Numerical investigation on wave transmission characteristics of perforated and non-perforated pile breakwater

Naveen Rao¹, Pradeep Suryanarayana Barimar Rao², Kaushik Nayak³, Shashank Kishor Pal³, Arunakumar Hunasanahally Sathyanarayana³, Praveen Suvarna³ and Pruthviraj Umesh³

¹Department of Civil Engineering NITK Surathkal, Mangaluru, Karnataka, India - 575025
²Transportation Engineering Consultant, 2500 Merchants Row Blvd, Apt 164, Tallahassee FL-32311
³Department of Applied Mechanics and Hydraulics, NITK Surathkal, Mangaluru, Karnataka, India - 575025

nrao19961@gmail.com, s.pradeep.rao@gmail.com, nayakkaushik.kn@gmail.com, shashankkpal@gmail.com, arunsaligram17@yahoo.com, civilsuvarna@gmail.com, pruthviu@gmail.com

Abstract. Dock operations, harbouring and many other port activities demand tranquil water condition. This makes breakwater structures more than essential in coastal engineering applications. For zero wave action, rubble mound or vertical wall breakwaters are used, and for small docks and shores, piles can be used as efficient breakwaters. The permeability of pile breakwaters also aides in keeping the shores clean as there is water circulation and keeps the interferences caused due to littoral drift to the minimum. Numerical study on the single row pile breakwater is carried out using an open source computational fluid dynamics (CFD) software REEF3D. Interaction of waves with non-porous pile breakwater is simulated in a three-dimensional numerical wave tank using REEF3D and resulted transmission coefficient is validated using the physical model studies as reported by Subba Rao et al. (1999). Further, the efficiency of porous piles over non-porous piles is studied by simulating wave conditions by varying wave height, wave period, water depth and percentage porosity of the piles. It has been observed from the present study that porous piles are more efficient in wave attenuation compared to non-porous piles. The reason is that perforations increase turbulence during wave interaction which results in a better wave attenuation.

1. Introduction

For maintaining tranquillity in harbours and docks, artificial structures are necessary to block the waves or to steady the waves. For perfect tranquillity conditions, bulky structures like rubble mound breakwaters and vertical wall breakwaters are built. When perfect tranquillity conditions are not necessary like for smaller harbour (for fishing, recreation, etc.) and at places with large littoral drift and onshore-offshore sediment movements, unconventional harbours such as a floating breakwater or pile breakwaters can be erected [1–3]. Some of the successfully constructed and functioning pile breakwaters include pile breakwaters at Auckland harbour in New Zealand [4], concrete pile breakwater (1.4 m
Suitable pile breakwaters can be designed according to tranquillity requirements and based on littoral movements of the given location. The uses of piles as breakwaters can have a number of possibilities of designs like single row piles or double row of piles, and further, the piles can be perforated or non-perforated and again the porosity of perforated piles can be varied to give different results for a given wave condition. The permeability of pile breakwaters also aides in keeping the shores clean as there is water circulation [5] and keeps the interferences caused due to littoral drift to the minimum.

Out of the numerous studies carried out on piles as breakwaters to assess wave attenuation characteristics some of the significant studies include closely spaced piles breakwater [6], single row and two rows of non-perforated and perforated piles by varying the pile spacing [4,7–13] and pile arrays of four rows [14].

The present paper is a numerical study on wave attenuation characteristics of single row perforated and single row non-perforated pile breakwater. The pile breakwater models are simulated using an open source software known as REEF3D, which can be used for the investigation of the hydrodynamic performance of pile breakwater. The obtained results for non-perforated piles are validated with the experimental results achieved by [15]. The validated REEF3D model is used to study the effect of perforations on wave attenuation characteristics.

2. Numerical model

With increasing research happening in the field of coastal engineering, numerical studies are slowly gaining credibility since numerical models are highly flexible, can be scaled according to the researcher’s wish, repeated simulation and experimentation can be carried out with different input conditions and most importantly with minimum or no cost involved. Some of the numerical studies using REEF3D in the coastal engineering field include ocean wave energy conversion, wave interaction with structures [16–18]. REEF3D is an open-source computational fluid dynamics (CFD) program which focusses deeply on hydraulics, environmental engineering and offshore, coastal and marine CFD. It can analyse free surface flows of varied engineering complexities because of the usage of the level set method [19–21].

The present numerical model solves the incompressible Navier-Stokes equation in three dimensions using a RANS turbulence closure. Wave propagation with greater permanence and accuracy is obtained using a Cartesian mesh. To provide a tight pressure-velocity coupling staggered grid with projections method, which resolves the pressure is adopted. Irregular boundaries are contemplated by the ghost cell immersed boundary method. The model is fully parallelized based on the domain decomposition strategy and MPI (message passing interface). The level set method is used to model the free surface. [22]

2.1 Governing equations

Incompressible Reynolds-averaged Navier–Stokes (RANS) equations are resolved in REEF3D along with the continuity equation to resolve the fluid flow problem[22].

\[
\frac{\partial u_i}{\partial x_i} = 0
\]  

\[
\frac{\partial u_i}{\partial t} + U_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu + \nu_t\right) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + g_i
\]  

Where \(u\) designates time-averaged velocity, \(\rho\) is the density of the fluid, \(p\) is the pressure, \(\nu\) is the kinematic viscosity, \(\nu_t\) is the eddy viscosity, and \(g\) is the acceleration due to gravity. Pressure is
determined by the projection method, and the consequent Poisson equation is solved by BiCGStab solver. The K–ω model is adopted for turbulence modelling.

