

# CFD STUDY ON WAVE TRANSMISSION OF SUBMERGED HEMISPHERICAL SHAPED ARTIFICIAL REEF (HASR) BREAKWATER

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**Abstract.** Coastal erosion is the recession of shorelines and loss of land caused by waves, currents, and wind. Hemispherical Shaped Artificial Reefs (HSAR) can act as submerged breakwaters to mitigate erosion, offering structural protection while enhancing aquatic habitats and biodiversity. Designed to provide shelter for marine life, HSARs combine engineering with ecological benefits. Previous experimental studies on wave transmission over submerged breakwaters were conducted at the Hydraulic and River Engineering Laboratory of Bangladesh University of Engineering and Technology. This study demonstrates wave transmission across HSAR breakwaters using the Volume of Fluid (VOF) method with the Reynolds-Averaged Navier–Stokes (RANS) equations in the FLOW-3D numerical suite. The reefs were modeled using RHINOCEROS 5.0 software. The main objective is to determine wave transmission through numerical simulation. First, the model was validated against experimental results for submerged breakwaters. Further simulations assessed transmission with varying HSAR structural heights and designs. The findings showed close agreement between simulations and experiments, with percentage errors ranging from 4.1% to 16.7%. Results emphasize the significance of structural height in reducing the wave transmission coefficient,  $K_t$ . HSARs outperformed thalame breakwaters in transmission reduction, proving beneficial for coastal protection, environmental sustainability, and aquatic life.

**Keywords:** HSAR breakwater, wave transmission coefficient, erosion, coastal

## Introduction

Coastal erosion is a natural phenomenon resulting from the interaction between natural processes and system (Prasad and Kumar, 2013). Shoreline shifts subsequent from erosion and accretion are natural processes that occur over several time scales. These can occur in response to smaller (short-term) events such as earthquakes, normal wave action, tides and winds, or response to major (long-term) events such as glaciation or ecological cycles that can significantly change sea levels (rise and fall) and tectonic activity (Leatherman et al., 2011). Coastal protection of the shoreline is rarely required, however in a few locations the dynamic shoreline has become a problem, in some cases a major and expensive problem, and in almost all these cases the problem is related to human interference or encroachment on the shoreline (Subiyanto et al., 2024; Benda and Dunne, 1997). There are several different methods used to avoid beach erosion in different places. Breakwaters are usually introduced as an example of coastal protection

to protect and stabilize the coastal area from the impact of waves and other hydrodynamic forces. Some of the most common hard protection instead of breakwater are seawalls, revetment, groin, floating structure, and submerged breakwater. The submerged breakwater as shown in *Figure 1*, can provide an efficient shoreline conservation solution with low environmental impact if employed in conjunction with beach nourishment. In popular tourism beach area, the submerged type of breakwater is considered more frequently as a soft solution in solving coastal engineering problem (Hall, 1999; Seabrook and Hall, 1998). Submerged breakwaters can help stabilize the shoreline while reducing adverse effects on neighboring beaches. Due to their reduced environmental and visual effects, submerged breakwaters have become attractive as coastal protection for recreational and residential coastal areas.



*Figure 1. Submerged breakwater along the coastal area.  
Source: Hall (1999).*

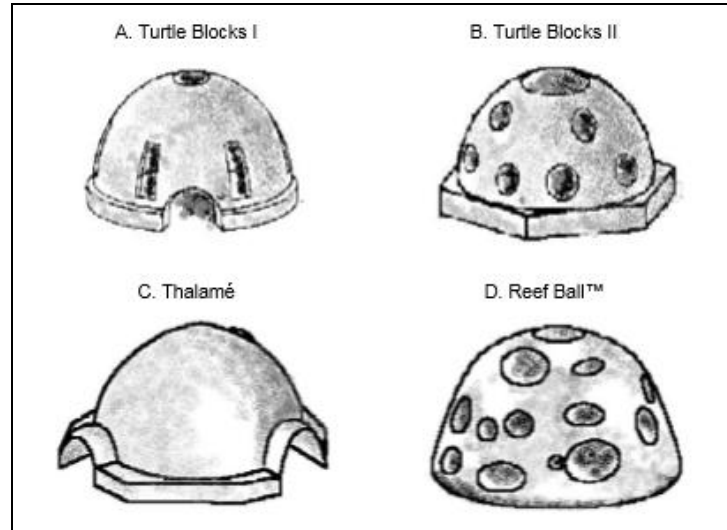
### ***Effectiveness artificial reef breakwater on protecting coastal***

