Lowland Technology International 2018; 20 (2): 229-236
International Association of Lowland Technology (IALT): ISSN 1344-9656
Special Issue on: Green Technology for Sustainable Infratructure Development

Research Paper

Submerged breakwaters design development based on artificial oyster reef

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ARTICLE INFORMATION

Article history:

Received: 03 January, 2017
Received in revised form: 21 March, 2017
Accepted: 21 July, 2017
Publish on: 07 September, 2018

Keywords:

Submerged breakwaters,
Low crested and submerged structures (LCS),
Artificial oyster reef,
Coastal protection

ABSTRACT

Due to the problem on coastal erosion is getting more severe currently, there should be the study on the potential impacts of coastal protection structures on the erosion and sediment movement on areas under influence of currents, tides and storm surges. The various kinds of coastal structures can be applied to solve, or at least, to reduce these problems. The present study focuses on detached breakwaters and artificial reefs which are classified as Low crested and submerged structures (LCS). It is used also to provide reducing for the hydraulic loading to become required level where the dynamic equilibrium can be maintained at the shoreline. To accomplish the mentioned goal, the design of LCS structures is needed to allow the transmission of a definite amount of wave energy over the structure by overtopping and also letting transmission occurred through the porous structure. Not only the term of mechanism but also the nature dynamics of the ecosystem are considered to create flexible and sustainable infrastructure while enhancing nature values. The coastal protection measures by using nature and natural processes are expected to have positive impact not only in nature and safety but also in other functions such as recreation or economy. In the present study, artificial oyster reef in Oesterdam, The Netherlands, is studied based on the geometric form, movement of particle shells inside, composition of structure of oyster reef related with the ability to reduce the wave energy.

1. Introduction

Coastal area is typically described as interface or transition areas between land and sea where interaction processes occurs (Scialabba, 1998). Economically, coastal area is important, including growth of agriculture, shipping, ports, industrial facilities, coastal fisheries, aquaculture, forestry and tourism. Coastal areas are ecologically essential, as they provide a number of environmental goods and service the transfer of energy and living organisms between land and sea systems, under principle of short-term weather, long-term climate cycles, characteristic and behavior of tides and change in sea level (Scialabba, 1998).

Nowadays the loss of coastal areas has been unavoidable. The serious concerning and preservation of

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Note: Discussion on this paper is open until March 2019

coastal area is sufficiently needed. The study of coastal protection structure in terms of impact to the surrounding and ability to protect shoreline is related with the different geography and specific characteristic and behavior of waves and tides in specific area. Nevertheless, erosion problems has led to major efforts to manage coastal erosion problems and restore coastal capacity in order to accommodate short-and long-term changes induced by human activities, extreme events and sea level rise (Morton, 2003). The erosion problem becomes worse whenever the solving solution applied is inappropriate. Often erosion is addressed locally at specific places or at regional or jurisdictional boundaries instead of at system boundaries that reflect natural processes. This anomaly is mostly attributable to insufficient knowledge of coastal processes and the protective function of coastal systems (Morton, 2003).

Focusing on the applying coastal protection structure to the field, several choices of structures have been selected according to each type of shoreline. In the present study, the low crested and submerged structures (LCS) are studied. Due to their advantage, LCS is becoming very common to be used as coastal protection or in combination with artificial sand nourishment. The main function of the submerged breakwater is to reduce the hydraulic loading by providing wave-breaking by allowing some wave transmission, results in reduction of wave in lee side of the submerged breakwater to maintain the dynamic equilibrium of the shoreline. Practically, submerged structures are designed to allow the transmission of wave partly go over the structure and also some transmission through the structure to create wave breaking and energy dissipation on shallow crest (Pilarczyk, 2003).

The history of coastal protections structures is not only the engineering approach concerning but also the influence to the surrounding in terms of ecosystem is usually concerned. The Pacific Oyster C. gigas was introduced by the shellfish industry in the Oosterschelde estuary in 1964 (Drinkwaard, 1999), after mass mortality of the native European flat oyster Ostreaedulis (Drinkwaard, 1999). The expansion has occurred into adjacent water bodies including the Wadden Sea by forming resistant reefs, the oysters induce structural changes in the ecosystem. It is concluded that bed area is still expanding while decrease of the fraction live animals may indicate adjustment of the stock size to the local conditions (Smaal and Kater, 2012).

