

# Artificial Reefs as Shoreline Protection Structures

**Haryo Dwito Armono**

Seabed and Underwater Engineering Laboratory, Ocean Engineering Department,  
Faculty of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya 60111.  
Email : armono@oe.its.ac.id

## **Abstract**

Most of the earlier studies on artificial reefs have been carried out by biologists and marine scientists rather than coastal engineers. Their investigations focused on the biological – environmental aspects such as assemblage of fish in the vicinity of reefs, reef productivity, or comparative studies between artificial and natural reefs. Only a few researchers investigated the hydraulic or engineering aspects of artificial reefs. Meanwhile, other studies, mostly carried out by coastal engineers, emphasized the utilization of reefs as submerged breakwaters only. This paper presents a synopsis on artificial reefs as coastal protection measures.

A brief overview of artificial reefs utilization as shoreline protection system and the engineering aspects based on environment and ecology are presented in this paper. Emphasis has been placed on highlighting the factors that influence the engineering and design of artificial reefs as shoreline protection structures. Artificial reefs hydrodynamics features as breaking wave, shifting frequency, and reducing incoming wave, as well as current pattern and shoreline adjusting behind the artificial reefs are presented. The utilization of artificial reefs as shoreline protection structure are proposed following the equation to estimate the wave transmission coefficient to assist in designing and implementing artificial reefs as shoreline protection structures.

**KEYWORD:** Artificial Reefs, Submerged breakwater, Coastal Engineering,

## **1. INTRODUCTION**

The European Artificial Reef Research Network (EARNN) defined artificial reefs as a submerged structure placed on the substratum (seabed) deliberately, to mimic some characteristics of a natural reef (Jensen, 1998). Artificial reefs refer to man-made structures that serve as shelter and habitat, a source of food and a breeding area for marine animals (White et al., 1990); they are also used for shoreline protection (Creter, 1994) or as surf-wave generating devices (Craig, 1992). Recently, the term has been used to refer to a variety of submerged structures sunk in the nearshore area (Harris, 1995).

They are normally placed in designated areas to improve or recover environmental resources, that is, in an area with (i) low productivity or where habitat and environment has been degraded such as an eroded shoreline (Creter, 1994); (ii) natural reef flat degradation (Clark and Edwards, 1994) or (iii) in an area where waves need to be generated for surfers (Craig, 1992, Black, 2000). However, most of the artificial reefs have been used successfully as fish production enhancement structures, especially in Japan and United States of America (Grove et al., 1989 and 1994; McGurrin and Reef, 1986; McGurrin et al, 1989; Stone 1985; and Stone et al., 1991).

As mentioned above, most of the earlier studies on artificial reefs have been carried out by biologists and marine scientists rather than coastal engineers. Their investigations focused on the biological – environmental aspects such as assemblage of fish in the vicinity of reefs, reef productivity, or comparative studies between artificial and natural reefs. Only a few researchers investigated the hydraulic or engineering aspects of artificial reefs. Meanwhile, other studies, mostly carried out by coastal engineers, emphasized the utilization of artificial reefs as submerged breakwaters only.

Although from hydrodynamics point of view the artificial reefs and submerged breakwater are similar, in this paper, the term of ‘artificial reefs’ refers to the structures to enhance fish habitat and productivity, while the term of ‘submerged breakwater’ refers to shoreline protection structures. Furthermore, ‘submerged structures’ refers to both structures. This paper presents a synopsis on artificial reefs used as coastal protection measures. The hydrodynamic aspects of submerged structures will be presented following with stability consideration and shoreline adjustment behind the structures.

## 2. HYDRODYNAMIC ASPECTS OF SUBMERGED STRUCTURES

### 2.1. Wave Transmission Consideration

Submerged structures dissipate incoming wave energy by forcing waves to break on top of the crest as the freeboard of the reefs decrease. Wave attenuation also occurs due to turbulence and nonlinear interaction between the reef and the incoming waves. Figure 1 shows the global and local effects occurring at artificial reefs. In the time domain, the waves behind the reef seem to be shorter and smaller than in front of the reef. In the frequency domain, this would be expressed by a decrease in the integral of the energy density spectrum (wave height reduction) and a deformation of the spectrum (Bleck and Oumeraci, 2001).

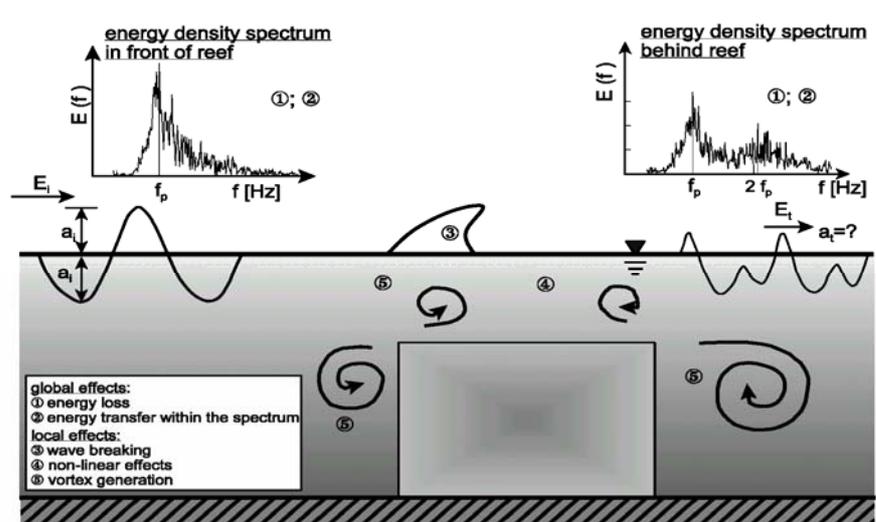
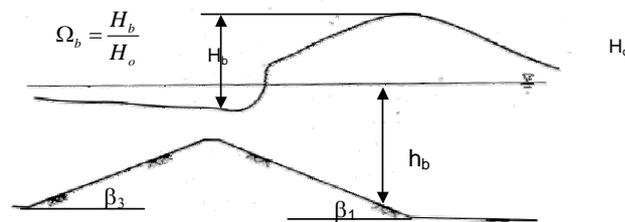


