



NUMERICAL INVESTIGATION OF HYDRODYNAMIC CHARACTERISTICS AND FORCES ON THE SUBMERGED NAHRIM MODULAR ARTIFICIAL REEF USING MESHLESS METHOD



FINAL REPORT

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EXECUTIVE SUMMARY

The present work describes the implementation of particle-based method of Smoothed Particle Hydrodynamics (SPH) DualSPHysics model to simulate to conduct the numerical investigation of hydrodynamic characteristics on the submerged NAHRIM modular artificial reef. Three different porosity model have been tested into various range of wave height following the similar setup from the experiment. The numerical model is then validated against theoretical solutions and experimental results which investigated respectively: i) the hydrodynamic characteristics surrounding the submerged breakwater, ii) the influence of submergence level to the wave transmission and iii) effect of porosity to the wave transmission. The differences of modelling with control, 50% porosity and 0% porosity conditions are highlighted. The results demonstrate the capability of DualSPHysics to represent the hydrodynamic characteristics and estimate the wave attenuation when interacting with submerged coastal breakwater. The applicability of DualSPHysics to coastal engineering problems is already enhanced, being the model that capable of generating waves, random sea states and nonlinear free surface. The numerical data in the present work can provide reliable basic data, including wave transformations, velocities, and dynamic pressures, for other CFD models validation.

KEYWORDS: SPH; DualSPHysics; wave-structure interaction; wave transmission coefficient; submerged breakwater

1.0: Project Background

Waves propagating from deep water to coastal areas are affected by bottom bathymetry, such as submerged breakwaters, resulting in wave refraction, shoaling, and breaking. Submerged breakwaters are becoming attractive to coastal engineer because they have many advantages including keeping the aesthetic value of coastal scenery and restore beach by trapping natural sediments. The main function of a submerged breakwater is to force waves to break in advance owing to a sudden decrease in water depth, such that the energy is attenuated. Energy dissipation around submerged breakwaters is due to two factors which are wave breaking over the structure and vortex generation at both sides of the submerged breakwaters. However, their design can sometime be complicated with complex geometries. Accurate prediction of wave properties as well as the hydrodynamic behavior over a submerged breakwater is still complex and challenging. Therefore, it is very important to understand the characteristics and the impact of wave transmission of wave over submerged breakwaters.

Over recent decades, various studies have been conducted on wave propagation over submerged breakwaters experimentally and numerically. The experimental data are still used by researchers to verify the reliability of their numerical models. Although a lot of reliable data can be obtained from laboratory experiments, most study will investigate the submerged breakwater performance at various wave properties through their transmission of wave coefficient (K_t), i.e., the ratio of the transmitted to the incident wave height. In general, the wave transmission coefficient increases with submergence depth and wave period and decreases with raising the incident wave height and the breakwater crest width. Detailed information about the hydrodynamic characteristics (such as flow field and impact force) around the submerged breakwater is still insufficient. As we know, numerical simulation can provide detailed information on the hydrodynamics around submerged breakwater, which is not easily observed by physical experiments. With the development of computational technique and more accurate numerical schemes, numerical studies of wave transformations over submerged breakwaters have become increasingly feasible and popular.

Numerous numerical models applied to coastal engineering are mature for practical purposes, coastal structure design and storm event prediction. Boussinesq-type models and non-linear shallow water models are efficient and accurate models for many coastal engineering studies. Non-hydrostatic models like SWASH (*Zijlema, Stelling and Smit, 2011*)

can even use multiple layers in the vertical direction. However, depth-integrated models cannot capture phenomena such as plunging wave breaking, overtopping, and having problem in handling complex geometric layouts. Mesh-based Reynolds-averaged Navier-Stokes (RANS) can accurately capture the free surface profile but with some challenges and drawbacks. These problems involve the necessity of using specific free surface capturing technique, numerical diffusion due to the computed flow convection term, and difficulties in adjusting the grid framework for porous media with complex geometries (Maza, Lara and Losada, 2015).

All the problems mentioned for grid-based methods usually needed to be solved using finer meshes and coupling method. Meanwhile, alternative method of meshless method is available which based on the Lagrangian formulation of the Navier-Stokes equations. Meshless methods can efficiently handle problems characterized by large deformations at interfaces, including moving boundaries and do not require special tracking to detect free surface. The Lagrangian nature of DualSPHysics models makes them very suitable for modelling real life engineering problems. Several studies on coastal engineering applications based on SPH, for example, wave propagation over a beach (Monaghan and Kos, 1999), solitary waves (Dominguez et al., 2019), surf zone hydrodynamics (Lowe et al., 2019), wave run-up on dikes (Subramaniam et al., 2019), and wave forces on vertical walls and storm walls (Didier et al., 2014; Altomare et al., 2015). In addition, the discrete porous medium could be fully discretized using particles without introducing further simplifying assumptions.

In this study, a new model of submerged breakwater by NAHRIM will be implemented to investigate the effect of its shape, submergence level and porosity on the wave transmission coefficient (K_t). Experimental and simulations have been conducted on three different porosity which the transmission coefficient for each case was calculated and compared. The model is at first validated by comparing the wave elevation without the submerged breakwater with theoretical solution to ensure the target wave arrives at the desired location. Then, regular wave interaction has been simulated, and the results of velocity and pressure have been analyzed. Finally, main outcomes of wave transmission coefficient were discussed.

2.0: Experimental Investigation

Prior to the numerical investigation, laboratory experiments were conducted by NAHRIM in their 2D wave flume. The wave flume is 50.0 m length, 1.5 m width and 2.0 m height, as shown in Figure 1.0. The bottom of the wave flume is flat for the first half then slope is installed near the end of the flume on the right-hand side. The flume is equipped with an electric motor-driven, piston-type wave maker at one end of the wave flume and absorber made of a rubble mound at the other end. The submerged breakwater was placed at $x = 41.5$ m from the piston and 4.5 m from the wave absorber. The single structure is 0.24 m length, 0.1 m width and 0.13 m height. The single structure then stacked together to form a broad crested breakwater structure which is 0.8 m length, 0.32 m height and the width is the same as the width of the wave flume, i.e., 1.5 m. This will make sure that the flow in the flume can be treated as 2D. The overall setup is shown in Figure 2.0.

Two wave gauges (WP3 and WP4) were placed in the wave flume for recording wave propagation and transformation over the submerged breakwater. There are other wave gauges also installed along the wave flume to verify that the flow is two dimensional but not however included in the data analysis. The wave gauge WP4 was placed at $x = 42.5$ m away from the wave maker. The wave gauge WP3 was placed to verify the generated wave characteristics and the incident waves are not corrupted by reflected waves. For the regular wave calibrations, a wave train of 60 fully developed waves were run and wave heights derived from the average of max and min, crest and trough in each single wave were recorded. Video camera recordings were also used to capture the interaction and hydrodynamic characteristics of wave propagation over the submerged breakwater.

The still water depth, d , is fixed at 0.42 m in the experiment with 3 different level of submergence depth, d' . The structural height was kept constant, corresponding to relative water depths, $h/d = 0.74, 0.73$ and 0.72 throughout the entire experiment. 3 different regular wave conditions (three different wave heights with same wave period) were investigated in the experiment. These wave conditions were conducted for 3 different setups of porosity of the submerged breakwater, i.e., the control, 0% porosity and 50% porosity. The wave conditions for the setups are shown in Table 1.0 and 2.0, in which d' is the submergence level, H_s is the wave height and T_p is the wave period.

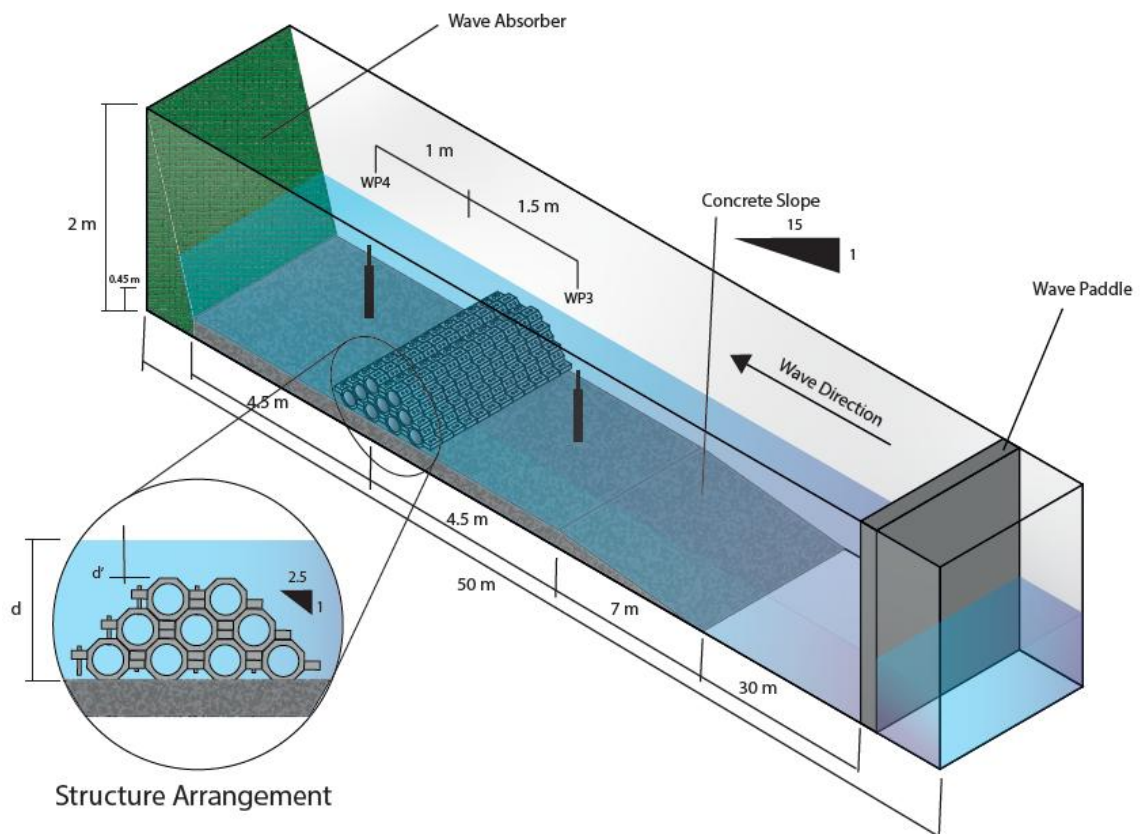
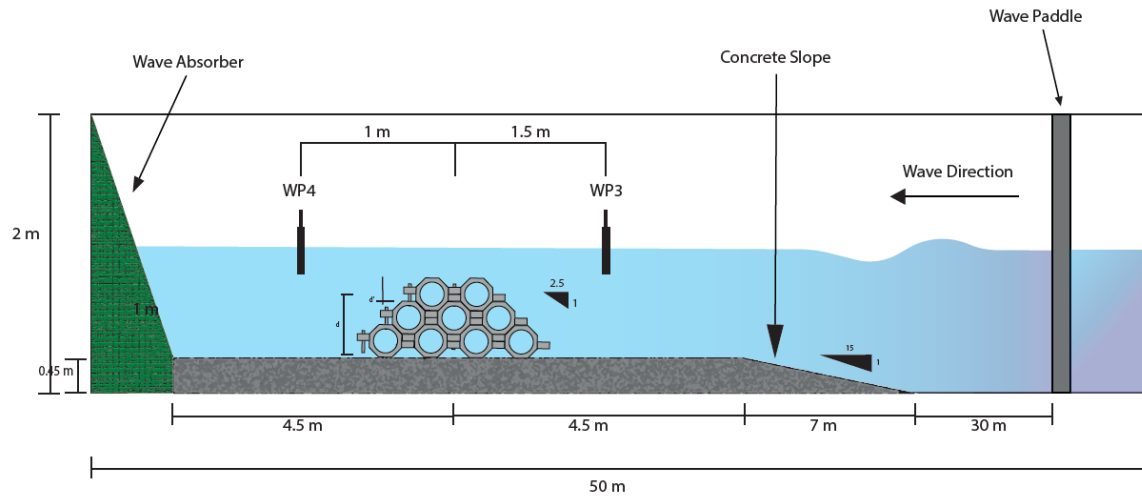