After applying oyster reef, they have been used to reduce the rate of erosion of the sand nourishment and to maintain the sediment balance. From an engineering perspective, it has effect in term of the flow, wave action, sedimentation, erosion patterns inside and surrounding the reefs. Therefore, the aims of the present study are i) to determine the suitable size and shape of Artificial oyster submerged breakwater, ii) to study the behavior of parameter related to transmission coefficient and iii) to select the proper formula to determine the transmission coefficient of artificial oyster reef for specific condition of the shoreline.

2. Methodology

The Shore Protection Manual (United States Army Corps of Engineers, 1984) stated that the efficiency of submerged breakwater or, in the present study, artificial oyster reef can be determined by the transmission coefficient, K_T. In order to determine the wave transmission coefficient on oyster reefs several parameters must be determined beforehand. These parameters are determined by collecting data on existing artificial oyster reefs at the Oesterdam location. Data such as shell movement within the reef, weight, density of oyster reefs, and oyster/sediment ratio were some of the determined parameters. The calculation is done by computing the wave transmission of the significant wave over/through a “reef” breakwater.

In practice, constructed artificial oyster reefs are usually placed below the mean sea level. Artificial oyster reef reduces waves by allowing water to pass through the structure and partly over the top of the reef, forcing the waves to break or loose energy (van der Meer et, al., 2005). The calculation of transmission coefficient is done by comparing the certain wave height after that phenomenon with the incident wave height before. It can be explained in **Fig. 1**. Nevertheless, the reduction of the wave energy allows the sediments to drop out of suspension increasing sedimentation rates in the reef and its vicinity. Moreover, submerged artificial reef would be worked only under the certain period depending on the height of wave, level and depth of the sea. The greater the submergence, the less the wave energy will impact the structure, and the less effective the structure will be for wave attenuation. Therefore, the efficiency of the reef depends both on the water level and significant wave height.

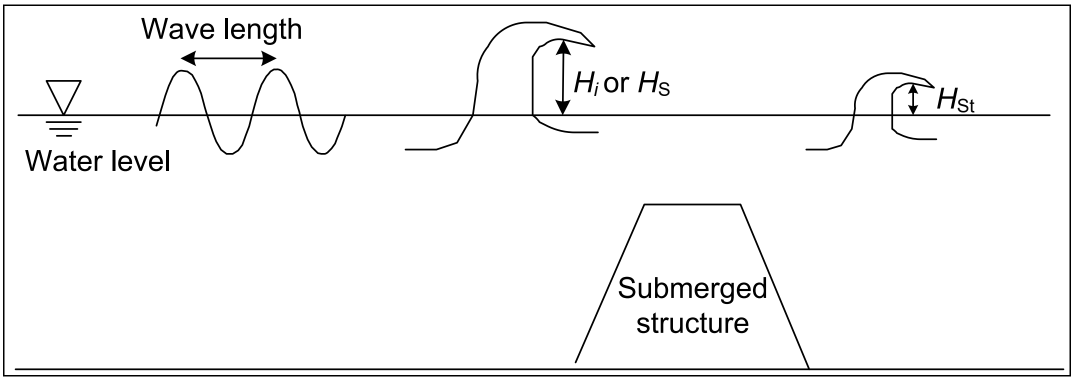

Fig. 1. Water level and wave height.

2.1 Shell movement

In term of stability, movements of oyster shell inside the reef have been observed by contribution of the 30 pink oyster shells at each reef. Pink oyster shell has been placed at specific point under the metal gabions with the square quadrant to show the exact point of placed pink oyster shell and also to be reference for observation of the point after one week later. In order to obtain factor which consist in stability checking, after placing the pink oyster shell, coordination of each shell and quadrant have been collected by Differential Global Positioning System (DGPS), an enhancement to Global Positioning System that provides GPS accuracy to about 10 cm in case of the best implementations. Displacements of pink oyster shell have been taken in to account by using the Microsoft excel to calculate.