Figure 1. Global and Local Effect on Artificial Reefs (Bleck and Oumeraci, 2001)

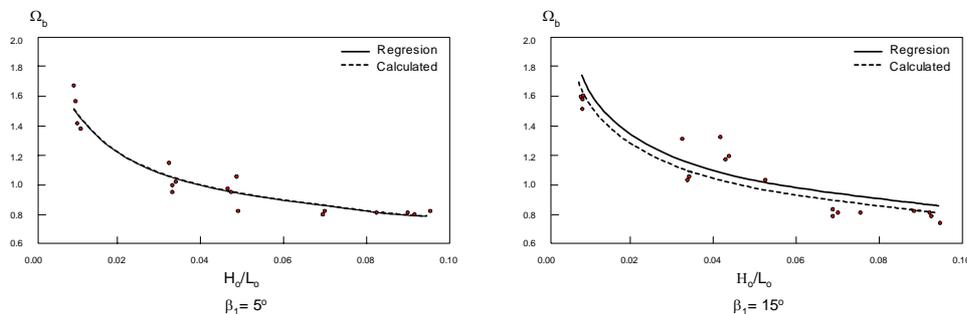
The design of shoreline protection structures or breakwaters is usually based on the wave transmission coefficient  $K_T$ . Lower  $K_T$  values show increased effectiveness of the breakwater. Since they are submerged, wave transmission coefficients for artificial reefs are much higher than those for structures with a crest above the water level. However, as the incident wave amplitude increases, the wave transmission coefficient generally decreases. This indicates that the structure is more effective in affecting larger waves; therefore, a submerged structures can be used to trigger breaking of high waves (CERC, 1984).

Field observations during construction of artificial reefs at Yugawara Coast in Japan (Ohnaka and Yoshizawa, 1994) showed that a reef with a large crown width had considerable wave dissipation compared to that with a small crown width. It was also clearly observed that the transmitted waves were obstructed by the induced breaking wave due to the reef, as shown in the supporting laboratory experiments (Ahrens, 1987, Seabrook, 1997, Armono, 2003). Aono and Cruz (1996) also confirmed the damping effect of the reefs on breaking and non-breaking waves.

A detailed breaking wave study over artificial reefs (represented by triangular submerged obstacles) outlined by Smith and Kraus (1990) reported that for regular waves, plunging and collapsing breakers were predominant. The breaking waveform was affected by the return flow. A secondary wave shoreward of the main wave crest was generated which caused the wave to break before the incident wave had reached the depth-limited breaking condition as shown in Figure 2.18. The breaker height index ( $\Omega_b = H_b/H_o$ ) increased in the presence of a strong return flow. The strongest return flow was obtained if the seaward slope,  $\beta_1$ , was steep and the deep-water wave steepness,  $H_o/L_o$ , was small as shown in Figure 2b.



a. Typical Incipient Wave Breaking



b. Typical Breaker Height as a function of Deepwater Steepness

Figure 2. Breaker Height at Submerged Breakwater (Smith and Kraus, 1990)

The wave breaking effect increases with a decrease in crown depth as noted by Yoshioka et al (1993) and Ohnaka & Yoshizawa (1994). Also, the longer the traveling distance of broken waves, i.e., the wider the crown of the reefs, the higher the wave-dissipating effect as shown in the Figure 3. The figure shows the influence of the ratio of the crown width (B) and deep-water length ( $L_0$ ) to the transmission coefficient of wave height KT. In this figure, KT is the ratio between the transmitted wave height ( $H_t$ ) and the incoming deep water wave height ( $H_0$ ). F is the freeboard (distance between structures' crest to water level) as shown in Figure 4.

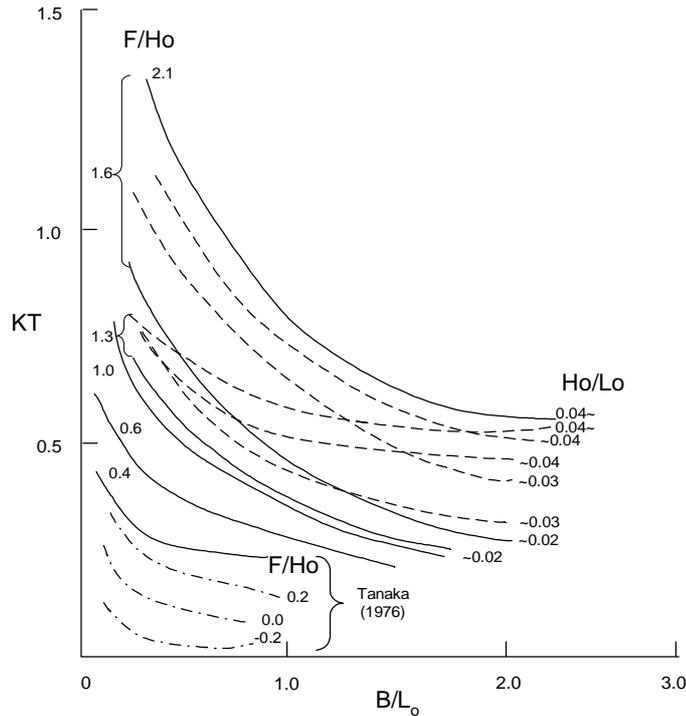


Figure 3. Transmission Characteristics of Artificial Reefs (Yoshioka et al, 1993)