An artificial reef is a submerged (or partially tidal) structure that is deliberately placed on the seabed to imitate certain functions of a natural reef, such as protecting, regenerating, concentrating or enhancing populations of living marine resources (Higgins et al., 2022; Lokesha et al., 2013; Marsh and Kaufman, 2012; Stewart, 1987). Artificial reef must undergo some evaluation to determine the performance itself to ensure it can be applied in the real condition especially at the shallow water. Artificial reefs provide shelter, feeding, spawning, playing grounds, rest real and temporary stop-over for fish and create their local ecological system. Pressure waves created by currents impinging on solid reef structures are recognized by fishes and provide them an orientation to the reefs. Concrete is a material with a high success rate for artificial reefs. Concrete used in artificial reefs can last up to 500 years, providing a long-term solution. Concrete also has a high resistance to sulphates and other chemicals that can break down the composition of a structure in saltwater. Moreover, if concrete is mixed with a low concrete water ratio, the permeability will be reduced once it has been mixed with concrete. Some studies were carried out on physical aspects of artificial reef and conducted by researchers. The strength, stability and method of construction of reefs are the physical principles involving factors such as material science, civil engineering and physical oceanography (Lokesha et al., 2013). They were mostly directed towards

biological environmental aspects performed by biologist and marine scientist in the areas of assemblage fish in the reef vicinity, reef productivity, comparative studies between artificial and natural reefs. The turbulence over the reef which is combining with the friction of water created among the reefs will reduce the energy passing the reefs by wave breaking.

### ***Hemispherical shaped artificial reef breakwater***

Artificial reef structures can be utilized as submerged breakwaters, providing wave attenuation for shoreline erosion control plus habitat enhancement (Harris, 2003). Artificial reefs or breakwaters of the reef are rubble mound breakwaters of usually single-sized stones with a crest at or below sea level. They are usually constructed offshore (often parallel to the shore). 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 (Armono, 2003; Armono et al., 2001). The breakwater's sharp edges may cause fishing nets to burst. Artificial reef breakwaters with a hemispherical shape can be used as submerged breakwaters, reducing waves to reduce beach erosion and improve habitat (Harris, 2003). The HSAR submerged composite breakwater made of several perforated hollow HSAR was suggested in this study. The flow is complicated by features like turbulent flow, which happens near reefs and when waves crash on the surface above (Sindhu et al., 2015). The hollow, bottom-seated, smooth-shaped HSARs were chosen because of their hydraulic stability, ability to lessen fishing net tearing, ability to create coherent eddies with upward flow, and ability to give fish hiding places. *Figure 2* displays the various HSAR unit types.



***Figure 2. Type of HSAR units.***  
*Source: Armono et al. (2001)*

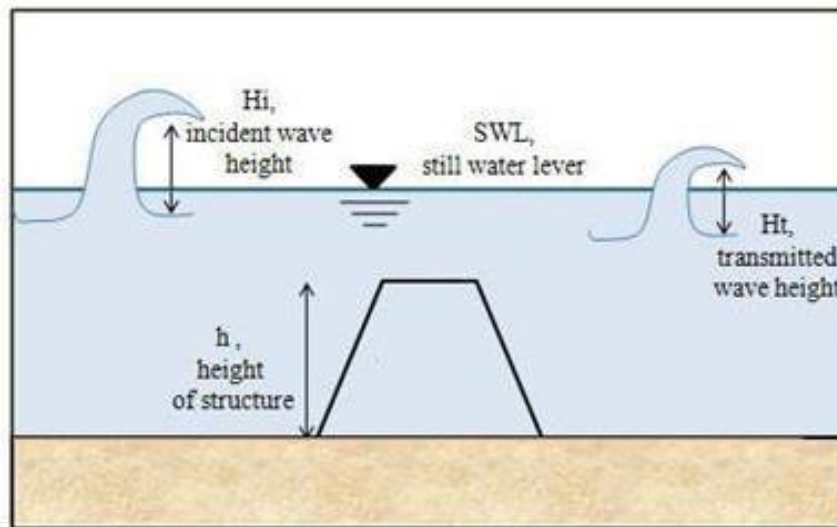
### ***Wave transmission over breakwater***

The quantity of energy that overtops or travels through the structure is known as wave transmission. The purpose of an effective submerged breakwater is to induce wave attenuation, or a loss of energy, by limiting the amount of energy that may travel through the structure. The transmission coefficient is the ratio of the height of the waves

that are transferred behind the breakwater to the height of the waves that are incident. Therefore, the wave transmission coefficient  $K_t$  is formulated as:

$$K_t = \frac{H_t}{H_i} \quad \text{Eq. (1)}$$

where,  $H_t$  = transmitted wave height,  $H_i$  = incident wave height. Eq. (1) shows the relation of wave transmission resulting from a submerged structure.  $H_t$  represents the height of the wave after it passes the breakwater at a certain point.  $H_i$  represents what the wave height, at the same point, would be if the submerged breakwater was not there. Depending on the design, it is anticipated that the wave height will drop by a specific height after passing over the building. Wave energy is attenuated less when the transmission coefficient is higher. Meticulous design is necessary to obtain the best performance and effectiveness according to waves and environmental characteristics of subjected area (Brancasi et al., 2022; Rahimzadeh et al., 2014; Rahman et al., 2006). *Figure 3* shows the wave height decrease after hitting the submerged breakwater.