2.2 Oyster reef density and relation between shells and sand Dn_{50}

The weight of the artificial reef was determined by collecting 15 cylinder samples from each reef. The weight of 12.5 cm diameter, 11.5 cm height cylinder samples were measured both of wet and dry conditions. The average of the weight was computed. Nevertheless, the ratio between shells and sediment of taken samples were calculated, including the sieve analysis of sediment to indicate the size particle of sediment. All of the results of weight measurement are used in formula in terms of ρ in stability checking formula.

The analysis of value of Dn_{50} which is the nominal diameter of materials rock of the oyster shell was also done by measuring the size of oyster in the same taken cylinder sample. After separation of shell and sediment, shell size from each sample was measured and calculated to determine the average value of Dn_{50} for each reef. Values of Dn_{50} for sediment was also determined by sieve analysis after getting the fraction of shell and sediment.

Unfortunately, the stability in terms of weight and size is difficult to investigate, as ratio of incident significant wave height, H_i, to the nominal diameter of materials rock, Dn_{50}, of greater than 6 (H_i / Dn_{50}>6) has not been used in study because these values will cause instability of the structure (Marcel et al., 2010). Beside the oyster shells was filled inside the iron gabions, so after passing though the wave and wind for several years those oyster reefs are still growing and working as submerged breakwater.

2.3 Water level and wave height

The data was enumerated and analyzed with reasonable adjustment and adapt it for appropriated used. A station of Marollegat, located near the Oesterdam is used in this research to obtain the H_i, water level, wave length, L_{op} and peak period, T_P. Value of Hi equal to 0.85 meter and water height is ranged from -1.55 meter to 2.15 meter. The meaning of important parameters can be shown in **Fig. 1**.

2.4 Wave transmission coefficient

In terms of shoreline control the final morphological response provide results from the time-averaged transmissivity. In case of simulations in the designing process such as in numerical simulation, it is necessary to know the variation in the transmission coefficient for various submergence conditions. Usually when there is need for reduction in wave attack on structures and properties the wave reduction is of interest (Pilarczyk, 2003). In that case the effectiveness of the measures taken will depend on their capability to reduce the waves.

In this study several formulas were tested and later a sensitivity analysis was performed to see how the wave transmission coefficient change based on different on the formulas and conditions. There are three different formulas which are J.W. Van der Meer, (1994), d'Angremond et al. (1996) and modified d'Angremond et al. (1996). In all formulas the value of the transmitted significant wave is going to be the incident wave height affected by the wave transmission coefficient (Eq.1).

$$H_{St} = K_T H_S \quad [1]$$

Considering artificial oyster reefs as low crested submerged structures, J.W. Van der Meer, (1994) formula can be used for determining the transmission coefficient. The value of the transmitted significant wave is going to be the incident wave height affected by the wave transmission coefficient. The parameters are as shown in **Fig. 2**.

$$K_T = \left(\frac{0.031H_s}{D_{n50}} - 0.24\right)\frac{h_c}{D_{n50}} - \frac{5.42H_s}{L_{op}} + \frac{0.0323H_s}{D_{n50}} - 0.0017\left(\frac{B_k}{D_{n50}}\right)^{1.84} + 0.51 \quad [2]$$

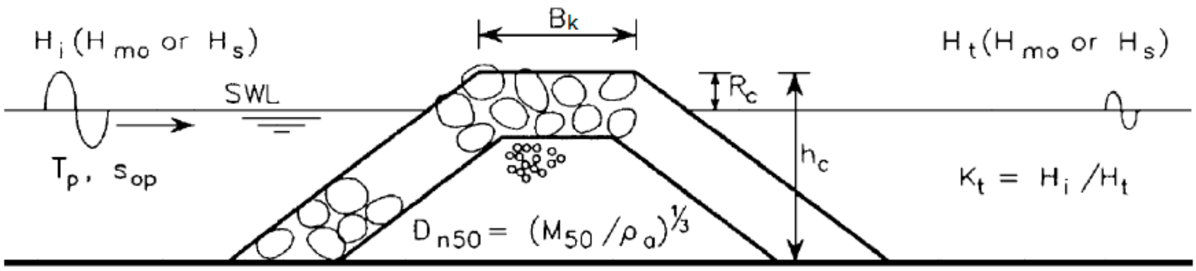

Fig. **2**. Definitions of governing parameters involved in wave transmission (van der Meer et, al., 2005).