The effect of reef width in reducing the wave transmission coefficient was also confirmed by Seabrook (1997), based on an extensive laboratory study on wide crest submerged rubble mound breakwaters over different water depths. A design equation for wave transmission estimation has been proposed and is valid for a relative depth ( $h/d$ ) of between 0.56 and 1.

$$KT = 1 - \left( e^{-0.65 \frac{F}{H_i} - 1.09 \frac{H_i}{B}} + 0.047 \frac{B.F}{L.D_{50}} + 0.067 \frac{F.H_i}{B.D_{50}} \right) \quad [1]$$

$D_{50}$  is the nominal armour unit diameter or the median size (50%) armour unit given by  $D_{50} = (M_{50}/\rho_a)^{1/3}$ ,  $M_{50}$  is the mass of the median size armour unit and  $\rho_a$  is the mass density of the armour material. Figure 4 explains the variables used in the equation above.

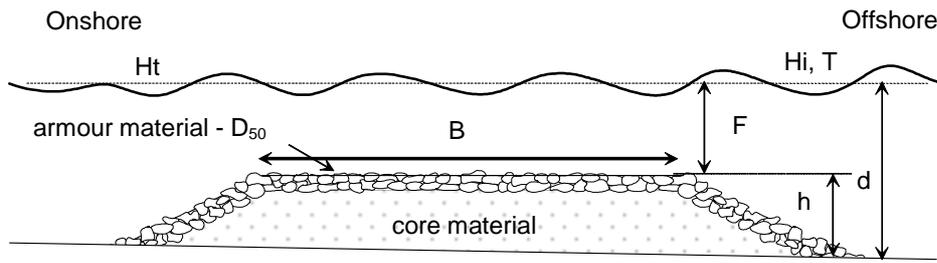


Figure 4. Wide Crest Submerged Breakwater

A new type of artificial reef, called the Aquareef, is shown in figure 5 has been proposed for seaweed substrata and habitat enhancement (Hirose et al, 2002). The required number of front row units is determined by comparing the  $n$  or  $B$  value obtained by the transmitted wave height determined from Figure 6.

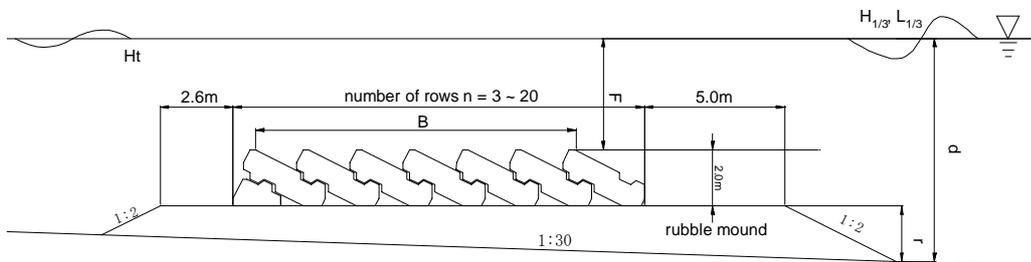


Figure 5. Aquareef

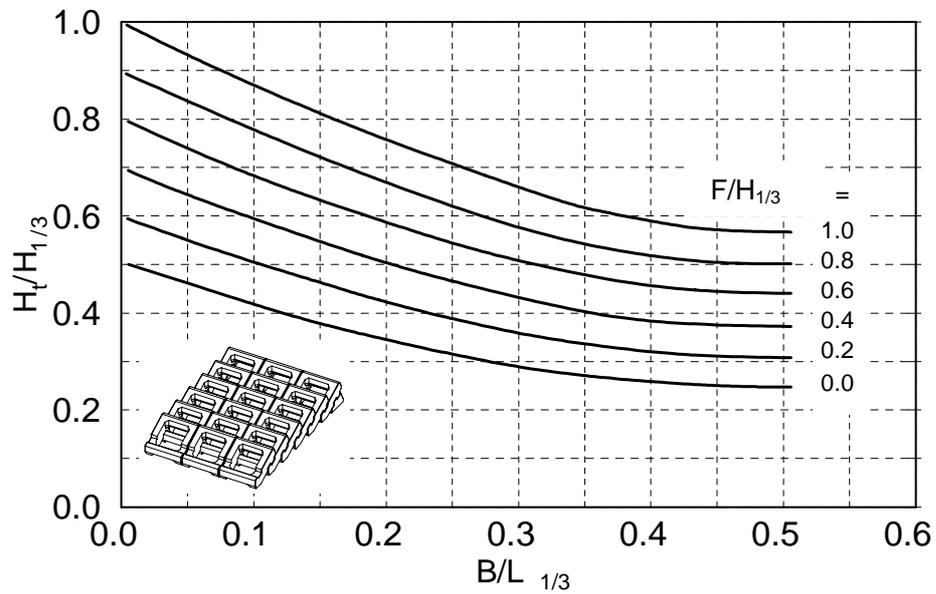


Figure 6. Aquareef Design Chart based on Transmitted Waves Coefficient (Hirose et al 2002)

$H_{1/3}$  and  $L_{1/3}$  refer to the incoming significant wave height and wave length, while  $F$  is the freeboard. The chart is recommended for the placement of artificial reefs on the seafloor with a bottom slope less than  $1/30$  and for a significant wave height less than 6.5m.