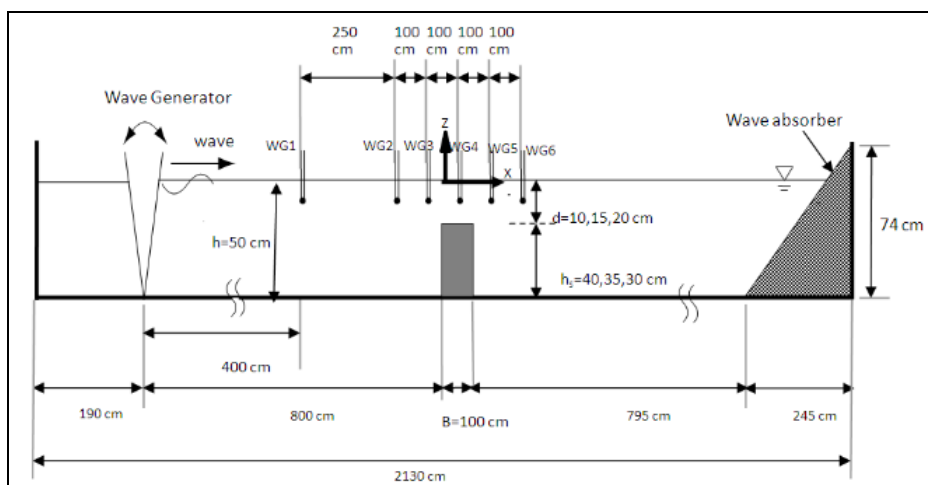
**Figure 3.** Wave height decreases after hitting the submerged breakwater.  
Source: Arnouil (2008).

### ***Previous study of wave transmission over submerged breakwater through numerical and experimental works***

The previous study from Fauzi et al. (2017) about numerical model of artificial reef of its performance and hydrodynamic condition using Flow 3D. This work uses an artificial reef model consisting of hexa reef, star reef, cube, seadome and bottle reef. From the results it shows that seadome breakwater performance has the best value of wave transmission. Previous research studied on the reliability of 3D numerical simulation on wave transmission over artificial reefs. Hall and Seabrook (1998) studied the design equation for transmission at submerged rubble mound breakwaters. The results of a number of 2-D and 3 D tests were taken to determine the effect of depth of sub mergence, crest width, breakwater slope and armour diameter on the wave transmission characteristics of submerged. The solution presented provides a relatively good estimate of transmission at submerged breakwaters over a wide range of

conditions, including broad crested submerged breakwater. The proposed equation does, however, provide a design tool useful for preliminary design and feasibility studies. Sindhu et al. (2015) studied of develop semi-empirical equation for co-efficient of wave transmission,  $K_t$ . In the paper, it also studies the coefficient of wave transmission characteristics,  $K_t$  of submerged reef breakwater under varying wave characteristics, water depths and crest widths.

An extensive study was published by Hall (1999) also evaluated the wave transmission on submerged breakwater made of hollow hemispherical shaped artificial reefs. This study aims to establish a model for wave propagation through a submerged breakwater made up of multiple HSAR units and to determine the optimum reef configuration to minimize incoming wave energy. It present the transmission coefficient,  $K_t$ , which is the ratio between transmitted and incoming wave ( $H_t/H_i$ ), will be expressed as a function of depth submergence, wave height, wave period, reef crest width and reef configuration to observe and identify if any relationships or trends. Physical experimental studied was conducted by Rahman and Womera (2013) as shown in *Figure 4*. The two-dimensional experimental was carried out in the laboratory to investigate the performance of submerged breakwater in wave breaking as well as dissipating the incoming wave energy. The experimental study was carried in a two-dimensional wave flume of 21.3 meter in long, 0.76 meter in wide and 0.74 meter in height at the Hydraulics and River Engineering Laboratory of Bangladesh University of Engineering and Technology. Mahmoudi et al. (2017) also conducted experimental work to observe the transmission and reflection coefficients on the impermeable submerged breakwaters.