Figure 1.0: The flume for experiment in MHI Laboratory, NAHRIM

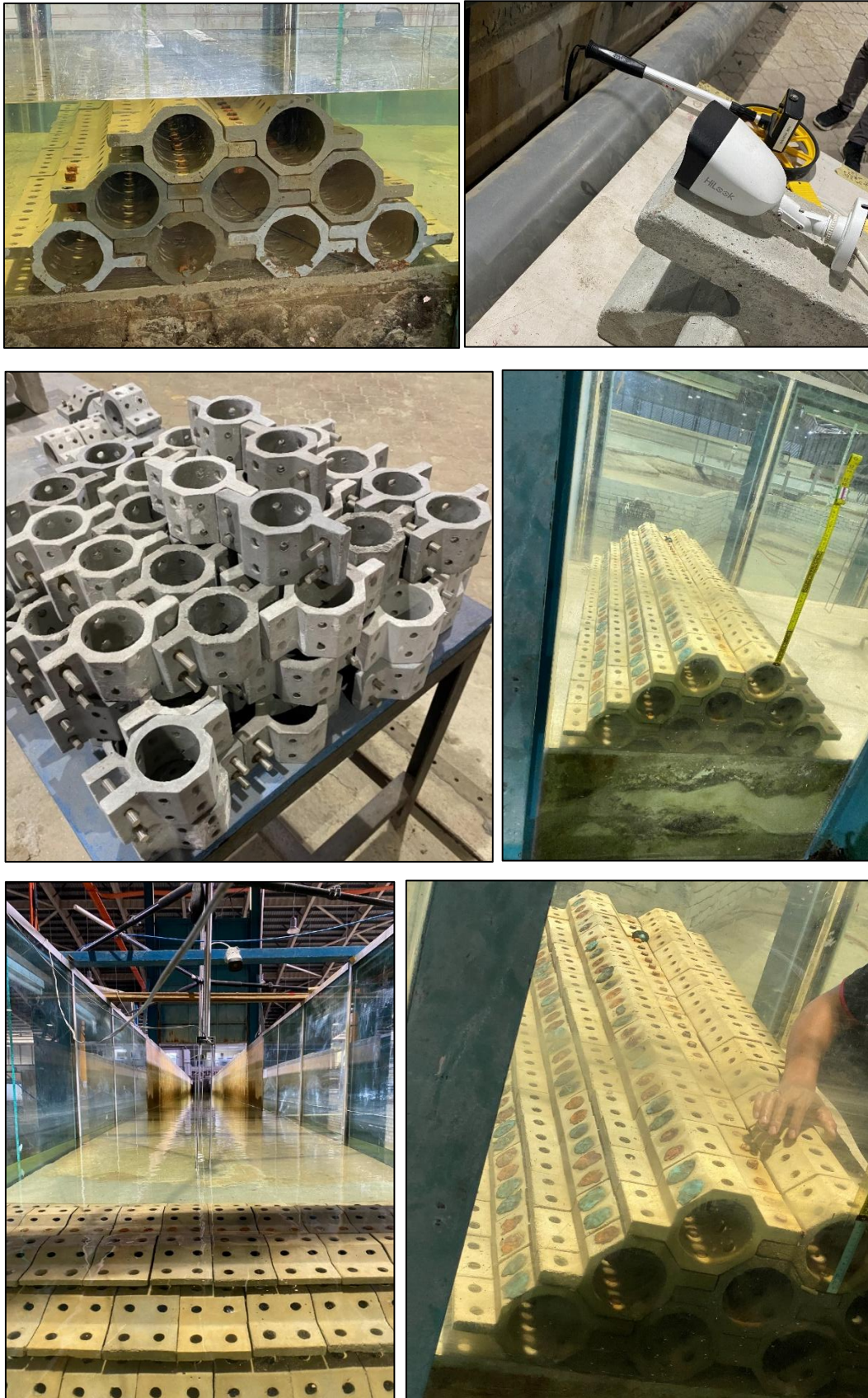


Figure 2.0: Layout of the experimental setup for the submerged breakwater

Table 1.0: Wave conditions for control

Submergence Level, d' (cm)	Wave Height, H_s (cm)	Wave Period, T_p (s)	Channel (mm)
5.0	5.0	2.0	3
			4
	10.0	2.0	3
			4
	15.0	2.0	3
			4
10.0	5.0	2.0	3
			4
	10.0	2.0	3
			4
	15.0	2.0	3
			4
15.0	5.0	2.0	3
			4
	10.0	2.0	3
			4
	15.0	2.0	3
			4

Table 2.0: Wave conditions for 0% and 50% porosity

Submergence Level, d' (cm)	Wave Height, H_s (cm)	Wave Period, T_p (s)	Channel (mm)
10.0	5.0	2.0	3
			4
	10.0	2.0	3
			4
	20.0	2.0	3
			4

3.0: Numerical Model of Smoothed Particle Hydrodynamics (SPH) method and DualSPHysics model

SPH is a fully Lagrangian and meshless method (Monaghan 1992) where the fluid is discretized into a set of particles or nodal points. These particles hold individual mass, position, velocity, density and other physical quantity which evolves over time. The contribution of the nearest particles is computed depending on the distance between particles and using a weighted kernel function. The DualSPHysics code is an open-source code (www.dualsphysics.org) developed by different research institutions in Europe led by University of Vigo (Spain) (Figure 3.0). The code, written in two programming languages,

namely C++ and CUDA, is optimized for CPU and GPU architectures in order to minimize the execution time and be able to perform complex SPH simulations at a reasonable time (Altomare et al., 2018).

In DualSPHysics, boundaries are described using a discrete set of boundary particles that exert a repulsive force on fluid particles when they approach the boundary particles. Dynamic boundary condition (DBC) is used, where boundary particles are forced to have the same properties as corresponding fluid particles. Thus, they follow the same momentum and continuity equation. Their density and pressure are updated but their positions and velocities remained unchanged during the numerical simulation. They remain fixed in position or move according to an externally imposed position such as wave maker and piston. DualSPHysics also provides support for open boundaries in the form of periodic boundary condition (PBC). In this study, we will use the Weakly Compressible SPH (WCSPH) to simulate the wave interaction with porous structures. Extra functionalities have been recently implemented in DualSPHysics code, such as active wave absorption, multi-layer pistons, moorings, and wave run-up. Modelling wave interaction with porous structure by using SPH method is relatively a new field of investigation and very few studies have been conducted in this field. Therefore, we recommend more studies to investigate the numerical capabilities of this approach and how to extend the application of the model.



Figure 3.0: Open-source software for pre-processing (DesignSPHysics), processing (DualSPHysics) and post-processing (Paraview and Blender)

4.0: Computational setup

Using similar setup of boundary and fluid domain described in the experiment, the submerged breakwater is modelled with main particulars presented in Figure 4.0. Both boundary and fluid domains are discretized using particles whose size and number depend on the initial particle spacing. In most of the case, with sensitivity analysis taken into consideration, we had implemented 0.01 m as the initial particle spacing. The size was considered adequate in capturing hydrodynamic details around the submerged structure. For the boundary, two layers of boundary particles are adopted to model the conditions of a numerical wave flume. The domain is modelled in 2D for control and 0% porosity and 3D for the case of 50% porosity. The size of holes of each model are small (0.02 m), making number of particles involved in the simulation larger. Figure 5.0 shows all the domain for 50% porosity while domain with 0% porosity is presented in Figure 6.0. The flume extended on the end side to allocate a beach as damping system in the simulation. Damping beach is set nearly equal to the wavelength to reduce any reflection from incident waves. The Wendland kernel is chosen for neighboring particles while simplistic scheme is used for the step algorithm. All models were designed in pre-processing of DesignSPHysics to create case file for the DualSPHysics.