Not only Eq.2 can be used but also both of the normal and modified of the d'Angremond et al. (1996) formula is considered because of the ratio between crest width and incident wave height (B/H_i) of Oesterdam artificial oyster reefs is more suitable for this formula also this formula does not consider the Dn_{50}. the transmission coefficient can be computed and compared to obtain the most correctly and acceptable results from

$$K_t = -0.4\frac{R_c}{H_i} + 0.64\left(\frac{B}{H_i}\right)^{-0.31}(1 - e^{-0.5\xi}) \quad [3]$$

The modified of the d'Angremond et al. (1996) formula is

$$K_t = -0.35\frac{R_c}{H_i} + 0.51\left(\frac{B}{H_i}\right)^{-0.65}(1 - e^{-0.41\xi}) \quad [4]$$

The calculation from the modified of the d'Angremond et al. (1996) formula showed that for very large crest freeboards the transmission coefficient reasonable becomes 0. Moreover, for a very large negative freeboard, the transmission coefficient is obviously reaching 1. However, the experiment result is most likely outside the range of practical applicability, for example a very high structure, small wave transmission may occur because of transmission through and not over the structure. Wave transmission varies fairly from small to large with decreasing freeboard. Considering that the parameter ranges are sometimes different from the ones investigated based on the present database, if the formula is used outside the boundary range (very large crest freeboards to very large negative freeboard), the inaccuracy estimation will be obtained. On the other hand, influence of crest width described in both formulas relies on a limited set of data.

Obviously, this variable has an effect on the accuracy of the formula. There is an evident on the occurred error in estimated values of K_t increases related with value of (B/H_i). So, for structures with (B/H_i) > 10, d'Angremond et al. (1996) equation overestimates the transmission coefficient. Unfortunately, after complex analysis the influence of the crest width is not very clear. To study the reason behind the deviation for high values of (B/H_i) it is necessary to understand that d'Angremond et al. (1996) equation's (Eq. 3) the function which indicated the impact of this set of parameter was retrieved by analyzing tests with zero freeboard in the old database. Also the curve used in d'Angremond et al. (1996) to describe the influence of the relative crest width has been shown in the two graphs of **Fig. 3**. If the relative crest width (B/H_i) is higher than 10, the error seems to be decreased. Furthermore, the right panel of the same **Fig.** shows the influence of the surf similarity parameter (ξ_{op}). If $\xi_{op} > 3$, the experimental values seem to be disposed towards the lower edge of the set of experimental values. Following by the result structures with (B/H_i) > 10, it is still accurate for calculation by using the d'Angremond et al. (1996) equation. In conclusions, high value of (B/H_i) would lead to an inaccurate calculation of K_t. Therefore, a maximum function has been derived instead of a constant value.