**Figure 4.** Experiment set up.  
 Spource: Hall and Seabrook (1998).

An option to use to use submerged type such hemispherical shaped artificial reefs (HSAR) to replace other breakwaters due to inexpensive, environmentally friendly, flexible, easy, economical on-site fabrication using a patented mould system and can be custom designed as habitat for selected benthic and pelagic species, including aquaculture applications propagation of corals. Although prior implementation on site, the preliminary study must be performed through computational modelling to comprehend and understand the significant effect of the structures on attenuate of waves in idealized situations. Therefore, the objectives of this study are divided into two parts

which: (1) to investigate the effect of relative structure height of HSAR breakwater on wave transmission,  $K_t$  with different wave periods and (2) to compare the performance of different types of HSAR breakwater design on wave transmission,  $K_t$ . To carry out this research, the numerical simulation was performed by using numerical simulation of Flow 3D software which is available in the UMT simulation laboratory.

## Materials and Methods

Figure 5 shows the flow of methodology for this study. The research begins with the reconstructed the model by using CAD software named RHINOCEROS version 5.0 in modelling phase, simulating the model by using CFD software named FLOW-3D in pre-analysis and post-processing phases. After that, the result will be gained and analyse to achieve the aim of the project.

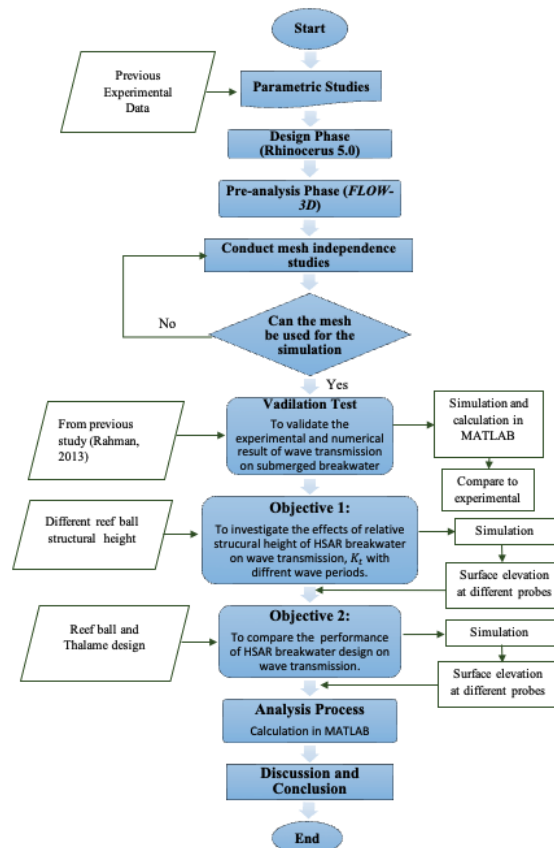


Figure 5. A flowchart shows the general methodology of this study.

### Design phase

The first phase was designed the model of the reef ball with different structure height that will be used in the simulation whereas the second phase was designed as thalame of HSAR breakwater. The latter was to compare the performance with reef ball and thalame breakwater. For this research, a scale of 1:4 model was used to conduct the test in the numerical simulation. The dimension and figure of the reef model are shown in

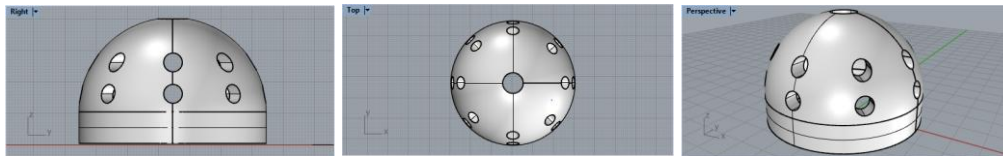
Table 1 and Figures 6 whereas the dimension and figure of the thalame model are shown in Table 2 and Figures 7.

**Table 1. Principal dimension of Reef Ball.**

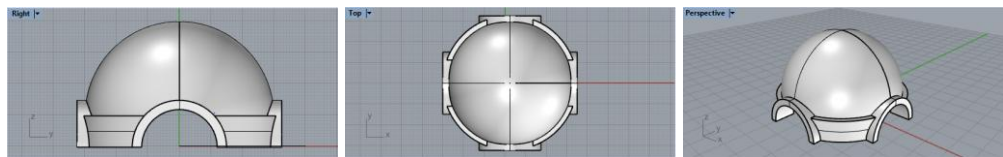
Measurement	Detail
Height (meter)	0.3, 0.35, 0.4
Diameter of base (meter)	0.6
Thickness (meter)	0.1
Number of holes	16

**Table 2. Principle dimension of Thalame.**

Measurement	Detail
Height, (m)	0.4
Diameter of Base, (m)	0.6
Thickness, (m)	0.1
Number of holes	4



**Figure 6. Side view of Reef Ball (Left side); Top view of Reef Ball (Center); and perspective view of Reef Ball (Right side).**



**Figure 7. Side view of Thalame (Left side); Top view of Thalame (Center); and Perspective view of Thalame (Right side).**

Validation test was carried up to compare the results of wave transmission coefficient from the experimental study by Rahman and Womera (2013). The experimental set up was modelled in the flow 3D and imposed with similar wave condition as shown in Table 3.