Moreover, Armono (2003) studied the wave transmission over hemispherical shape artificial reef as submerged breakwater as shown in Figure 7. The relationship between transmission coefficient ( $KT$ ) and water depth ( $d$ ), relative structure height ( $h/d$ ), wave height ( $H_i$ ), wave period ( $T$ ), wave steepness ( $H_i/gT^2$ ), reef crest width ( $B$ ), and reef configuration was examined visually to observe and identify if any relationships or trends were present. The equation for wave transmission coefficient  $KT$  is proposed as follows:

$$KT = \frac{1}{1 + 14.527 \left( \frac{H_i}{gT^2} \right)^{0.901} \left( \frac{B}{gT^2} \right)^{-0.413} \left( \frac{h}{B} \right)^{-1.013} \left( \frac{h}{d} \right)^{4.392}} \quad [2]$$

The proposed equation above is valid for the following range:  $8,4.10^{-4} < H_i/gT^2 < 94,7.10^{-4}$ ;  $9,81.10^{-3} < B/gT^2 < 105,15.10^{-3}$ ;  $0.350 < h/B < 0.583$  and  $0.7 < h/d < 1.0$ .

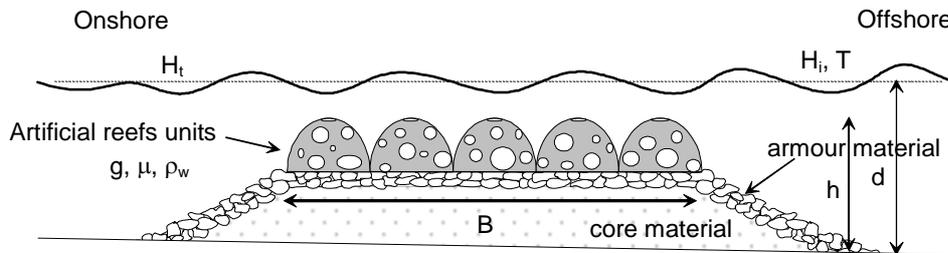


Figure 7. Hemispherical Shape Artificial Reefs as Submerged Breakwater

The attacking frequency distribution (number of waves in a given time) graph of incoming waves was essential in the design of an artificial reef as a wave dissipating structure. As shown in Figure 8, wave height is the main consideration when the non-overtopping artificial reefs are intended to dissipate wave energy (Yoshioka et al, 1993). As shown in Figure 2.21b, the attacking frequencies of a 2m wave height were reduced after the installation of a high crown reef. However, if the reefs were used to stabilize the beach line, wave frequency was the main consideration, as shown in Figure 8c. For the same wave height, for example 2m, the lower attacking frequencies were obtained after the reefs with a shallow crown depth were installed.

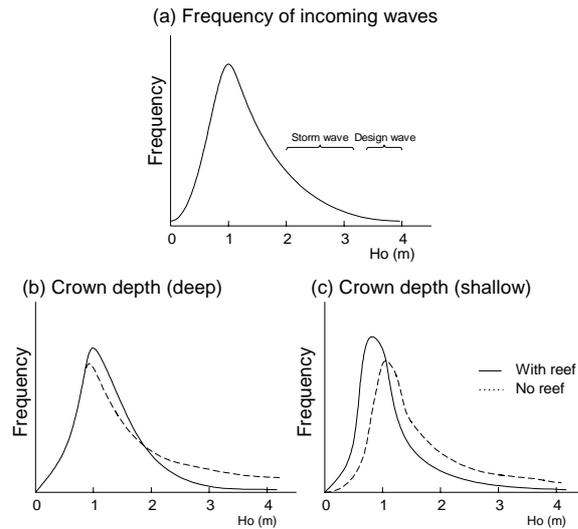


Figure 8. Typical Wave Frequency Distribution (Yoshioka et al, 1993)

## 2.2. Stability Considerations

The stability of a reef due to waves and currents also should be considered in the design of an artificial reef. The reef must not overturn or slide. Therefore, the friction between the reef and the sea floor must be greater than the horizontal component of the hydrodynamic forces (Takeuchi, 1991). Another consideration is that local scouring/erosion and accretion of sediments in the reef vicinity should not lead to partial or complete burial of the reefs as this affects reef stability and efficacy. The process of structure-induced scour is somewhat different for waves than for steady currents; the largest scour depth occurs with a steady current (Eadie and Herbich, 1987). In a steady current, the maximum scour in front of hemispherical shape artificial reefs is approximately 67% of its diameter (Shamloo, et al, 2001).

The stability of artificial reef blocks can be examined using the Stability Number ( $N_s$ ) (Hudson et al, 1979), as given below:

$$N_s = \frac{\gamma_a^{1/3} H}{(R-1)W_a^{1/3}} \quad [3]$$

where  $H$  is wave height,  $W_a$  is weight of reef units,  $\gamma_a$  is specific weight of reefs,  $R$  is the ratio between reef and water specific weight =  $\gamma_a/\gamma_w$ . In practice (CERC, 1984), the stability coefficient ( $K_D$ ) is commonly used. The stability coefficient for artificial reefs or breakwater blocks can be determined from the stability numbers  $N_s$  which are obtained from laboratory tests using the following relationship:

$$N_s = (K_D \cot \theta)^{1/3} \quad [4]$$

where  $\theta$  is the slope angle of the reef toe. Typical  $K_D$  values for breakwater armour units are available in Shore Protection Manual (CERC, 1994) and higher  $K_D$  values give more stability. As noted by Nakayama et al (1993), the stability number can be considered to depend on the ratio of reef depth and the incoming wave height ( $h/H$ ) and wave period ( $T$ ).

