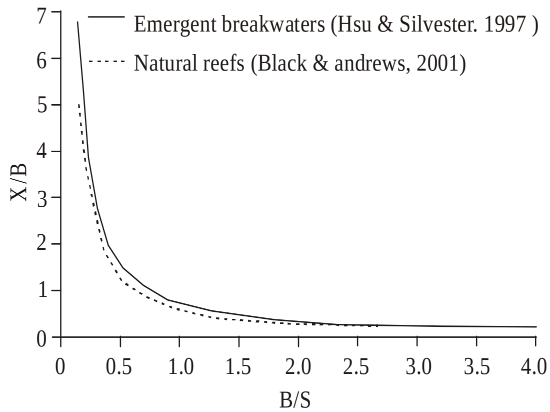

Fig. 2: Predictive relationship B/S and X/B

models developed for generalized offshore breakwaters but these empirical models have predicted wrongly, this is evident from the fact that SBWs that were constructed for the purpose of accretion (sand build-up) end up forming erosion in there lee. This has prompted the study to establish a predictive empirical model exclusively for the SBWs. At the end of this study a predictive empirical model that is exclusively for the submerged breakwaters will be established based on the X/B, B/S ratio to predict the mode and magnitude of salient formation. The results from both a numerical model and aerial/satellite imagery will be validated based on results from beach profile survey. With these results a predictive empirical model will be established and this predictive empirical model will then be tested on the study area to ascertain it accuracy. A similar predictive empirical model has been established by Silvester and Hsu (1997) and Black and Andrews (2001) in the past. Figure 2 shows a reproduced predictive relationship between B/S and X/S for natural submerged reefs (Black and Andrews, 2001) and emergent breakwaters (Silvester and Hsu, 1997).

REFERENCES

Anonymous, 1984. Shore Protection Manual (SPM), Vol. 1 and 2. US Army Crops of Engineers, Vicksberg.

Bird, E.C.F., 1985. Coastline Changes. Wiley and Sons, New York, pp: 219.

Bilan, D., 1993. The Preliminary vulnerability assement of the Chinese coastal Sea Level rise. Proceedings of the IPCC eastern hemisphere workshop, Tsukuba, August.

Black, K. and C. Andrews, 2001. Sandy shoreline response to offshore obstacles: Part 1. Salient and tombolo geometry and shape. J. Coastal Res., S1(29): 82-93.

Burcharth, H., S. Hawkins, B. Zanuttigh and A. Lamberti, 2007. Environmental Design Guidelines for Low Crested Structures, Elsevier, The Netherlands, pp: 400.

Dally, W.R. and J. Pope, 1986. Detached breakwaters for shore protection. CERC-IR-86-1. In: Vicksburg, MS: US Army Corps of Engineers, Coastal Engineering Research Centre.

Dean, R.G., A. Browder, M.S. Goodrich and D.G. Donaldson, 1994. Model tests of the proposed P.E.P. reef installation at Vero Beach, Florida. Tech. Rep. UFL/COEL-94-012, Coastal and Oceanographic Engineering Department. University of Florida, Gainesville, FL, pp: 28.

Dean, R.G., R. Chen and A.E. Browder, 1997. Full Scale Monitoring Study of a Submerged Breakwater. Coastal Engineering, Palm Beach, Florida USA, 29: 291-315.

Dean, R.G. and R.A. Dalrymple, 2001. Coastal Processes with Engineering Applications, Cambridge University Press, Cambridge, pp: 488.

Deguchi, I. and T. Sawarangi, 1986. Beach Fill at two coasts of different configuration. Proceeding of 20th International Conference on Coastal Engineering ASCE, Taipei, Taiwan, pp: 1032-1046.

DeWitt, H. and J.R. Weiwen Feng, 2002. Semi-Automated construction of the Louisiana coastline digital land-water boundary using landsat TM imagery, Louisiana's Oil Spill Research and Development Program, Louisiana State University, Baton Rouge, LA 70803.

Douglas, L. and J.R. Weggel, 1987. Performance of a perched Beach-Slaughter Beach, Delware. Proceeding Coastal Sediments '87. ASCE, pp: 1385-1398.

Funakoshi, H., T. Shiozawa, T. Tadokoro and S. Tsuda, 1994. Drifting characteristics of littoral sand around submerged breakwater. Proceeding International Conference on Hydro-technical Engineering for Port and Harbor Construction, Yokosuka, Japan, pp: 1157-1178.

Galgano, F.A., S.P. Leatherman and B.C. Douglas, 2004. Inlets dominate U.S. east coast shoreline change. J. Coastal Res.

Gopinath, E. and P. Seralathan, 2005. Rapid erosion of the coast of Sagar island, West Bengal India. Environ. Geology, 48: 1058-1067.

Gourlay, M.R., 1981. Beach processes in the vicinity of offshore breakwaters. 17th International Conference on Coastal Engineering (Sydney, Australia), pp: 1320-1339.

Hakeem, J., W. Jort, P. Andy and C. Tim, 2010. Modeling the Effect of Nearshore Detached Breakwaters on Sand Macro-tidal coasts. Environmental Agency, Bristol, ISBN: 978-1-84911-181-2.

Hanson, H. and N. Kraus, 1990. Shoreline response to a single transmissive detached breakwater, Proceedings of 22nd International Conference on Coastal Engineering ASCE, Delft, The Netherlands, pp: 2034-2046.