**Table 3. Parameter for validation test.**

Relative Structural Height, $h_r/h$	Wave Height, $h$ (m)	Wave period, (s)
0.6	0.13	0.2
		0.4
		0.6
		0.8
		1.0

Source: Rahman and Womera (2013).

From the data incident wave height,  $H_i$  and transmitted wave height,  $H_t$  will be calculated to get the wave transmission coefficient,  $K_t$ . The standard percentage error was used to determine the precision of the results. The percentage of error formula is as Eq. (2).

$$\%_{error} = \left( \frac{(exp. - theoretical)}{theoretical} \right) \times 100 \quad \text{Eq. (2)}$$

In this project, there are two parametric studies that need to be focused. The parametric studies are as follows.

***Investigate the effects of relative structural height of HSAR breakwater on wave transmission,  $K_t$  with different wave periods***

For this variable, nine simulations have been run with different wave periods and different relative structural height,  $h_s/h$  as shown in *Table 4*. Reef ball breakwater type of HSAR were selected to find the effects of different structural height and different wave periods on wave transmission,  $K_t$ . *Figure 8* shows the reef ball structural height,  $h_s$  and the still water depth,  $h$ . For the simulation test 1, 2, 3 the structural height is 0.3m while for simulation test 4, 5 and 6 the structural height is 0.35 and simulation test 7, 8 and 9 structural height are 0.4m. The still water depth,  $h$  was set at 0.5m. Wave height in the wave flume simulation remain same that is 0.13m. *Figure 9* shows the probes, submerged structure of HSAR positions and initial free surface elevation which being set up in the computational domain. The first probe was measured the incident whereas the second prob was measured the reflected waves throughout the simulation period. After finished, the data of free surface elevation against time will be calculated in MATLAB to find incident wave height,  $H_i$  and transmitted wave height,  $H_t$ . To calculate wave transmission coefficient,  $K_t$  it can be calculated by using formula in Eq. (1). Then, the effects of different structural height and different wave periods can be discussed in wave transmission resulted.

***Table 4. Parameter study of wave transmission with different relative structural height,  $h_s/h$ .***

No of Simulation Test	Relative Reef Ball Height, $h_s/h$	Wave height (m)	Wave period (s)
1	0.6	0.13	1.5
2		0.13	1.7
3		0.13	2.0
4	0.7	0.13	1.5
5		0.13	1.7
6		0.13	2.0
7	0.8	0.13	1.5
8		0.13	1.7
9		0.13	2.0

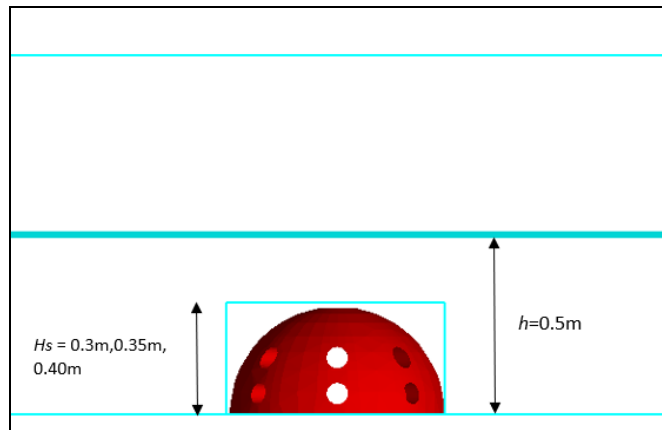


Figure 8. Structural height,  $h_s$  and still water depth,  $h$ .

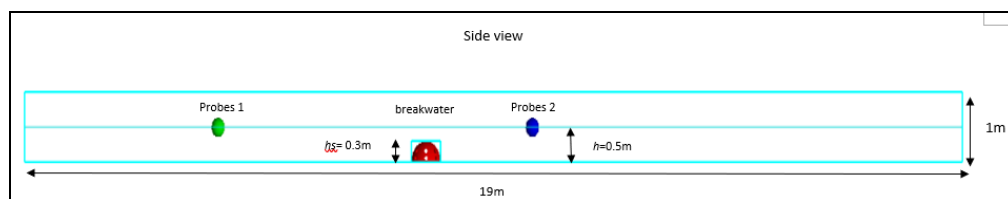


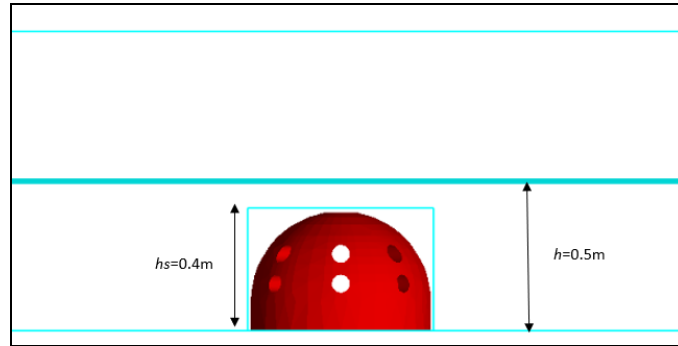
Figure 9. Set-up computation domain in Flow 3D.