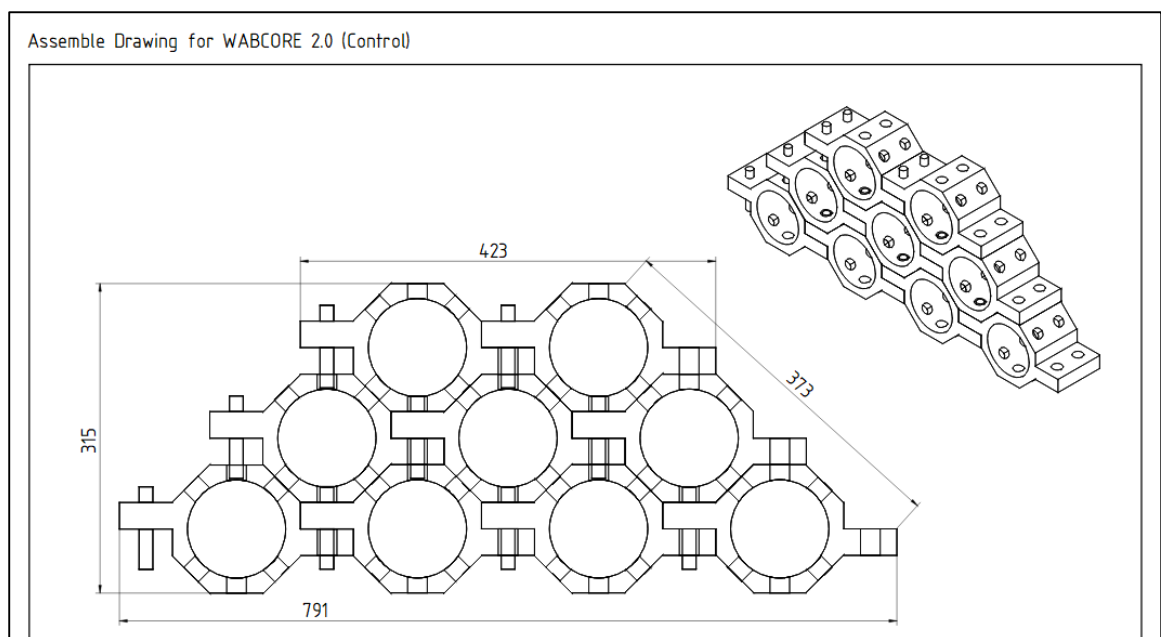
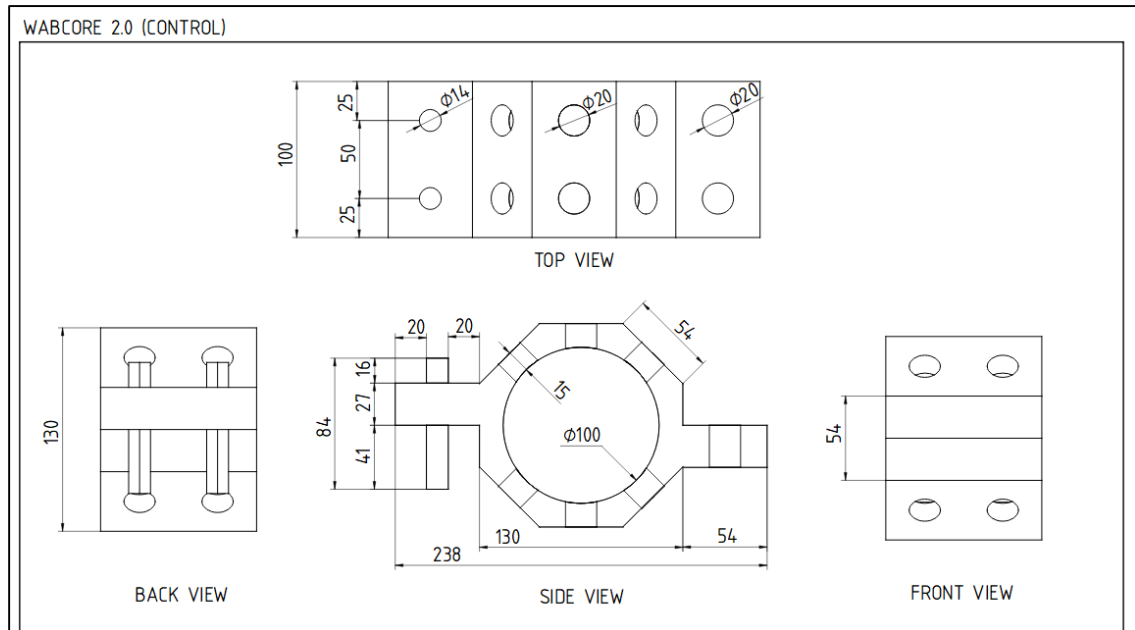
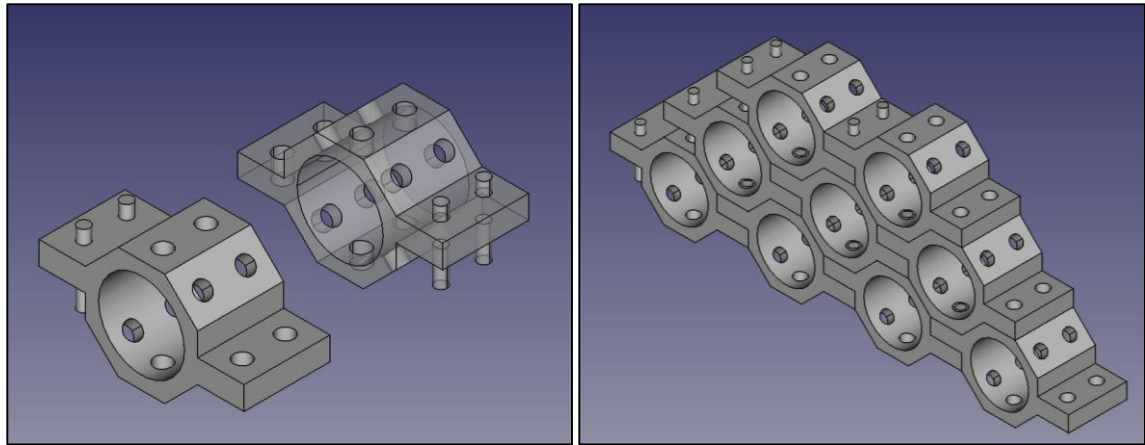


Figure 4.0: Model design for modular (Control)

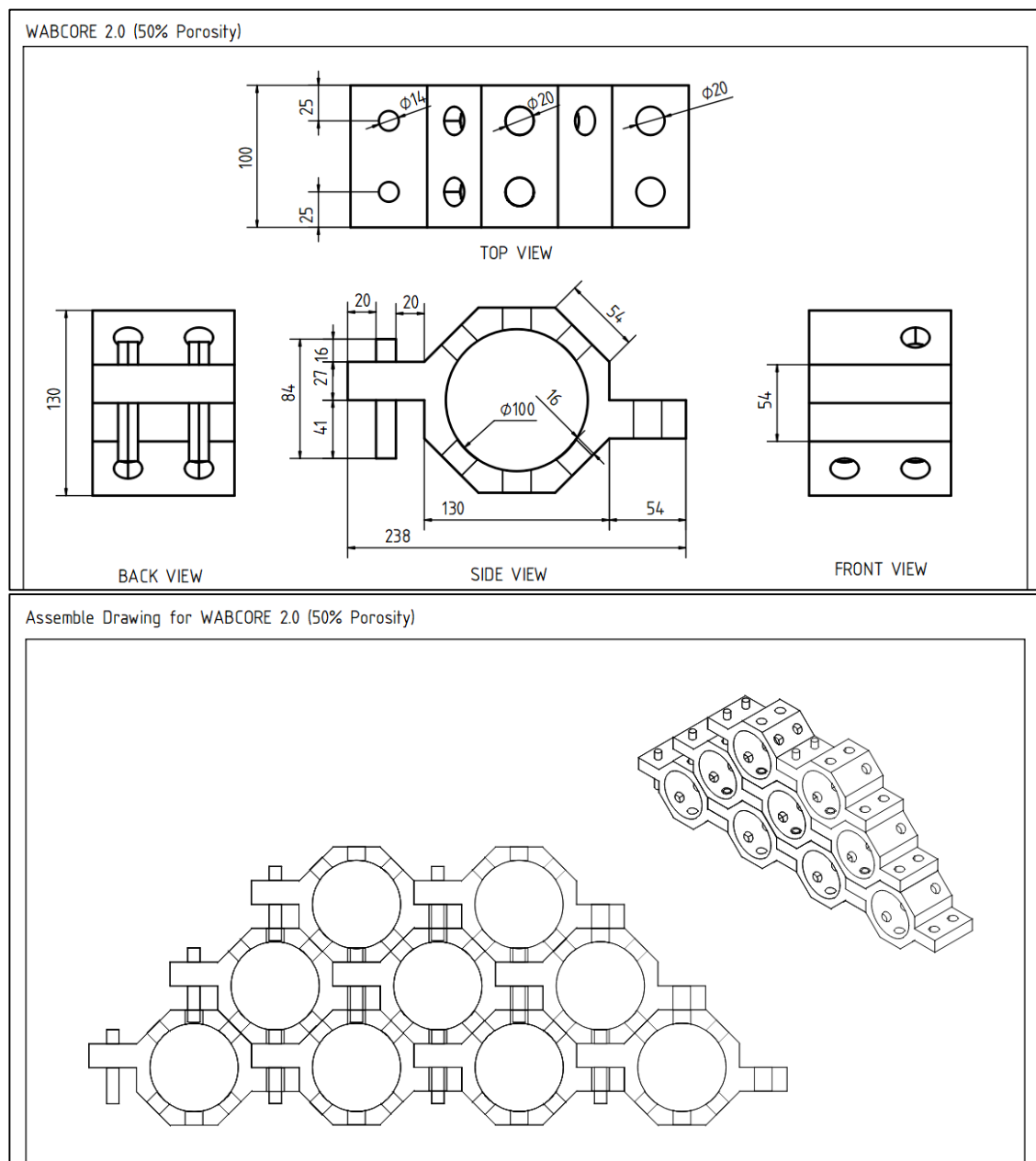
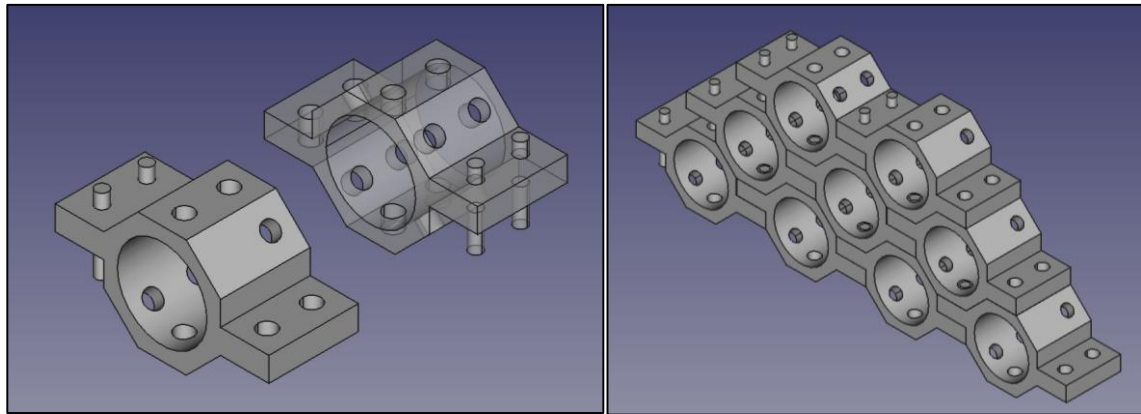