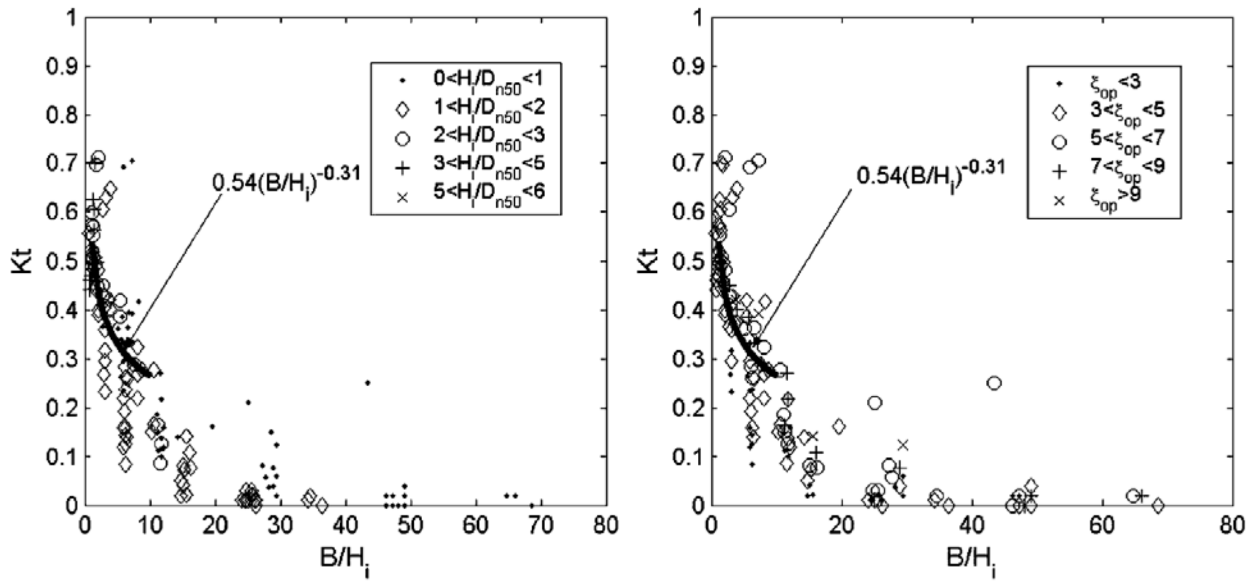

Fig. **3**. Influence of B /H_i on K_t for structures with zero freeboard and all data sets (van der Meer et, al., 2005).

3. Results and discussion

3.1 Value of K_t from each formula

The results from three different formulas, indicated that the period where the artificial oyster work under the wave conditions at Oesterdam is from the crest freeboard, R_c, range from 1.75 m to -0.95 m. The value of K_t varies from 0.82 (very small amount of reduction) at water height 1.75 m to 0.079963 (very large amount of reduction). The result quite varies depended on the formula. J.W. Van der Meer (1994) formula calculate the transmission coefficient based on the ratio of Hs and Dn_{50} meanwhile d'Angremond et al. (1996) equation has no concern on the ratio of Hs and Dn_{50} and obviously that J.W. Van der Meer (1994) formula overestimates value of K_t , comparing with the rest equation.

From Eq.1, the transmission coefficient started to go under boundary of the formula water level 1.65 above reef until the 0.05m above reef crest (working period). Effective transmission wave reduction is obtained during water level 1.15 (50% wave reduction) above reef until the 0.05 m above the reef crest (99% wave reduction). Transmission coefficient at R_c equal to 0 is 0.056434 (highest obtained value in this case).

From Eq.2, the transmission coefficient started to be calculated under boundary of the formula from water level 1.45 m above reef until the 0.35 m below the reef crest. Effective transmission wave reduction is obtained during water level 0.65m (50% wave reduction) above reef until the 0.35m below the reef crest (99% wave reduction). Transmission coefficient at R_c equal to 0 is 11.1 (67% wave reduction not the highest transmission coefficient which provided from equations). The maximum value of the transmission coefficient is obtained at water level 0.35m (99% wave reduction).

From Eq.3, the transmission coefficient started to be calculated under boundary of the formula from water level 0.75 m above reef until the 0.75 m (impossible to happen in our case because of the height of oyster reef which only 0.25 m) below the reef crest. Effective transmission wave reduction is obtained during water level 0.15 m (50% wave reduction) above reef until the 0.75 m below the reef crest (99% wave reduction). Transmission coefficient at R_c equal to 0 is 0.432905 (45% wave reduction not the highest transmission coefficient which provided from equations). The maximum value of the transmission coefficient is obtained at water level 0.75 m (99% wave reduction).