**To compare the best performance of HSAR breakwater design on wave transmission**

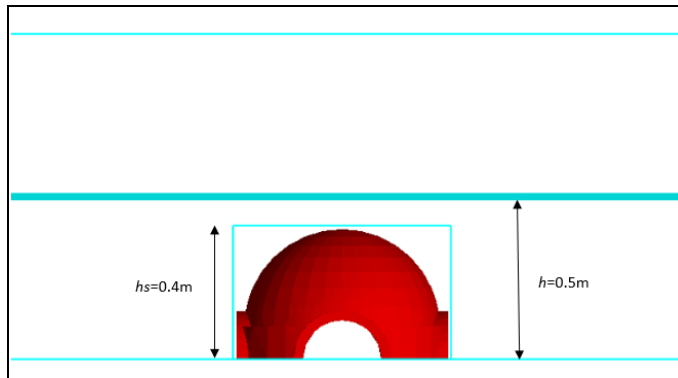
The objective was to study about the effects of two types HSAR breakwater with difference wave period. Two types of design HSAR breakwater which was thalame and reef ball were selected to compare the performance of breakwater on wave transmission,  $K_t$ . To compare the design of HSAR breakwater, 6 simulations of will be tested. First, 3 simulations of reef ball breakwater with different wave periods and another 3 simulations of thalame breakwater with different wave period (Table 5). The structural height,  $h_s$  of the reef ball and thalame are 0.4 as shown in Figure 10 and Figure 11. The still water depth was set 0.5m. Data free surface elevation at each probe had been selected to calculate incident wave height,  $H_i$  and transmitted wave height,  $H_t$ . The results of wave transmission will be calculated by using formula in Eq. (1). Then, the results will be compared to find lowest value of wave transmission coefficient,  $K_t$  between reef ball and thalame breakwater. The best design of HSAR breakwater will be determined from the best results of wave transmission.

Table 5. Parameter in wave transmission with different design of HSAR breakwater.

Relative Structural Height, $h_s/h$	Wave height (m)	Wave period (s)
Reef Ball	0.13	1.5
	0.13	1.7
	0.13	2.0
Thalame	0.13	1.5
	0.13	1.7
	0.13	2.0



**Figure 10.** Reef ball height and still water depth.



**Figure 11.** Thalame height and still water depth.

## Results and Discussion

### Validation

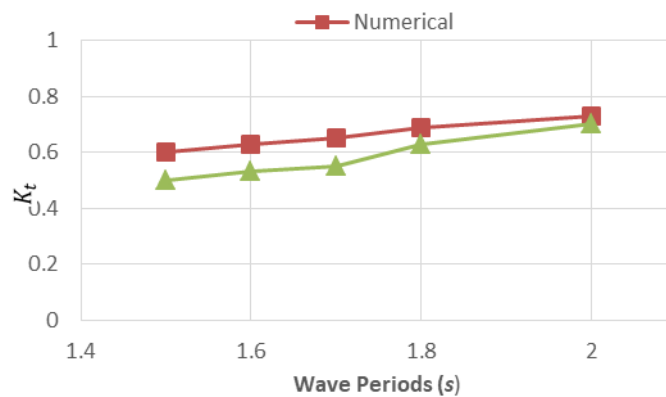
Purpose of this validation is to check the correctness of the simulation data with the data in experiment studies (Rahman and Womera, 2013). Based on *Table 6*, it shows that the percentage error for each point of wave transmission against wave period. As shown in the table, as the wave periods increase, the percentage error for each point of wave transmission against wave period. As shown in the table, as the wave periods increase, the percentage error decreases which is close to 4.1% error. The percentage difference of wave transmission coefficient,  $K_t$  between numerical and experimental are between 4.1%-16.7%. The transmission coefficient for both simulated and experimental result also decreases as the wave period increases. From this result, the difference between both methods can be discuss as the differences in model design and parametric variable that are used for this study. The graph presented in *Figure 12* has shown upward trend of wave transmission coefficient as wave period increase like experimental data. It is obvious as wave period increase, the wave transmission coefficient also increases. Hence, the result has shown a good agreement between simulated result against experimental results. The main difference of the results between simulated and experimental is due to the probability of difficulties in defining the real situation during numerical simulation configuration. It is assumed that the experimental results represent the real behaviour of the object or model while the simulation results represent the behaviour of the same object based on its theoretical model. There are several possible explanations to the discrepancy and one of which is regarding to the number of waves employed during simulations. It is impossible to employ many waves

through numerical simulation because the time consumed for simulation work is relatively height. Hence, the simulated result showing a close relation because there are a few points which lie far away from cluster of the data and the regression lines of experimental data.