Figure 5.0: Model design for modular (50% Porosity)

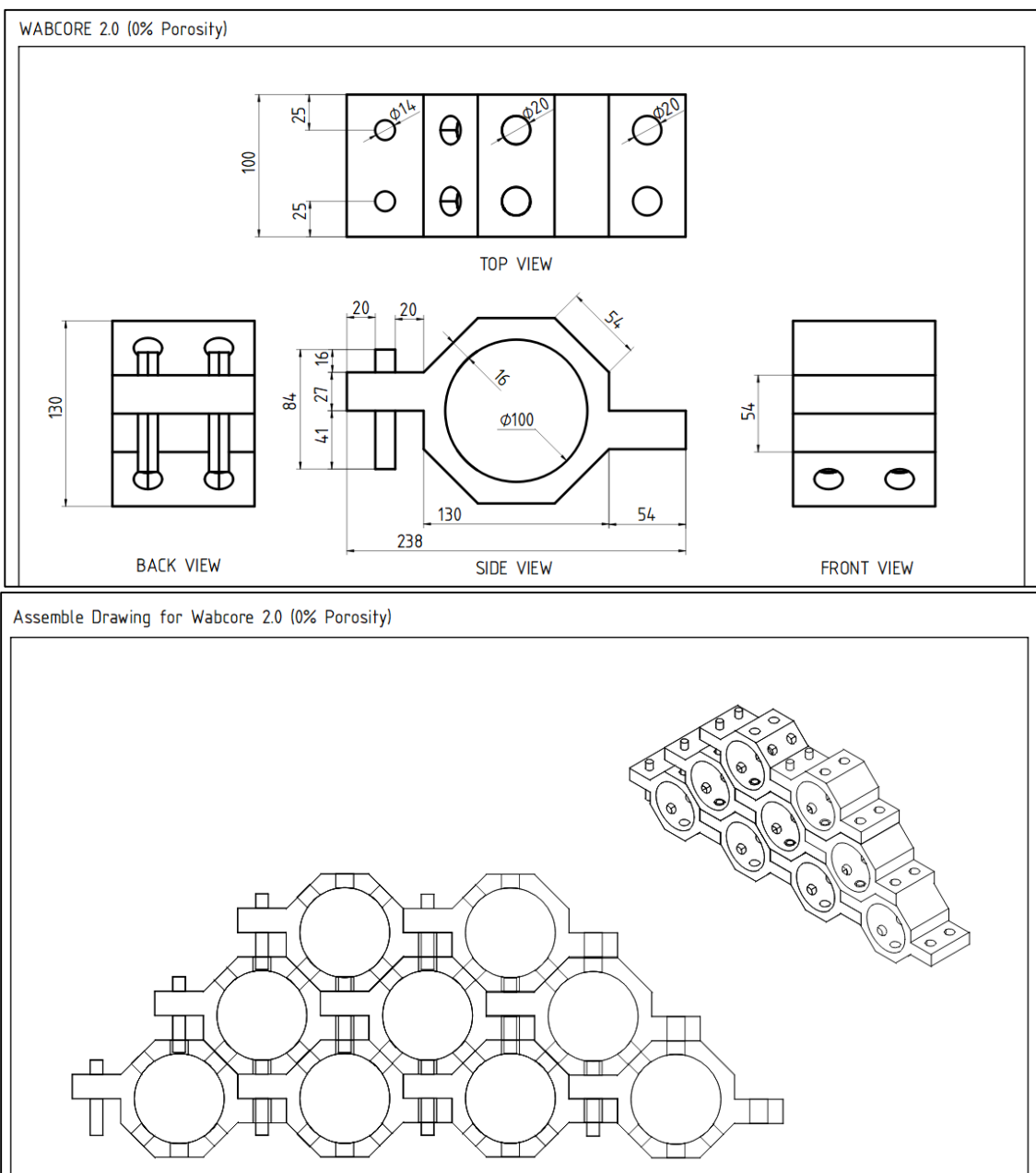
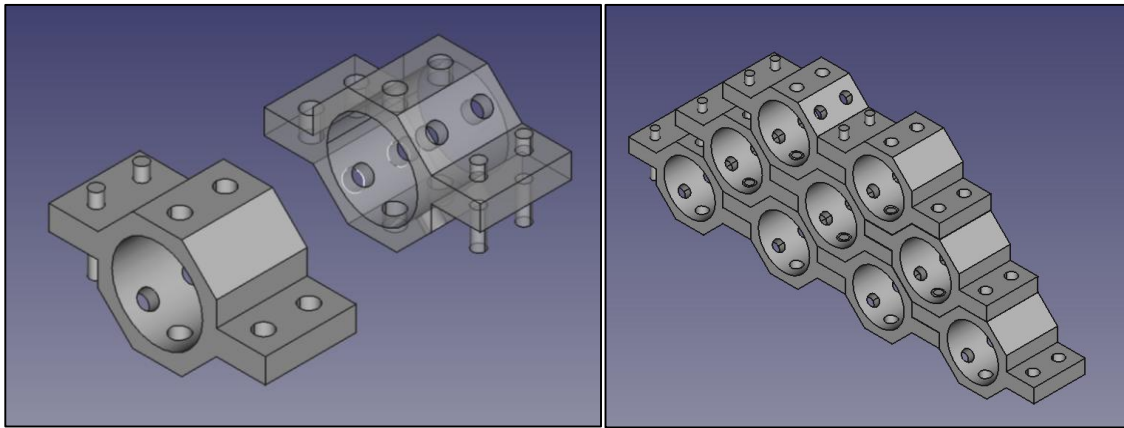


Figure 6.0: Model design for modular (0% Porosity)