3.2 Suitable formulas for designing

The results show that, the difference can be observed through the difference formula. So selection of proper formula needs to be concerned. J.W. Van der Meer, (1994) (Eq.2) overestimates value of K_t comparing with the d'Angremond et al. (1996) equation (Eq.3). Modified d'Angremond et al. (1996) equation)Eq.4) seems to provide less value of K_t. Working period water level for this reef suggested by both J.W. Van der Meer, (1994) and d'Angremond et al. (1996) equation is from 1.65m above reef crest until 0.05 m above reef crest. In addition, 0.95 m above reef crest until 0.25 m below reef crest are suggested by Modified d'Angremond et al. (1996) equation. Obviously, it can be seen that Eq.2 overestimate value of K_t , comparing with the rest equation (**Fig. 4**). In the case at Oesterdam, value of Dn_{50} which is the nominal size is extremely varied so the average value may not the good represent value for the reef itself. Moreover, the ratio between Hi and Dn_{50} of our oyster reef almost out of the boundary. The effect of

*Dn*50 of shell under the gabion is needed to be investigated. Taking the mentioned problems into account, Value of K_t provided by Eq. 2 seems not to supply proper value for designing oyster reef.

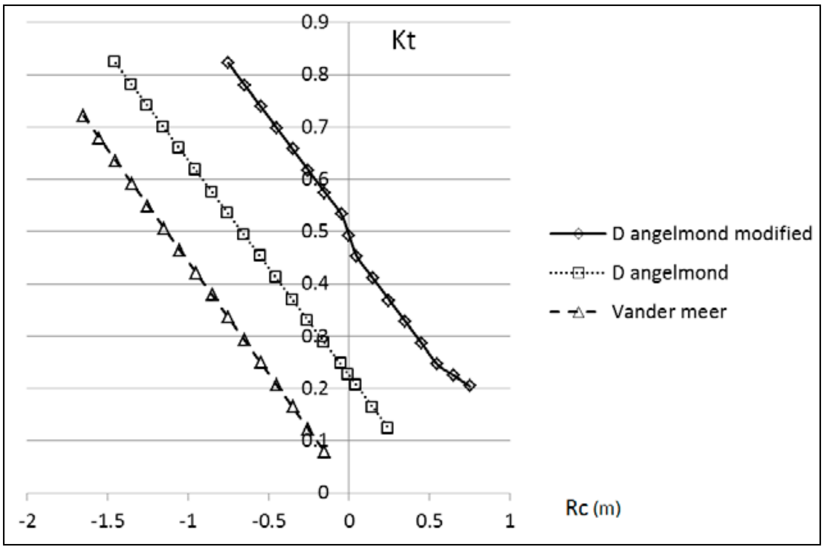

Fig. 4. Results comparison.

The d'Angremond et al. (1996) equation indicated the impact of this set of parameter was retrieved by analyzing tests with zero freeboard in the old database (Marcel et al., 2010). The results showed that the working water level range provided by d'Angremond et al. (1996) formula suit the oyster reef due to its height. According to dataset and the certain situation of the reef, an accuracy of predicted results was obtained by d'Angremond et al. (1996) formula. In term of engineering, not only the most proper formula is needed to be considered but also the formula which provide the safety is also concerned to provide the conservative designing results. Modified d'Angremond et al. (1996) formula provided the most conservative and accurate formula accorrding to ratio of reef width and incident wave height (H_i). As mentioned J.W. Van der Meer (1994) formula calculate the transmission coefficient based on the ratio of Hs and *Dn*50 meanwhile both of d'Angremond et al. (1996) equation has no concern on the ratio of Hs and *Dn*50 which more suitable for our study. Because of effect of *Dn*50 of our reef could not be accurate measured.

3.3 Designing improvement

The selection of proper formula which suit to each certain shoreline condition is important because the different formulas can consider different parameters and provide different results. After consideration of three formulas and study based on our case in Oesterdam, result shows that the artificial oyster reef needs the suitable formula to determine the efficiency because of the way artificial oyster reef as submerged breakwater, the ways artificial oyster reef was built, the uncertain value of *Dn*50, the condition that oyster need to grow and live such as exposure time and the force of the wave to reach the reef. So the results show that the artificial oyster reef condition was well concerned but not in term of breakwater parameter.