**Table 6.** The percentage error between numerical and experimental results.

Wave period (s)	Numerical data	Experimental data	Percentage error (%)
0.2	0.6	0.5	16.7
0.4	0.63	0.53	15.5
0.6	0.65	0.55	15.4
0.8	0.69	0.63	8.7
1.0	0.73	0.7	4.1

Source: Rahman and Womera (2013)



**Figure 12.** Wave transmission coefficient against wave periods in numerical and experimental.

**Investigate the effects of relative structural height of HSAR breakwater on wave transmission,  $K_t$  with different wave periods**

Table 7 shows the results of wave transmission,  $K_t$  obtained from simulation of reel ball breakwater with different relative structural height,  $h_s/h$ . From Figure 13, it prevails that as relative structural height increases,  $h_s/h$  the transmission coefficient,  $K_t$  decreases respect to wave periods. The reef ball breakwater was not totally performed for the larger wave periods based on the result obtained. At  $T=2s$  the value of which is 0.7, 0.6 and 0.58 higher compared to other at relative structural height, 0.6, 0.7 and 0.8. Wave periods and relative structural height affected the wave transmission coefficient from the result gained. The percentage of wave height reduction is shown in Table 8. Reef ball breakwater of relative structural height,  $h_s/h$  at 0.8 show good in percentage of wave reduction that is around 42.62%-50.81%. The lowest percentage of wave reduction with around 30%-41.37 % in reef ball with relative structural height 0.6. This shows that the reef ball breakwater is good in wave reduction when the relative structural height increases.

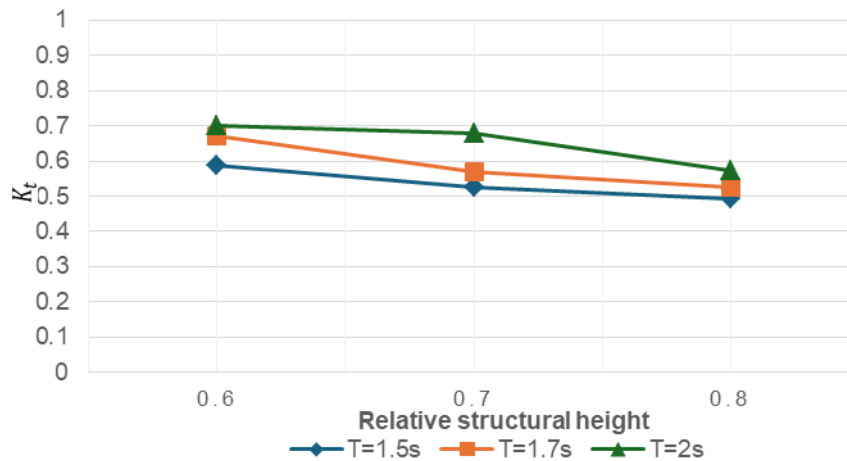
**Table 7.** Wave Transmission Coefficient,  $K_t$  of each wave periods.

Relative Structural Height, $h_s/h$	Wave height (m)	Wave period (s)	Incident wave height, $H_i$	Transmitted wave height, $H_t$	Transmission coefficient, $K_t$
0.6		1.5	0.58	0.34	0.59
	0.13	1.7	0.58	0.39	0.67
		2.0	0.6	0.42	0.7

0.7	0.13	1.5	0.59	0.31	0.53
		1.7	0.58	0.33	0.57
		2.0	0.59	0.4	0.68
0.8	0.13	1.5	0.61	0.3	0.49
		1.7	0.59	0.31	0.53
		2.0	0.61	0.35	0.58

**Table 8.** Percentage wave reductions.

Relative Structural Height ( $h_s/h$ )	Wave period (s)	Wave reduction (%)
0.6	1.5	41.37
	1.7	36.21
	2.0	30
0.7	1.5	47.46
	1.7	43.1
	2.0	34.43
0.8	1.5	50.81
	1.7	47.46
	2.0	42.62