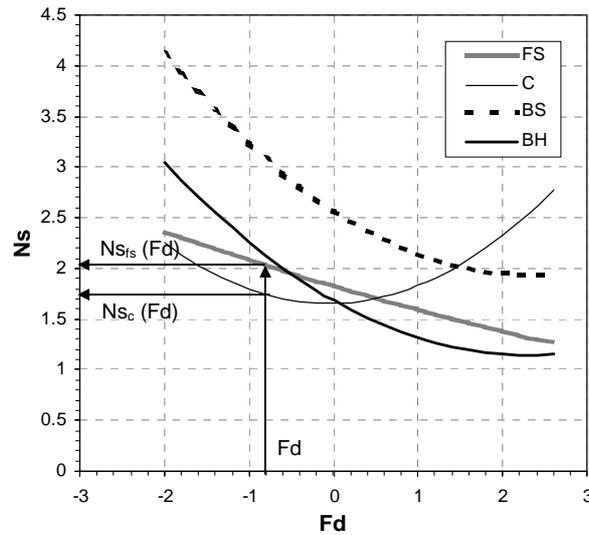


Figure 9. Damage Curves for Initiation of Damage (Vidal et al, 2000)

A methodology for evaluating the stability of an armour unit of a low crested and submerged breakwater was proposed by Vidal et al (2000) by categorizing submerged breakwaters into five sections; Front Slope (FS), Crest (C), Back Slope (BS), Front Head (FH) and Back Head (BH). The damage curve that relates the non-dimensional freeboard  $F_d$  (a ratio of freeboard to the diameter of armour units) with stability number  $N_s$  for a given damage level for each section is provided in Figure 9.  $N_s$  is the critical stability number and is defined as  $N_s = H_i / \Delta D$  and relates wave height ( $H_i$ ), armour unit relative submerged density ( $\Delta = \rho_s / \rho_w - 1$ ) and armour unit diameter ( $D$ ) for a given damage level. The curves are valid only for the experimental range  $2.01 < F_d < 2.4$  and cannot be used to assess the damage in any submerged breakwater which has a structural parameters different from those of the model. The materials properties of the model are: main armour:  $D_{50} = 2.49\text{cm}$ ,  $D_{85}/D_{15} = 1.114$ , density  $\rho_s = 2650\text{ kg/m}^3$  and porosity  $= 0.45$ ; underlayers and core:  $D_{50} = 1.90\text{cm}$ ,  $D_{85}/D_{15} = 1.366$  and porosity  $= 0.44$ ; slopes 1:1.5 with crest width 0.15m.

From Figure 9, the size of armour unit can be assessed for each section. For example the armour unit size required for the crest of a submerged breakwater with a front slope of 1:1.5 can be estimated as:

$$D_c = D_{fs} \frac{N_{s_{fs}}(F_d)}{N_{s_c}(F_d)} \quad [5]$$

where  $D_c$  is the size of armour unit of the crest,  $D_{fs}$  is the diameter of the front slope armour units that will be used to estimate non-dimensional freeboard  $F_d = F/D_{fs}$ , where  $F$  is the freeboard.  $N_{s_{fs}}$  and  $N_{s_c}$  is the critical stability number for front slope and crest armour unit, respectively. The stability of a hemispherical shape artificial reef (HSAR) can be analyzed according to equation [5] assuming that the reef acts as the crest of a submerged breakwater.  $D_{50}$  for the front slope of base armour unit of HSAR can be represented by  $D_{fs}$  to estimate  $F_d$ . The stability of base armour unit for the proposed

submerged breakwater (HSAR) can also be determined from the curves given in Figure 9.

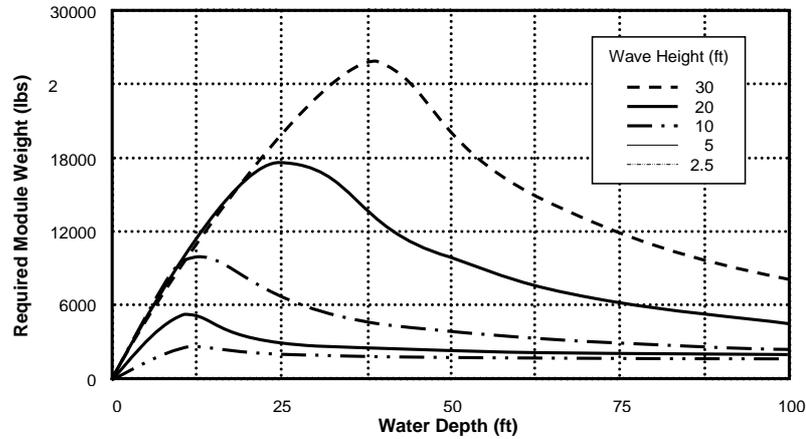


Figure 10. Typical Reef Ball™ Stability Curve for 12 sec Wave Period (Roehl, 1997)

For a hemispherical shape, the stability curves for estimating the required single module weight for particular wave period and height can be determined based on Morrison Equation. Typical curves are given in Figure 10 for a 12 second wave period. The curves were plotted based on the laboratory observations of applied maximum wave force  $F_w$  (consisting of drag ( $F_d$ ) and inertial force ( $F_i$ )) on a single Reef Ball™ unit. The multiplication of coefficient of friction, the reef weight ( $W_{dry}$ ), buoyancy ( $F_b$ ) and lift forces ( $F_l$ ) is the resisting force ( $F_r$ ). If the maximum wave force is less than the resisting force, the Reef Ball™ remains stable. These forces can be expressed in the following equation:

$$F_w = \left( \sqrt{F_d^2 + F_i^2} \right) FS \quad [6a]$$

$$F_r = \mu (W_{dry} - F_b - F_l) \quad [6b]$$

where  $FS$  is factor of safety. Since  $F_w < F_r$ , the minimum weight of a Reef Ball unit can be obtained by combining equation 6a and 6b:

$$W_{dry} > \frac{F_w}{\mu} + F_b + F_l \quad [7]$$

Equation 7 is the final stability equation as shown in Figure 10. The design curves are good only for single units resting on the sea floor and should not be used for rubble mound artificial reefs where interlocking occurs. Additional stability curves for different wave periods and Reef Ball™ sizes were given by Roehl (1997).