Harris, M.M. and J.B. Herbich, 1986. Effects of breakwater spacing on sand entrapment. J. Hydraulic Res., 24(5): 347-357.

Lamberti, A. and A. Mancinelli, 1996. Italian experience on submerged barriers as beach defence structures. Proceeding 25th International Conference on Coastal Engineering. ASCE, Orlando, USA, pp: 2352-2365.

Lesser, G.R., J.H. Vroeg, J.A. Roelvink, M. De Gerloni and V. Ardone, 2003. Modelling the morphological impact of submerged offshore breakwaters. Proceeding Coastal Sediments '03. World Scientific Publishing Co, Florida, USA on CD-ROM.

Mazda, Y., E. Wolanski, B. King, A. Sase, D. Ohtsuka and D. Kobashi, 1997. Coastal erosion due to long-term human impact on mangrove forest. Wetland Ecol. Manage., 10:1-9

McCormick, M., 1993. Equilibruim response to breakwaters. J. Waterway Port Coastal Ocean Eng. ASCE, 119(6): 657-670.

Moore, L.J., B.T. Benumof and G.B. Griggs, 1999. Coastal erosion hazards in Santa Cruz and San Diego Counties, California. J. Coastal Res., 28: 121-139.

Morton, R.A. and K.K. McKenna, 1999. Analysis and projection of erosion hazard areas in Brazoria and Galveston counties. Texas. J. Coastal Res., 28: 106-120.

Nir, Y., 1982. Offshore artificial structure and their influence on the Isreal and Sinai Mediterranean Beaches. Proceedings of the 18th International Conference on Coastal Engineering, pp: 1857-1855.

Nguyen, N.T., N.T. Nguyen and P.H. Luong, 2007. Studying shoreline changes using LITPACK mathematical model (case study in Cat Hai island, Hai Phong City, Vietnam). VNU J. Sci., Earth Sci., 23: 244-252.

Nurkin, B., 1994. Degradation of mangroves forest in South Sulawesi, Indonesia. Hydrobiologia, 285: 271-276.

Pope, J. and J.L. Dean, 1986. Development of design criteria for segmented breakwaters, Proceedings 20th international conference on coastal engineering. American Society of Civil engineers, Tapei, pp: 2144-2158.

Ranasinghe, R., N. Hacking and P. Evans, 2001. Multi-Function Artificial Surf Breaks: A Review, Report No. CNR 2001.015, NSW Dept. of Land and Water Conservation, Parramatta, Australia.

Ranasinghe, R., I. Turner and G. Symonds, 2006. Shoreline Response to Submerged Strutures: A review. Coastal Engineering, 53: 65-79.

Ranasinghe, R. and S. Sato, 2007. Beach morphology behind impermeable submerged breakwater under obliquely incident waves. Coastal Eng., 49(1): 1-24.

Ranasinghe, R. and S. Sato, 2007. Beach morphology behind impermeable submerged breakwater under obliquely incident waves. Coastal Eng., 49(1): 1-24.

Swan, S. and B. Stc, 1984. The coastal geomorphology of Sri Lanka. New England Res. Appl. Geog. 40: 125.

Seiji, W.N., T. Uda and S. Tanaka, 1987. Statistical study on the effect and stability of detached breakwaters. Coastal Eng. Japan, 30(1): 121-131.

Shore Protection Manual, 1984. Vicksburg, Miss. Department of the Army, Waterways Experiment Station, Corps of Engineers, Coastal Engineering Research Center; Washington, DC.

Silvester, R. and J. Hsu, 1997. Coastal Stabilization. World Scientific Publishing Co., Singapore, pp: 578.

Stauble, D.K., J.R. Tabar and J.B. Smith, 2000. Performance of a Submerged breakwater along a hardbottom influenced coast: Vero Beach, Florida. Proceeding of 13th National Conference on Beach Preservation Technology, Melbourne, Florida, USA, pp: 175-190.

Thampanya, U., J.E. Vermaat, S. Sinsakul and N. Panapitukkul, 2006. Coastal mangrove progradation of Southern Thailand. Estuarine Coastal Shelf Sci., 68: 75-85.

Tilmans, W.M.K., W.H.G. Klomp and H.H. De Vroeg, 1992. Coastal erosion-the Kerteh Case. Analysis of causative factors and mitigative measures using dedicated mathematical modeling tools, International Colloquim on Computer Applications in Coastal and Offshore Engineering.

Tomassicchio, U., 1996. Submerged breakwaters for the defense of the shoreline at Ostia: Field experiences, comparison. Proceeding 25th International Conference on Coastal Engineering. ASCE Orlando, USA, pp: 2404-2417.

Wamsley, T., H. Hanson and N.C. Kraus, 2002. Wave transmission at detached breakwaters for shoreline response modeling. *Technical Note ERDC/CHL CHETN-II-45*. Vicksburg, Mississippi US Army Engineer Research and Development Center, Coastal and Hydraulics.

U.S. Army Corps of Engineers, 2006. Types of and functions of coastal structures. Coastal Engineering Manual, Part VI, Chapter 2.

Zyserman, J.A., K. Jorgensen and E.D. Christensen, 1999. Sediment transport and morphology in the vicinity of shore parallel breakwaters. Proceedings Coastal Structures '99 (Santander, Spain), pp: 857-863.