**Figure 13.** Transmission coefficient,  $K_t$  against relative structural height,  $h_s/h$ .

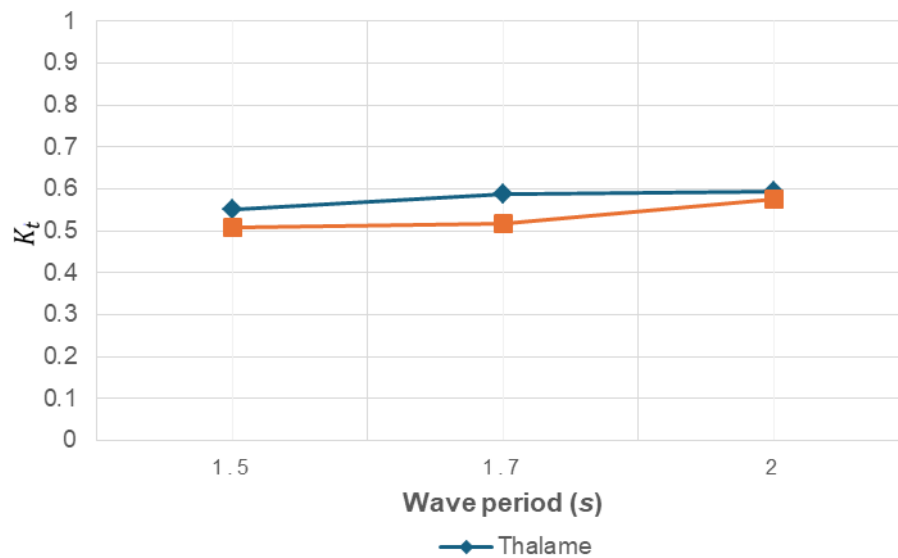
### To compare the performance of difference HSAR breakwater design on wave transmission

Table 9 shows the results of wave transmission between reef ball and thalame breakwater. These results will show the best design of hemispherical shaped artificial reef (HSAR) breakwater. The height and base diameter of two breakwater remain same. From the table shown, the results of wave transmission between reef ball and thalame with different wave periods does not show significant difference. Figure 14 presents wave transmission from reef ball and thalame breakwater with different wave periods. The graph shows upward trend of wave transmission coefficient,  $K_t$  with increase in wave periods. The graph also shows that the performance of reef ball breakwater is better compared to the performance of thalame breakwater. Reef Ball performance in reducing wave height is very good. At T=1.5s wave period test, reef ball resulted 0.51 compared to thalame 0.55 of wave transmission coefficient,  $K_t$ . Even so this value is not so much with thalame breakwater. The difference of wave transmission is not so different because the shape of two HSAR breakwater is approximately same. In addition, at 2.0s wave period test, wave transmission coefficient,  $K_t$  of reef ball are 0.57

while thalame 0.59. This shows that two types of HSAR breakwater, which is reef ball and thalame breakwater were not totally performed with larger wave periods.

**Table 9.** Wave transmission coefficient,  $K_t$  of Reef ball and Thalame breakwater.

Type of HSAR breakwater	Wave height	Wave period (s)	Incident wave height, $H_i$	Transmitted wave height, $H_t$	Transmission coefficient, $K_t$
Thalame	0.13	1.5	0.58	0.32	0.55
	0.13	1.7	0.58	0.34	0.59
	0.13	2.0	0.59	0.35	0.59
Reef Ball	0.13	1.5	0.59	0.3	0.51
	0.13	1.7	0.6	0.31	0.52
	0.13	2.0	0.61	0.35	0.57



**Figure 14.** Comparison of wave transmission coefficient of reef ball and thalame breakwater.

### Conclusion

The aim of this study is to investigate the wave transmission of the submerged breakwater under different wave periods using computational fluid dynamic. Based on the results several conclusions can be made based on the objectives of this study. From the beginning of this simulation, the study is to compare the results of wave transmission between numerical and experimental. The result has shown a good agreement between simulated results against experimental results. Thus, the outcomes of the CFD simulation showed a similar trend when compared with the experimental data based on qualitative observation on the graphs. From this aim, we can conclude that there is a result that differs from the physical experiment at the beginning of the simulation due to the unstable generated wave. In a nutshell, it is recommended to analyse the result at a certain point to be more precise and accurate for this study. The first objective for this study is to determine the effects of different structural height breakwater and wave periods on the wave transmission. The results show that as the relative structural height and wave periods increases, the wave transmission decreases. The HSAR breakwater was not totally performed for the larger wave periods based on the result obtained. Thus, the wave transmission coefficient of reef ball is affected by the structural height of breakwater and the wave periods. Based on the second objective

which is to compare the performance of different type HSAR breakwater that is thalame and reef ball breakwater. The different design of HSAR breakwaters affect the wave transmission after hit the breakwater. From the results obtained, we can conclude that the performance of reef ball breakwater is better compared to thalame breakwater. Reef breakwater generates lowest wave transmission coefficient,  $K_t$  compared to thalame breakwater models.

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### **Conflict of interest**

The authors confirm that there is no conflict of interest involved with any parties in this research study.

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