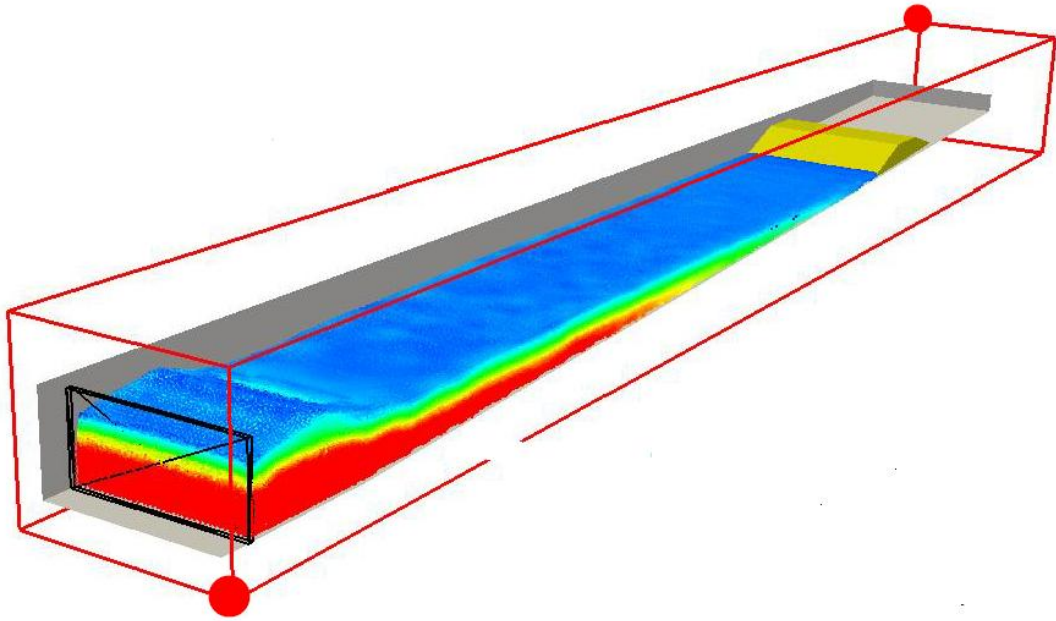


Figure 7.0: Numerical model setup

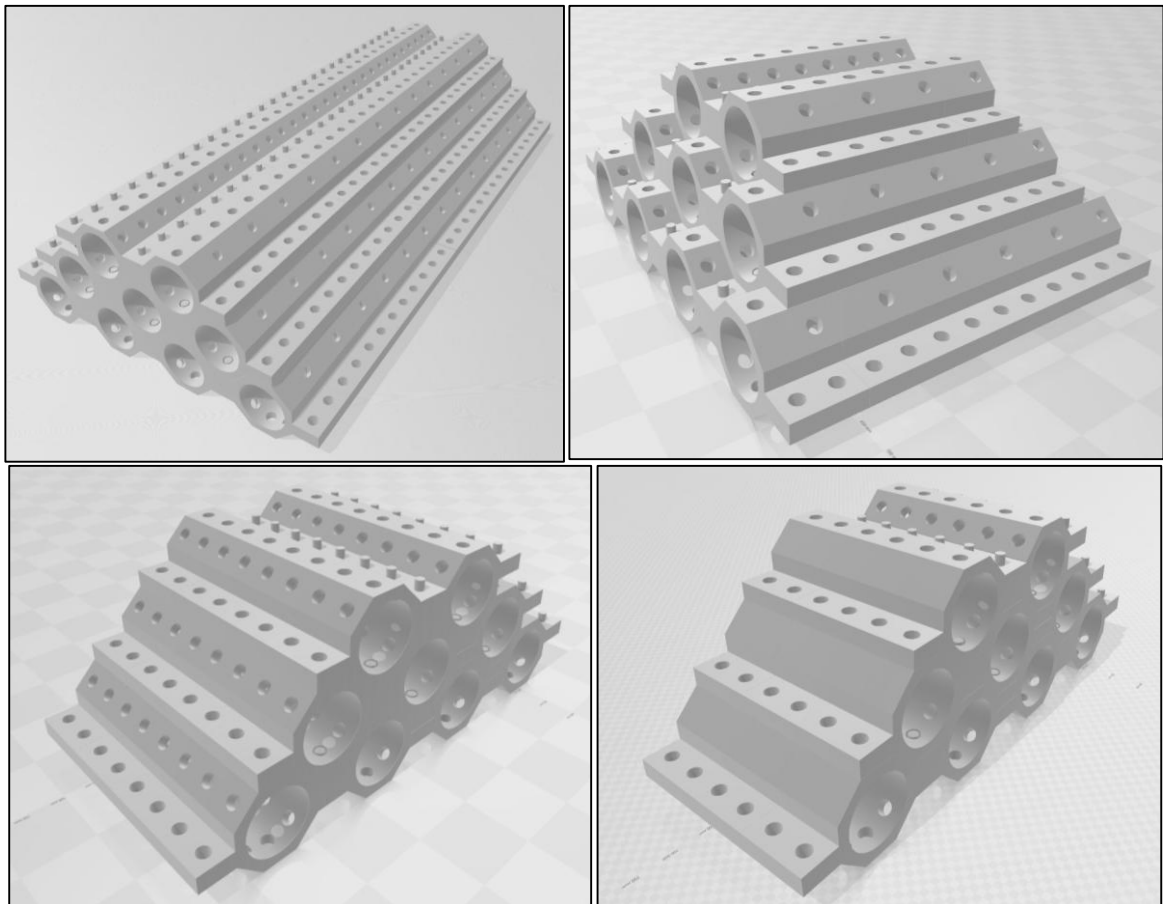


Figure 8.0: STL file for the structure assembly

5.0: Results and Discussion

In the numerical simulation, the computational time step is 0.05s and the total simulation time was 60 wave periods to obtain fully developed wave field. It is critical that we select the data when the waveform becomes stable. Therefore, initial run with no structure is needed to study the wave propagation at the location where the structure will be placed. This is to ensure the target wave arrives at the desired location.

5.1: Generation of wave propagation

Prior to the installation of the submerged breakwater, the wave profiles that the piston wavemaker produced were tested for two purposes: i) to verify the wave heights of regular waves generated and (ii) to establish the position of the submerged breakwater with a minimum reduction in the wave height while allowing gap between the structure and wave paddle for periodic solutions without being corrupted by reflection.

Free surface elevation probes were incorporated into the analysis. Figure 9.0 shows the location of the two probes used to locate the free surface elevation. One probe was meant to track the elevation before the slope and the other probe exactly at the position where the submerged breakwater will be. Simulations were performed in various wave heights to optimize the results. The findings are compared by theoretical results from the 2nd order stokes theory which indicates case of intermediate depth waves (Figure 10.0).

Results are shown in Figure 11.0 where straight lines represent findings from DualSPHysics SPH in comparison with theoretical results. The wave profiles agree well with the theoretical solutions. The time record of the wave advancement for $H_s = 0.05$ and $H_s = 0.10$ showed a minimum wave dissipation at each probe, with largest reduction of less than 10% in the wave height throughout the simulation. Visualization could be enhanced by depicting the particles onto the surface via *IsoSurface.exe* in DualSPHysics.

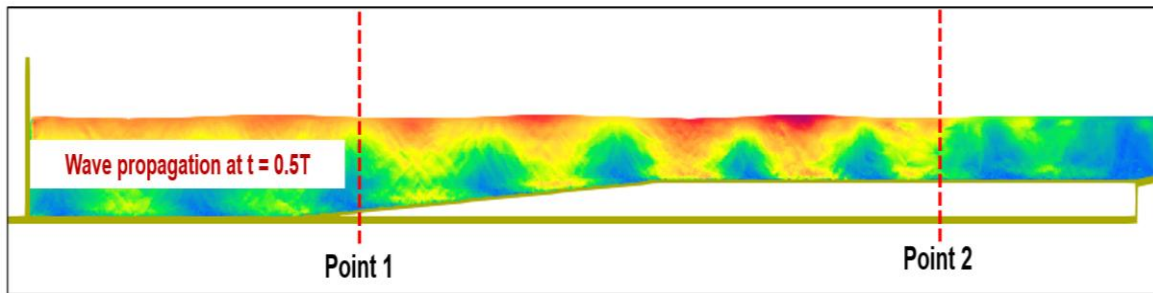


Figure 9.0: Location of two probes for tracking free surface elevation

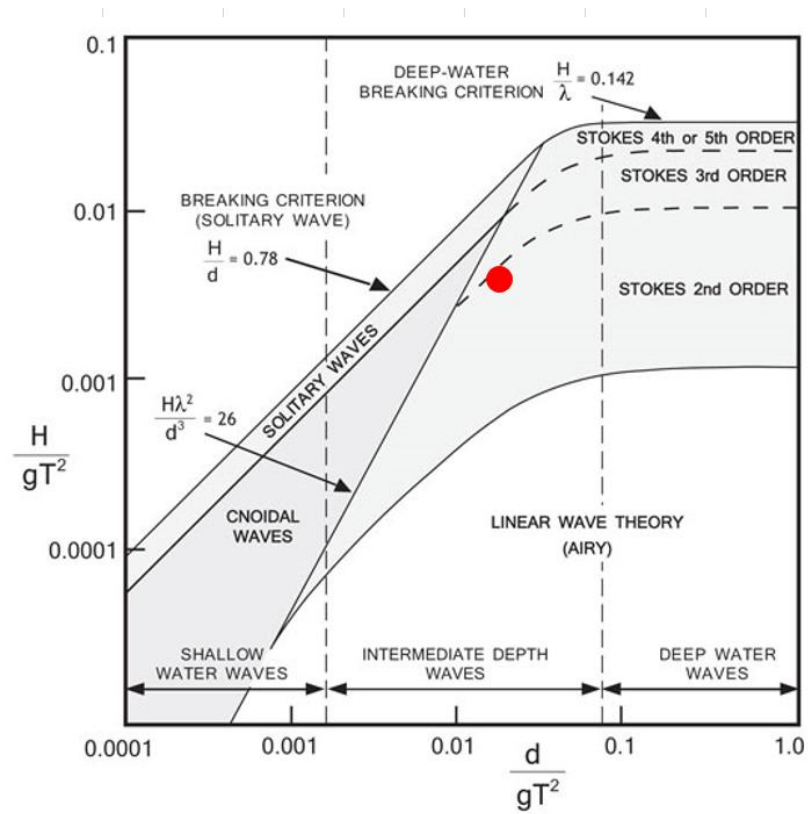


Figure 10.0: 2nd order stokes theoretical projection for intermediate depth waves

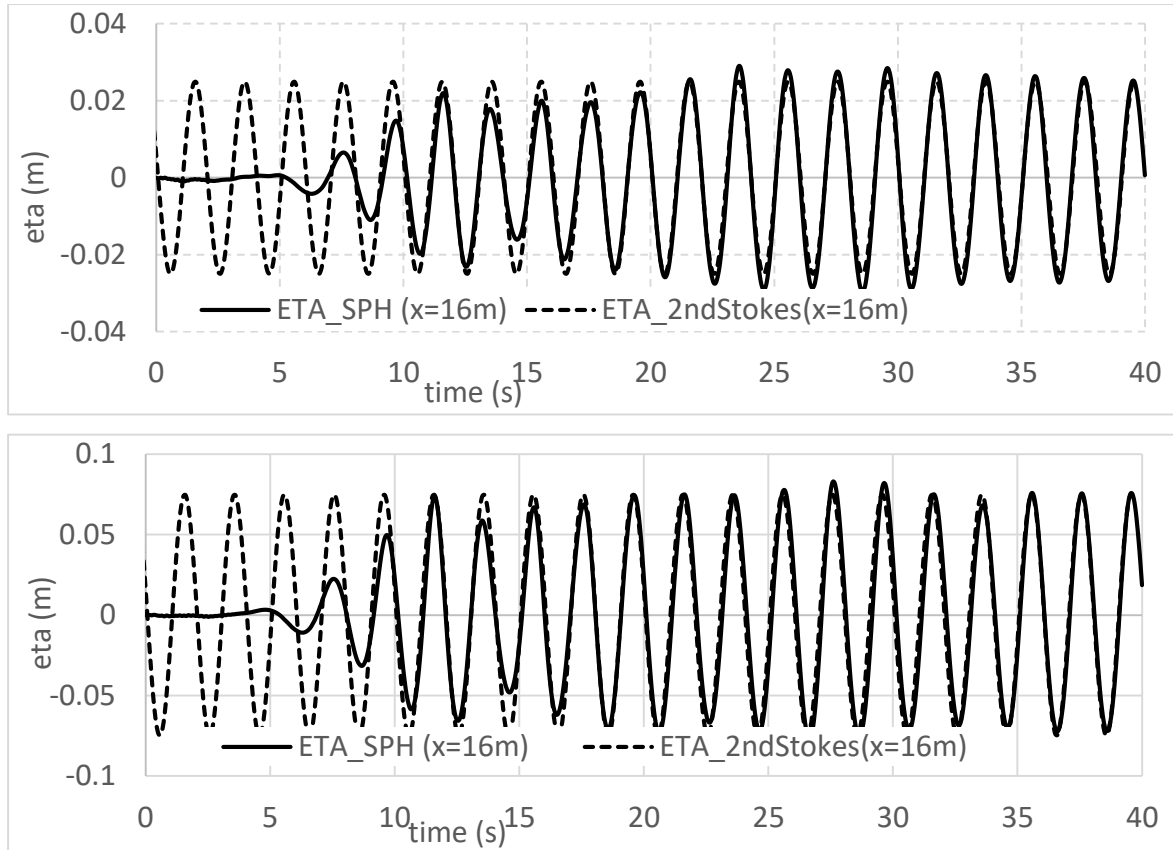


Figure 11.0: Wave elevation at target area computed against theoretical findings for $H_s = 0.05$ (upper graph) and $H_s = 0.15$ (lower graph)

5.2: Free surface elevation

The transformation of regular wave as it propagates over the submerged breakwater is monitored in the experiment and the data is compared with DualSPHysics as shown in Figure 12.0. The process of the interaction between regular waves and the submerged breakwater can be traced for different submergence depth and wave heights. It is noteworthy that $t = 0.25T$ denotes the moment in which the wave has fully developed and reached its stable stage. The waves, as they travel to the crest of the submerged bar (at $x = 45$ m), gradually become slightly higher due to the shoaling effect in Figure 12.0-17.0. The wave deforms due to shoaling on a smaller submergence depth ($d = 0.425$ m) as it reaches the top of the breakwater and propagates over the flat bottom. Figure 13.0 shows some vertical asymmetry in the wave over the submerged breakwater. The wave crests become steep, and the wave troughs become wide, which indicate the effect of nonlinear in this shallow-water region due to the decrease of water depth.