The stability analysis and design charts for Aquareef are presented in Figures 11. In Figure 2.16  $K_n$  is the wave force coefficient, which is the ratio of resisting force to the product of specific weight of water ( $\gamma_w$ ), significant wave height ( $H_{1/3}$ ) at the toe of rubble mound and the projected surface area ( $A$ ). The value of  $K_n$  was obtained from laboratory experiments and is expressed as

$$K_n = \frac{F_r}{\gamma_w H_{1/3} A} \quad [8]$$

where  $F_r$  is the resisting force, which is the product of the underwater reef weight ( $W_{wet}$ ) and friction coefficient ( $\mu$ ). Vertical forces such as buoyancy and lift force are not considered, as experimental observations shows that these forces are small compared to the horizontal forces.

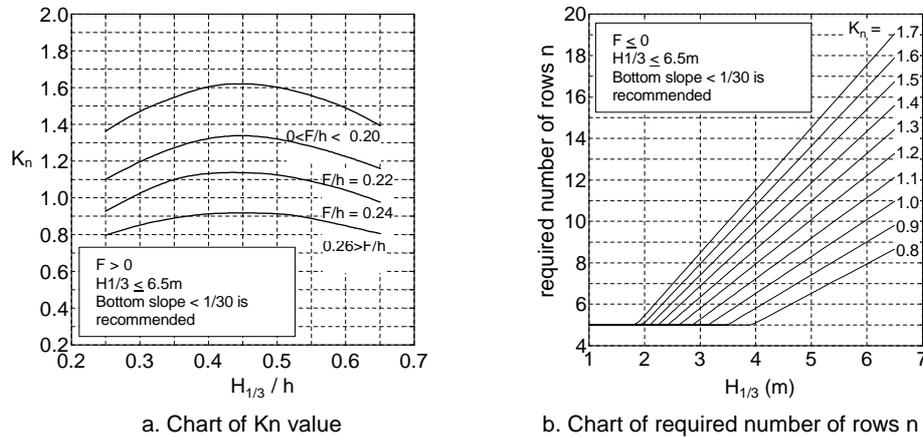


Figure 11. Design Chart for Aquareef based on Stability (Hirose et al, 2002)

### 3. SHORELINE ADJUSTMENT DUE TO ARTIFICIAL REEFS.

Field observations (Newman, 1989) as well as laboratory studies (Bruno, 1993) confirmed that an artificial reef is effective in limiting the offshore transport of sediments. Moreover, Newman (1989) noted that the reef converts a significant amount of wave energy into current energy and produces a strong current along the crest of the reef. Therefore, more wave energy is converted to current energy along a coastline protected by a reef than an unprotected coastline that undergoes continuous wave breaking. Newman (1989) also found that the reef does not reduce alongshore current; therefore, the alongshore littoral drift can bypass the reef shadow zone without sediment deposition.

Examination of 123 aerial photographs of the shorelines of New Zealand and eastern Australia revealed that shoreline adjustment occurs due to the presence of offshore reefs (Mead and Black, 1999). They presented guidance based on reef parameters shown in Figure 2.22. From the observations, tombolos form when  $L_r/Y > 0.6$ , salients form when  $L_r/Y > 2.0$  and a non-depositional condition occurs when  $L_r/Y \approx 0.1$ . The distance between the tip of the salient and the offshore reef ( $Y_{off}$ ) can be predicted from the longshore dimension of the offshore reef ( $L_r$ ) and its distance from the undisturbed shoreline ( $Y$ ) as shown in Figure 12. The relationship between these variables is given as follows:

$$\frac{Y_{off}}{L_r} = 0.42 \left( \frac{L_r}{Y} \right)^{-1.36} \quad [9]$$

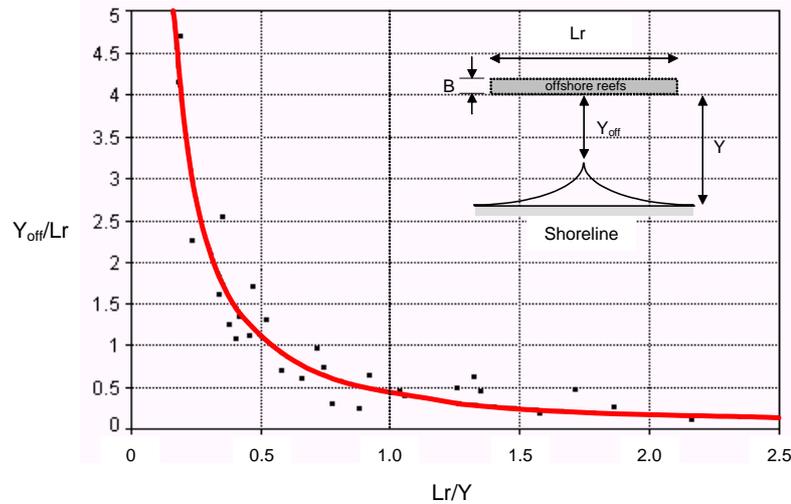


Figure 12. Shoreline Adjustment due to Offshore Reefs (Mead and Black, 1999)

According to Yoshioka et al, (1993), current flow patterns around the on-shore end of an artificial reef can be classified into four types, as shown in Figure 13. Pattern I shows that coupled circulation currents develop behind the reefs. As the length of reef ( $L_r$ ) increases, the effect of the opening section does not reach the central part of the reef (Pattern II). When the distance between reefs is narrow, circulation currents develop behind the two adjacent reefs (Pattern III). Furthermore, pattern IV is developed when no circulation currents are developed; i.e., when the gap between reefs ( $W_r$ ) is small compared to reef length ( $L_r$ ).