The results in **Fig. 4** indicated that R_c is one of the factors that has sufficient impact. The result revealed that for the oyster reef height (0.25m), the working period will be only from water level 0.75 m above reef (water level 1.0m above reef base) crest until 0.2 m below reef crest because of its height (0.25 m). After water level goes down to 0.25 m below crest of the reef or lower, the wave will be broken (loss energy) due to the sand but not the reef. Not only in term of working period but also in term of efficiency of wave reduction, resulting in initials value of wave reduction is only 22% (at water level 1.0m above reef base).

In practice, submerged breakwater will provide the sufficient amount of wave reduction when wave and water level are close to the reef crest. In conclusion, current oyster reef height (0.25m) does not provide sufficient wave reduction (both of working period and efficiency) in the area where the oyster was applied. However, considering its height (0.25m), the oyster reef already provides an acceptable working range because it can attenuate waves, by more than 22%, in a range up to three time of its height (0.75m above reef crest).

The artificial oyster reef is expected to grow 0.014 m per year so according to place where artificial oyster reef was applied effective submerged can be obtained by 9 or 10 years. But from engineering perspective, the artificial oyster reef in Oesterdam do not provide the sufficient results they can be improve in term of wave reduction and period of working.

In order to obtain the greater effectiveness, the suggested artificial oyster reef height would be 1.4 m according to tidal range at Oesterdam (range from 2.15m until -1.65 m as shown in **Fig. 5**). If value of R_c (which make value of transmission coefficient to go under the boundary and where reef start to work) at -0.75m and 22% of wave reduction is provided. So if the artificial oyster reef height equal to 1.4 m that means this oyster reef starts to provide 22% of wave reduction at the highest water level in that area at 2.15m and continue to provide the wave reduction until it reach the maximum (99% wave reduction) at 0.75 below the reef (0.65m above the reef bed). Therefore, the redesigned reef would be working efficiency form water level at 2.15m water level until the reef bed level (**Fig. 5**).

The slope of structure (**Fig. 6**) also plays a crucial role on formula in term of surf parameter. Result comparison indicated that mild slope of structure provided more efficient wave reduction (**Fig. 7**).

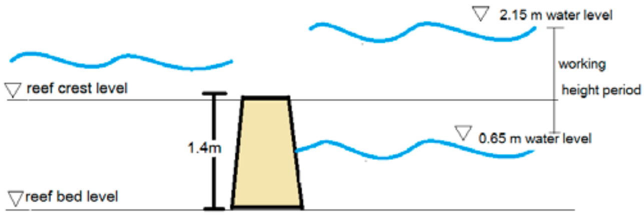

Fig. 5. Suggested reef height.

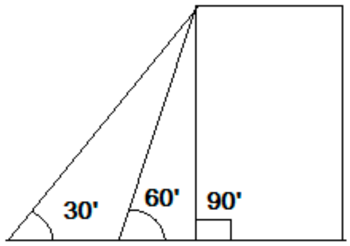

Fig. 6. Slope of artificial oyster reef.