High order harmonics is observed above the submerged breakwater where complex forms are found in the transmitted waves as the result of nonlinear interaction. Similar trend of nonlinear interaction can be observed in Figure 13.0, 15.0 and 17.0 for higher incident waves. Then, as these incident waves move into the leeward slope of the submerged breakwater, the amplitudes of the waves begin to reduce in a de-shoaling effect and the waves decompose into smaller amplitude waves. The transmitted wave is noticed to be reduced in comparison to the incident wave which will contribute to the value of wave transmission coefficient, K_t . The results of K_t for numerical model are compared to the experimental measurement and detailed results are presented in Table 3.0.

There are differences in the deforming process with the increases of wave height. The wave crests become steeper, and the wave troughs become flatter with the increases of the wave height. As all cases share the same wave period, asymmetry of the wave is not that significant. In general, numerical results show a good match to the experimental data with different of less than 10% in K_t and the model can provide a good presentation of the wave propagation and transformation. In some cases, the model is capable to estimate further reduction in K_t due to the possibility that the model can predict nonlinear effects on the interaction between wave and the submerged breakwater.

Table 3.0: Validation results on the transmission coefficient

Submergence Level, d' (cm)	Wave Height, Hs (cm)	Wave Period, Tp (s)	Channel (mm)	wave transmission coefficient		wave attenuation		Differences (%)
				kt_exp	kt_SPH	wA_exp(%)	wA_SPH(%)	
5.0	5.0	2.0	3	0.75	0.80	24.7	19.8	6.3
			4					
	10.0	2.0	3	0.66	0.68	34.5	32.1	3.6
			4					
	15.0	2.0	3	0.59	0.63	41.2	36.2	7.2
			4					
10.0	5.0	2.0	3	0.85	0.82	14.8	17.7	3.8
			4					
	10.0	2.0	3	0.78	0.77	21.5	22.0	1.9
			4					
	15.0	2.0	3	0.66	0.64	33.7	35.9	3.4
			4					
15.0	5.0	2.0	3	0.90	0.83	9.5	16.7	8.3
			4					
	10.0	2.0	3	0.81	0.72	19.0	27.6	10.7
			4					
	15.0	2.0	3	0.68	0.66	31.8	34.2	3.5
			4					

**Comparison of coefficient of
transmission K_t between experiment and
numerical SPH**

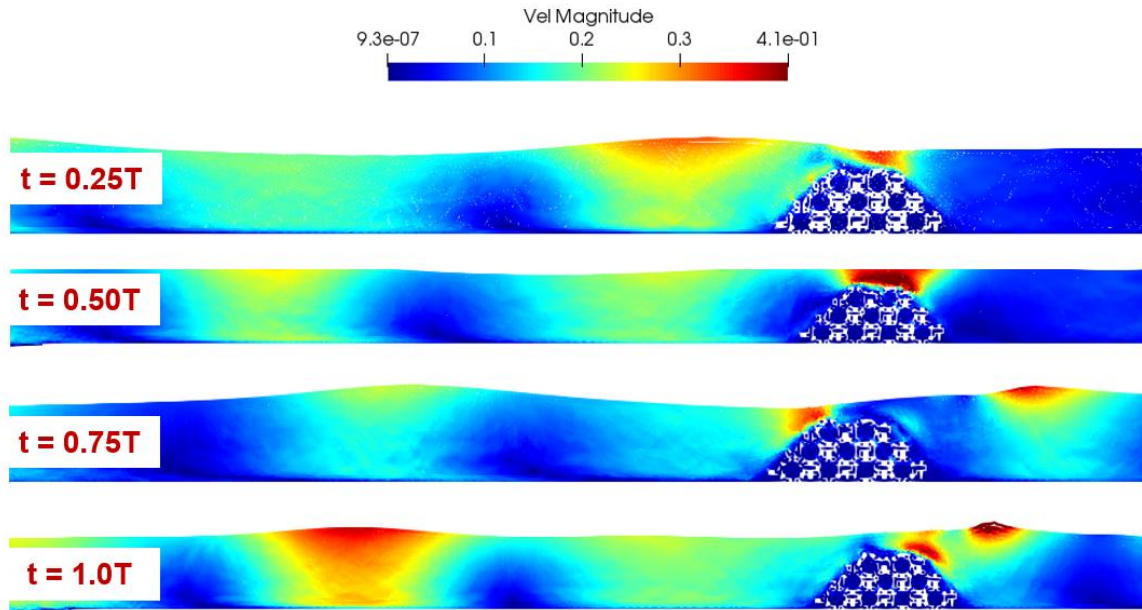


Figure 12.0: Wave propagation and deformation for $d = 0.425$ m and $H_s = 0.10$ m

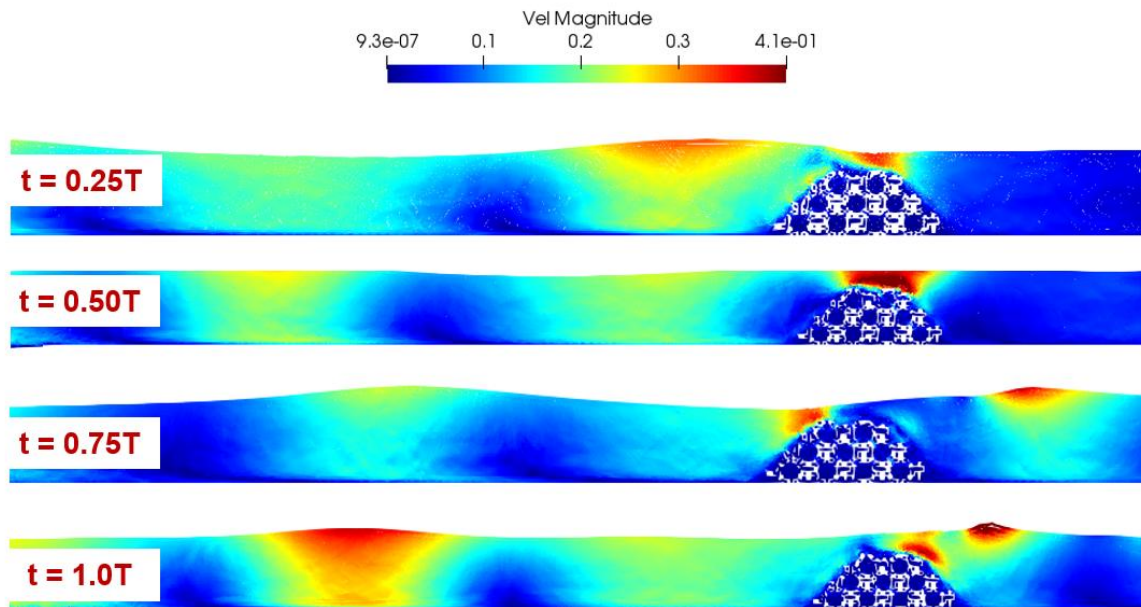


Figure 13.0: Wave propagation and deformation for $d = 0.425$ m and $H_s = 0.15$ m

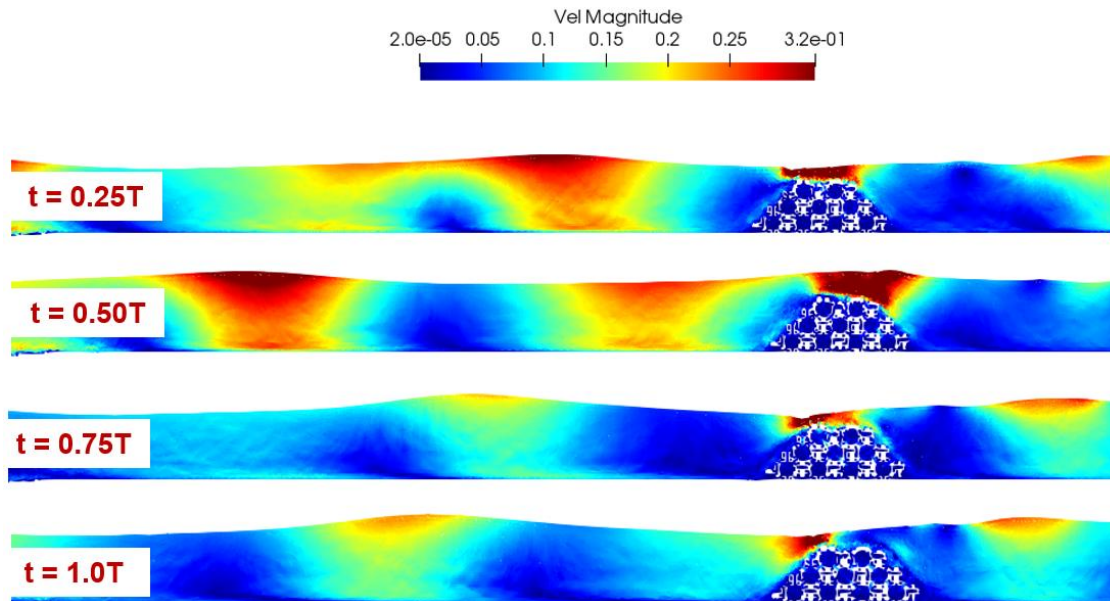


Figure 14.0: Wave propagation and deformation for $d = 0.430$ m and $H_s = 0.10$ m