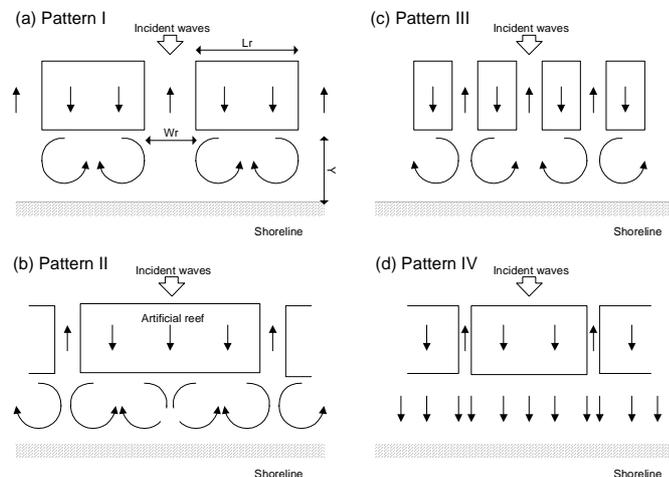


Figure 13. Current Patterns around Artificial Reefs (Yoshioka et al, 1993)

Behind the artificial reefs, circulation currents, in addition to the presence of longshore currents, reduce the rate of littoral drift and help accumulate sediments which cause the growth of a cusped spit from the shoreline. For an offshore breakwater with its crest above the water level, if the structure's length ( $L_r$ ) is great enough in relation to its distance offshore ( $Y$ ); i.e.:  $L_r < 2Y$ , a cusped spit may connect to the structure, forming a tombolo (CERC, 1984). However, as observed by Newman (1989), an

artificial reef, generally, does not induce a circulation current that leads to the development of a tombolo.

For the purpose of controlling sand accumulation and littoral drift, placement of reef which will produce flow Pattern I is recommended by Yoshioka et al, (1993). This is accomplished by setting the reef spacing at  $W_r > 0.25 L_r$  and  $Y < L_r < 4Y$ . Similar to Pattern I, a relatively good coastal littoral drift control effect can be obtained by creating flow Pattern II, although circulation currents only develop at the tips of the reefs. Furthermore, when a permeable reef structure is used and the distance between the reefs and the shoreline is short; i.e.  $L_r < Y$  (CERC, 1984), onshore currents flowing over the reef reach almost to the beach line and sometimes sand accretion does not develop behind the reefs.

A non-conventional arrangement of a submerged breakwater may also alter the incoming wave direction, which further reduces transmitted wave energy as shown in Figure 14. Numerical and experimental studies reported that energy dissipation could be enhanced if the wave refraction effect were mobilized to increase the wave height prior to breaking (Goda and Takagi (1998). By aligning the reefs longitudinally (Figure 14a), the artificial reefs were shown to be more efficient in dissipating wave energy than the conventional lateral artificial reefs system (Figure 14b). Knox (2000) proposed a wave transmission formula for a longitudinal arrangement of submerged breakwaters. On the other hand, an arrangement of several submerged breakwaters parallel to the shoreline (Figure 14b) has also been proven to reduce wave reflection and transmission. The reflection coefficients increase as the water depth decreases for impermeable and permeable submerged breakwaters (Mase et al, 2000).

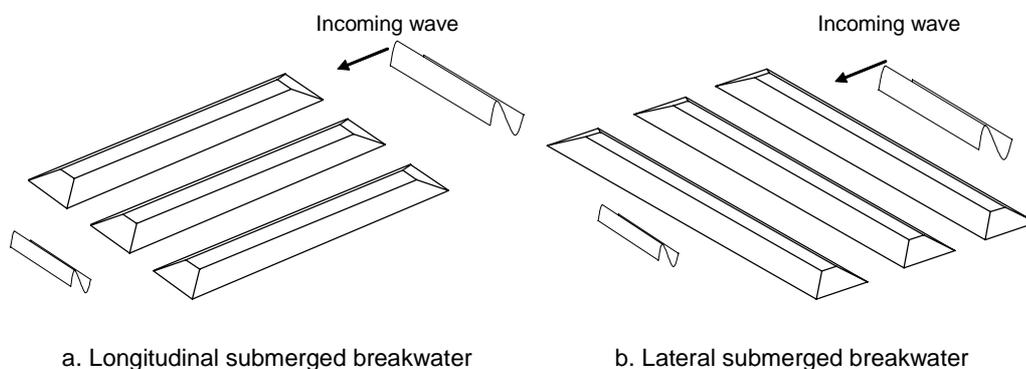


Figure 14. Non-conventional Arrangement of Breakwaters

#### 4. CONCLUSION

A brief overview of artificial reefs utilization as shoreline protection system and the engineering aspects based on environment and ecology has been presented. Emphasis has been placed on highlighting the factors that influence the engineering and design of artificial reefs as shoreline protection structures. A review of submerged breakwater design and hydraulic properties may also be found in Seabrook (1997) and Pilarczyk

(2003). From the various experiment and proposed equation to examine wave transmission coefficient  $K_T$ , the following can be highlighted:

- Wave transmission was proportional to water depth, and wave period. The wave transmission coefficient was found to increase as the water depth increased. The transmission coefficient was also found to increase with increasing wave period for a given water depth. As the water depth increases, the transmission coefficient increased for a given wave period.
- Wave transmission varied inversely with wave height and reef crest width. Wave transmission was found to decrease with the increasing wave height for a given water depth and wave period. The transmission coefficient was also found to decrease with increasing crest width for a given water depth and wave period.