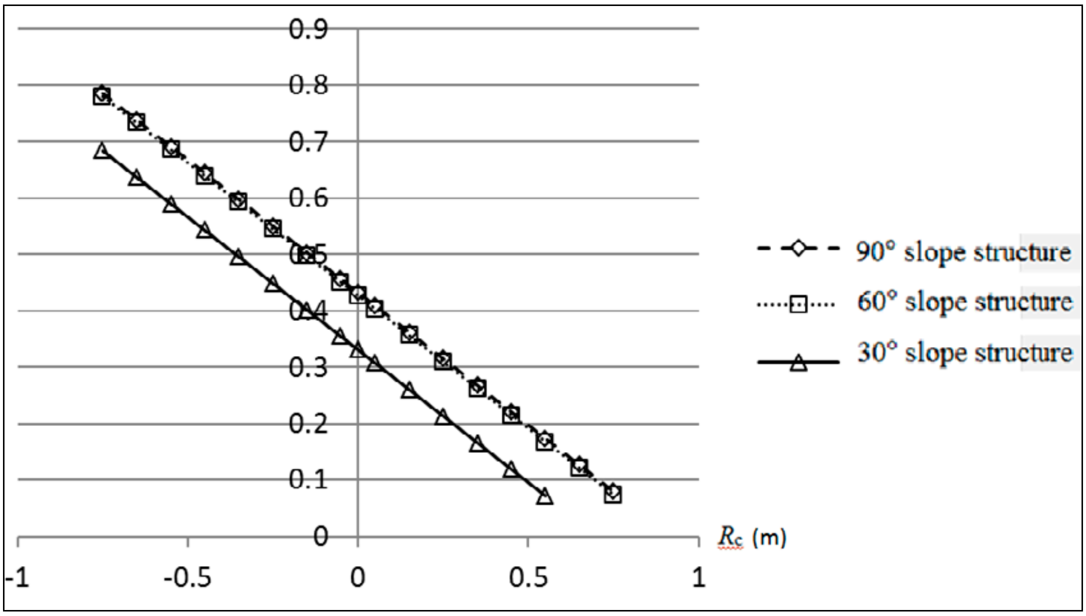

Fig. 7. Results comparison in term of slope of the structure.

The results showed that 30° mild slope of structure provided more than 10% of wave reduction comparing with 90° slope structure. Unfortunately at slope 60° the transmission coefficient improved only 1% more compared with 90° slope structure. The suggested slope of structure would be 30° in order to obtained more effective artificial oyster reef. To make a clear picture, at value of R_c equal to -0.25m, a 90° slope structure can provide 45% wave reduction meanwhile 60° slope structure provides 46% wave reduction and 30° slope structure results in 55% wave reduction. As there is no study about the slope of the structure but there is the study about the wave directions that can cause damage to the structures. The angle between the wave direction and the position of structure was observed. The results also show the high difference between 30° and 60°. Moreover, the small difference between 60° and 90° is found (Marcel et al., 2010). The results from the present study also show the good agreement.

4. Conclusions

In order to design effective submerged breakwater, knowing both of the specific condition of shoreline and wave characteristic are significant. Tidal range is one of the wave characteristic plays crucial role on designing of the submerged breakwater because it directly affects the efficiency of wave reduction by value of R_c. The height of the submerged breakwater is needed to be designed accordingly to the tidal range. Not only the height which related to tidal range and value of R_c but also the parameters such as the length, the crest width (B), nominal size of armor rock (Dn_{50}) and the shape are needed to be concern. Both of the length and the crest width also have an effect on the protection, for example the length does not have the direct influence on the wave reduction but it provides the significant influence on pattern of sediment in the lee zone.

In summary, case study in Oesterdam showed that the conditions of both of shoreline and structure parameter need to be seriously studied. However, the artificial oyster reef is still the new solution for shoreline protection. Oesterdam artificial oyster reef demonstrated a good example of insufficient consideration of engineering approaching. Artificial oyster reef has a lot of limitation in order to let them grow and sustain, on that time the ability to be sustainable and hospitable to the environment. Therefore, in order to combine environmentally adequate with sufficient engineering approaching, well understanding of shoreline condition, selection of material, parameter, and location of construction can be taken into account in order to select the proper formula for designing and achieve the goal of effective submerged breakwater

Acknowledgements

The authors would like to thank J.N. Salvador de Paiva for the helpful supporting and suggestion. Special thanks are also given to Department of Civil Engineering, KMUTT

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Symbols and abbreviations

K_T	Transmission coefficient
Dn_{50}	Number median represents that each number of particles greater or smaller than such value takes account of 50% of the total particles number.
H_i	Incident significant wave height
L_{op}	Wave length
T_P	Peak period
H_S	Incident wave height
H_{St}	Transmitted significant wave height
K_T	Transmission coefficient
hc	Structure height
S_P	Wave steepness
B	Crest width
R_c	Crest freeboard
ξ	Surf similarity parameter