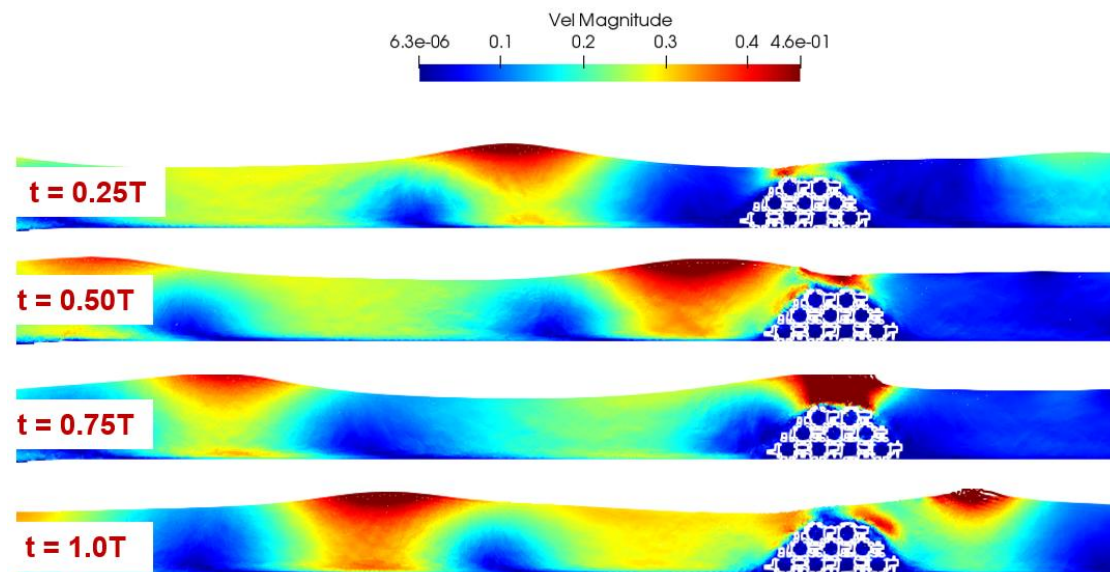


Figure 15.0: Wave propagation and deformation for $d = 0.430$ m and $H_s = 0.15$ m

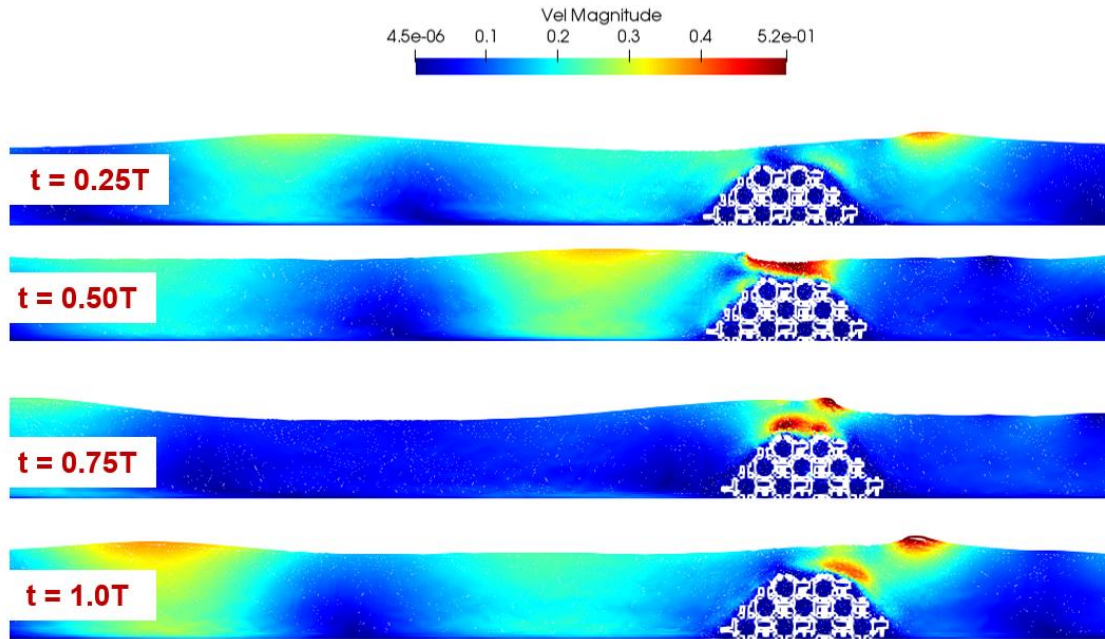


Figure 16.0: Wave propagation and deformation for $d = 0.435$ m and $H_s = 0.10$ m

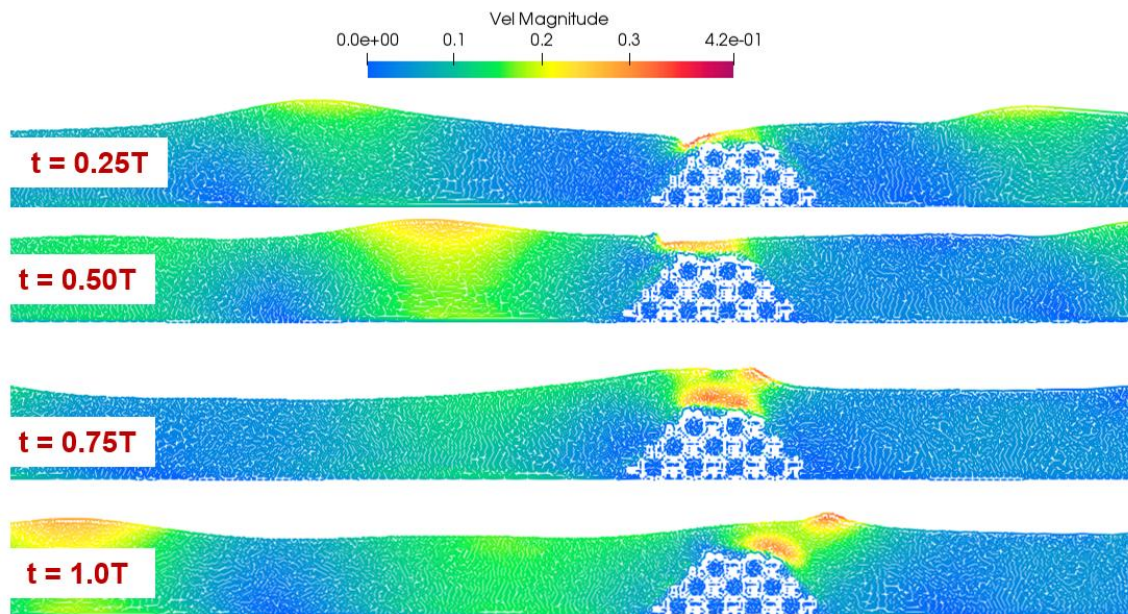


Figure 17.0: Wave propagation and deformation for $d = 0.435$ m and $H_s = 0.15$ m

5.3: Relative wave height and steepness

The transmission coefficient illustrates how well the submerged breakwater in reducing the wave height, the smaller the value of the transmission coefficient the better the submerged breakwater in reducing wave height. Figure 18.0 shows the effect of relative significant incident wave height on the characteristic of K_t . The results show that at $H_s/d = 0.12$ and low amplitude of incident wave, K_t is very high with values near to 0.90 which demonstrates that most wave energies were transmitted. It is noteworthy that K_t gradually decreases as wave height increases. This trend indicates that the submerged breakwater is more efficient for larger waves regardless of H_s/d conditions. Similar trend continues for others H_s/d conditions showing larger wave for higher wave attenuation. Smaller values of K_t can be related to nonlinear effects such as more wave-structure interactions and overtopping over the breakwater. At the maximum H_s/d , K_t significantly reduces to a value less than 0.70. Wave height parameter has a significant effect on the wave attenuation by submerged breakwater especially at minimal water depth (*Figure 19.0*).

The wave steepness is defined as the characteristic of individual waves calculated as wave height divided by wavelength. In general, a greater H_s/L indicates shorter wave period, and this allows friction to wavelength at the submerged breakwater crest. As wave period did not change throughout the simulations for all cases, effectiveness of the submerged breakwater in various wave period were not examined. Figure 20.0 presented the correlation between the transmission coefficient and the wave steepness. From the figure, the K_t from experiment tend to be higher than that of from numerical simulation. K_t value is 0.82 for $H_s/L = 0.008$ and 0.66 for $H_s/L = 0.024$. This shows that the application of submerged breakwater has significant impact for reducing the wave energy for higher wave steepness. Higher submergence ratio is likely effective to reduce K_t .

5.4: Flow velocities for different porosity

The temporal variations of horizontal velocities near the submerged breakwater for different porosity are shown in Figure 21.0. Some typical phenomena can be observed which is similar as the wave elevation. With the increase of the wave height and period, the asymmetry of the velocity lines becomes obvious. Another feature that can be observed is that as the waves come with higher wave height, the velocity magnitude appears with a steep crest. Comparison of transmission coefficient between the numerical results and the experimental data for different porosities are shown in Table 4.0 and 5.0. In 0% porosity

condition, most of fluid particles were repelled and contribute to the increase velocity near the submerged breakwater crest.

Generally, wave interaction with submerged breakwater can be classified into three parts. A part of the incident wave energy penetrates to the breakwater, another part will be reflected from the structure and the remained wave energy will be propagated over the breakwater slope. In the case of control and 50% porosity condition, more wave energy penetrates into the structure and then will either dissipate or settle inside the breakwater. Since the reflection depends on the permeability of the porous structure, the 0% porosity structure will contribute more to the reflection than the other two cases. As shown in Figure 21.0, wave easily propagate over the structure when the wave reaches the highest point, the maximum run-up is denoted by highest velocity magnitude. The wave front become sharpened and unstable, then starts to break and scattered fluid particles may even reach to the top or penetrate the structure. As a result, wave run-up and overtopping will be more significant for higher wave height. It should be noted that the detail flow around the interface boundary is not much important when investigating the whole hydraulic performance of submerged breakwater.