The use of artificial reefs as submerged breakwater support the paradigm shift in coastal engineering and management from hard structure approach to soft structure approach.

## 5. REFERENCES:

- Ahrens, J., (1987). **Characteristics of Reef Breakwaters**, Technical Report, CERC - 87-17, U.S. Army Coastal Engineering Research Center, Vicksburg, Mississippi, USA.
- Aono, T. and Cruz, E.C., (1996). "Fundamental Characteristics of Wave Transformation Around Artificial Reefs", **Proceeding of 25th International Conference of Coastal Engineering**, American Society of Civil Engineers, New York, USA, pp. 2298-2311.
- Armono, H.D., (2003). **Hemispherical Shape Artificial Reefs**, Ph.D Dissertation – Queens University, Kingston, Ontario, Canada
- Bleck, M., and Oumeraci, H., (2001). "Hydraulic Performance of Artificial Reefs: Global and Local Description", **Abstract of 28th International Conference on Coastal Engineering**, Cardiff, Wales, UK, paper no 287.
- Bruno, M.S. (1993). "Laboratory Testing of an Artificial Reef Erosion Control Device", **Coastal Zone '93**, pp. 2147 -2158.
- Coastal Engineering Research Centre (CERC), (1984), **Shore Protection Manual**, Vol 1 and II, U.S. Army Coastal Engineering Research Center, Vicksburg, Mississippi, USA.
- Eadie, R.W. and Herbich, J.B., (1987). "Scour about Single Cylindrical Pile due to Combined Random Waves and a Current", **Proceeding of 20th International Conference on Coastal Engineering**, American Society of Civil Engineers, New York, USA, pp. 1858-1870.
- Goda, Y. and Takagi, H., (1998). "Lateral Versus Longitudinal Artificial Reef System", **Proceeding of 26th International Conference of Coastal Engineering**, American Society of Civil Engineers, New York, USA, pp. 2152-2165.

- Knox, P.E., (2001). **Examination of the Performance of a Longitudinal Submerged Breakwater System**, M.Sc. Thesis – Queen’s University, Kingston, Ontario, Canada.
- Mase, H., Oki, K., Kitano, T. and Mishima, T., (2000). “Experiments on Bragg Scattering of Waves due to Submerged Breakwaters”, **Coastal Structures 99**, Vol. 2, I.J. Losada (ed), Balkema, Rotterdam, The Netherland, pp. 659-665.
- Mead, S. and Black, K. (1999). “A Multi-Purpose, Artificial Reef at Mount Maunganui Beach, New Zealand”, **Coastal Management Journal**, Vol. 27(4), pp. 355-365.
- Nakayama, A., Horikosi, N. and Kobayashi, H., (1993). “The Planning and Design of Multipurpose Artificial Barrier Reefs”, **Coastlines of Japan**, Vol. II, Y. Nagao (ed), American Society of Civil Engineers, New York, USA, pp 183-197.
- Newman, K.L., (1989). "Effect of Artificial Reefs on Nearshore Currents", **Proceedings of International Association for Hydraulic Research (IAHR) XXIII Congress**, National Research Council, Ottawa, Ontario, Canada, pp. B147-B164
- Ohnaka, S. and Yoshinawa, T., (1994). “Field Observation on Wave Dissipation and Reflection by an Artificial Reef with Varying Crown Width”, **Proceeding of Hydro-Port ‘94 International Conference on Hydro-Technical Engineering for Port and Harbor Construction**, PHRI, Yokosuka, Japan, pp. 365-376.
- Roehl, E.J., (1997). **The Stability of Manufactured Artificial Reefs**, MSc. Thesis, Florida Institute of Technology, Melbourne, Florida, USA.
- Seabrook, S.R., (1997). **Investigation of the Performance of Submerged Breakwaters**, M.Sc Thesis - Queens University, Kingston, Ontario, Canada.
- Shamloo, H, Rajaratnam, M. and Katopodis, C., (2001). “Hydraulics of Simple Habitat Structures”, **Journal of Hydraulic Research**, Vol. 39 (4), pp. 351 – 366.
- Smith, E.R. and Kraus, N.C., (1990). **Laboratory Study on Macro Features of Wave Breaking over Bars and Artificial Reefs**, CERC Technical Report 90-12, U.S. Army Coastal Engineering Research Center, Vicksburg, Mississippi, USA.
- Takeuchi, T., (1991). "Design of Artificial Reefs in Consideration of Environmental Characteristics", **Proceeding of Japan-US Symposium on Artificial Habitats for Fisheries**, Southern California Edison Co., Rosemead, California, USA, pp. 195-203.
- Vidal, C., Medina, R. and Martin, F., (2000). “A Methodology to Assess the Armour Unit Stability of Low Crested and Submerged Rubble-mound Breakwaters”, **Coastal Structures 99**, Vol. 2, I.J. Losada (ed), Balkema, Rotterdam, The Netherland, pp 721-725.
- Yoshioka, K., Kawakami, T., Tanaka, S., Koarai, M. and Uda, T., (1993). "Design Manual for Artificial Reefs", **Proceeding Coastlines of Japan - Volume II**, Yoshimi Nagao (ed.), pp. 93-107.