Table 4.0: Validation results on the transmission coefficient (0% Porosity)

Submergence Level, d' (cm)	Wave Height, Hs (cm)	Wave Period, Tp (s)	Channel (mm)	wave transmission coefficient		wave attenuation	
				kt_exp	kt_SPH	wA_exp(%)	wA_SPH(%)
10.0	5.0	2.0	3	0.94	0.71	6.5	28.5
			4				
	10.0	2.0	3	0.93	0.61	6.9	39.0
			4				
	20.0	2.0	3	0.67	0.62	33.0	37.8
			4				

**Comparison of coefficient of
transmission K_t between experiment and
numerical SPH**

Table 5.0: Validation results on the transmission coefficient (50% Porosity)

Submergence Level, d' (cm)	Wave Height, Hs (cm)	Wave Period, Tp (s)	Channel (mm)	wave transmission coefficient		wave attenuation	
				kt_exp	kt_SPH	wA_exp(%)	wA_SPH(%)
10.0	5.0	2.0	3	0.89	0.71	11.1	28.65
			4				
	10.0	2.0	3	0.91	0.93	9.3	6.25
			4				
	20.0	2.0	3	0.54	0.62	46.2	37.20
			4				

**Comparison of coefficient of
transmission K_t between experiment and
numerical SPH**

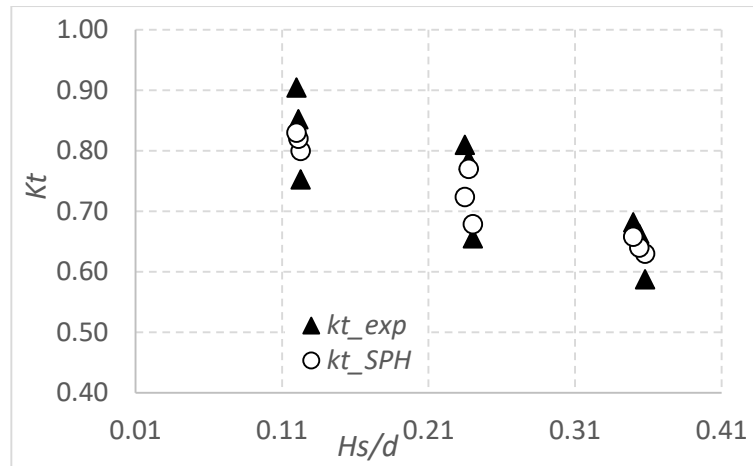


Figure 18.0: Transmission coefficient for various significant incident wave height

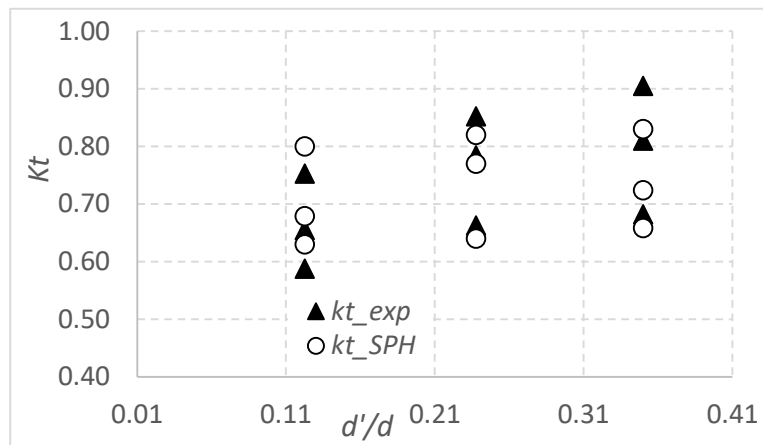


Figure 19.0: Transmission coefficient for various submergence level (freeboard)

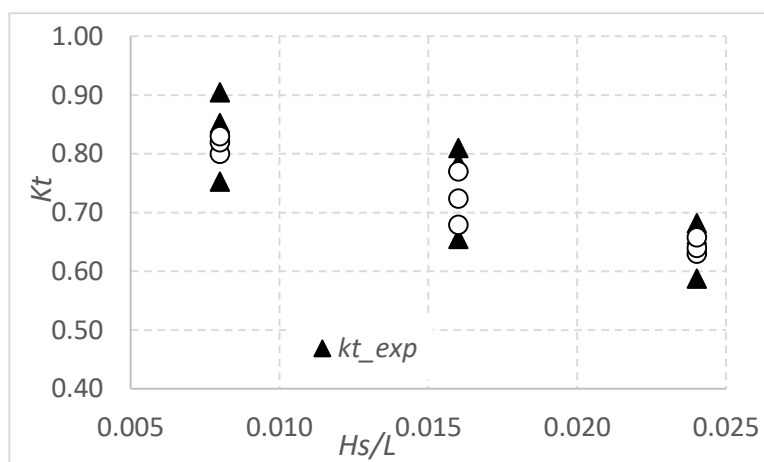


Figure 20.0: Transmission coefficient for various wave steepness

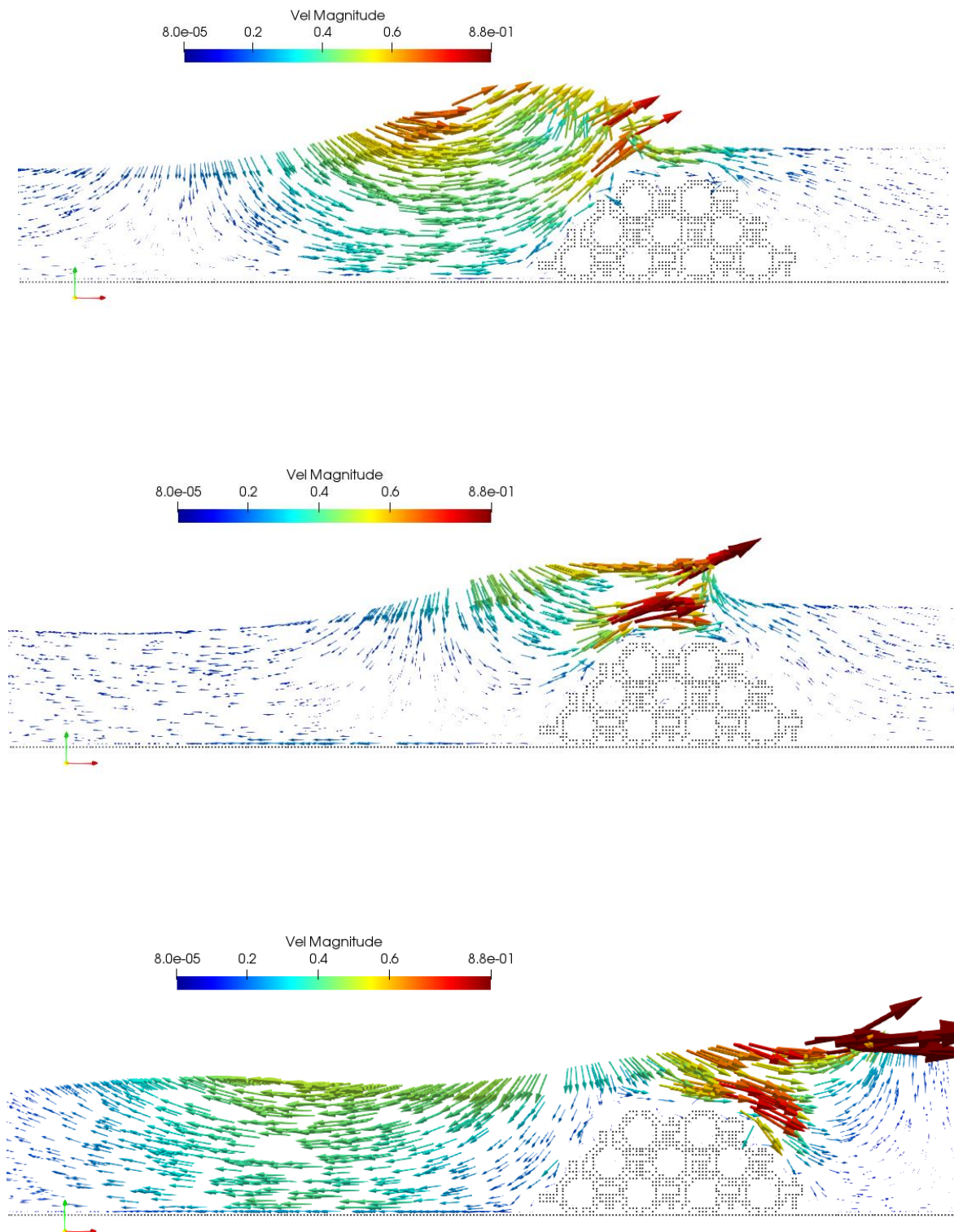


Figure 21.0: Wave breaking pattern through velocity vector at different time on the submerged breakwater for porosity case, $H_s = 0.20$ m.

6.0: Conclusions

The hydrodynamic performance and wave transformation of the submerged breakwater were investigated in this project using Smoothed Particle Hydrodynamics (SPH) of DualSPHysics. The proposed numerical model is based a fully Lagrangian and meshless method where the fluid domain is represented by a set of particles. The physical quantities of each particle, such as position, velocity, density, and pressure, are computed as an interpolation of the values of neighboring particles. The effects of various parameters, such as relative water depth, relative significant incident wave height, velocity and porosity were investigated on the characteristics of transmission coefficient, K_t . DualSPHysics was modified and employed to reproduce nonlinear hydrodynamic characteristics done by experimental. The capability of the numerical model has been demonstrated, in which the numerical results agree fairly well with the experimental. Overall, results show a significant correlation between tested conditions and the performance of submerged breakwater on the attribute in attenuating amount of K_t .

7.0: Gantt Chart

Activities	2022											
	Oct				Nov				Dec			
WEEK	1	2	3	4	1	2	3	4	1	2	3	4
1 st Discussion on details of project milestones, deliverables, and framework for the interim report.												
Identify all setup and parameters done in physical flume. Results from the physical experiment are then compiled for analysis.												
Signing of <i>Surat Setuju Terima</i> (SST) by UMT												
Finalizing the parameters, wave conditions and video pattern to simulate in DualSPHysics.												
First interim report (Preliminary results and findings).												
Visit to NAHRIM (2 nd Meeting)												
Preprocessing by DesignSPHysics												
Simulations run by DualSPHysics												
Results interpretation and analysis												
Convergence and sensitivity analysis												
3 rd Meeting and training with team NAHRIM												
Compilation of results and 1 st draft of journal framework to be review by all members												
Submission of 1 st draft Journal and final report writing												
Training and sharing session between UMT-IIUM-NAHRIM												
Follow-up on journal (January 2023) – Proofread stage												

8.0: References

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