2.2 Free surface
The level set method is used in modelling the free surface and it determines the shortest distance from the interphase designated by the signed distance function ($\varphi$). The sign of the function differentiates the two fluids at the interface and is shown in the following equation[22].

$$
\Phi (\vec{x}, t) \begin{cases} 
> 0 & \text{if } \vec{x} \text{ is in phase 1} \\
= 0 & \text{if } \vec{x} \text{ is in interphase} \\
< 0 & \text{if } \vec{x} \text{ is in phase 2}
\end{cases}
$$

Under the effect of the external velocity field $u_p$, the level set function is moved with the convection equation as mentioned below.

$$
\frac{\partial \varphi}{\partial t} + U_j \frac{\partial \varphi}{\partial x_j} = 0
$$

The convection term in Equation (4) is resolved with the Hamilton-Jacobi form of the WENO scheme [23] and third-order TVD Runge–Kutta scheme is adopted for the time stepping [24]. The level set function loses its signed distance property when the interface evolves. Hence the level set function is reinitialized after every time step to maintain this property and to safeguard mass conservation. In this paper, a PDE based re-initialization equation is resolved [25].

3. Simulation and validation of pile breakwater
Rigid cylindrical piles are modelled in a single row as shown in Figure 1, and the result is validated by comparing against the experimental results of Subba Rao et al., (1999)[28]. Wave interaction simulations are carried out on the single row of perforated and non-perforated piles by varying pore diameter, wave height, time period and water depth.

![Figure 1. The layout of piles with circular diameter D.](image)

3.1 Experimental model setup
Subba Rao et al., (2009) [15] has carried out physical experiments in a wave flume of the length of 50 m, depth of 1.1 m and width 0.71 m. The flume has a flap-type wave generator at one end and an absorption beach at the other end. The physical model pipes were galvanized iron pipes of diameter (D) 0.0335 m. Experiments were performed on a single row of piles and two rows of piles for different pile spacing within and between the pile rows.

3.2 Numerical model of pile breakwater
The pile breakwater is simulated in a three-dimensional numerical wave tank of length 16 m, width 0.201 m and of invariable height. The piles are modelled as rigid cylinders in stereolithography format.
using AutoCAD software and imported to REEF3D. Owing to the symmetry of the wave flume, in order to reduce computational time and memory space, the width of the wave tank is reduced to half, and the symmetry boundary condition is applied. The side walls and the top of the numerical wave tank are treated as symmetry planes. The bed of the tank and the surface of the piles are treated as a no-slip wall. The waves are generated at one end and absorbed at the other end of the numerical wave tank. The waves are generated using a relaxation method which ramps up the required values for the generated waves within a distance equivalent to one wavelength. These waves are absorbed using Active Wave Absorption, based on intermediate water theory. The Active Wave Absorption avoids reflections by generating a wave opposite of the reflected wave, thus cancelling it out. The method is more efficient in computational terms, as it does not require additional space.

3.2.1 Single row of non-perforated piles. Non-perforated piles in a single row are placed perpendicular to the incident wave as shown in Figure 2. The simulations are conducted for different test conditions by varying different parameters viz. clear spacing between the piles (b), wave height (H) and time period of wave (T) as described in Table 1.

![Figure 2. A numerical model of a single row of non-perforated pile breakwater](image)

Table 1. Experimental conditions for single row of pile breakwater

| Parameters                  | Water depth (d) = 0.4m                      | Water depth (d) = 0.5m                      |
|-----------------------------|---------------------------------------------|---------------------------------------------|
| Diameter of piles (D)       | 0.0335m                                     | 0.0335m                                     |
| Clear spacing between piles (b) | 0.5D                                        | 0.5D                                        |
| Incident wave height (H)    | 0.056m to 0.17m                             | 0.056m to 0.156m                           |
| Wave time period (T)        | 1.5s and 2s                                 | 1.5s and 2s                                 |
3.2.2 Single row of perforated piles. Perforated piles of pore diameter $D_p$ are placed in a single row with a fixed clear spacing of $0.5D$, and the alignment of pile row is perpendicular to the incident wave direction as shown in Figure 3. The pile breakwater modelling is done using AutoCAD software and imported to REEF3D. A clear spacing of $0.5D$ is adopted between the piles, and the numerical modelling is carried out for a single row of piles with the introduction of perforations. Three pores per horizontal layer are modelled with a vertical clear spacing of $0.5D$ provided between the perforations. Piles with a pore diameter of $0.15D$, $0.20D$ and $0.25D$ are provided which give porosity of $2.65\%$, $4.35\%$ and $6.25\%$ respectively. At any given cross-section of the pile along the perforations, three numbers of circular perforations are provided at right angles to the direction of wave attack. The simulations are conducted for different test conditions by varying different parameters viz. diameter of pores ($D_p$), water depth ($d$), wave height ($H_i$) and time period of waves ($T$) as described in Table 2.

Table 2. Experiential conditions for single row of perforated pile breakwater

| Parameters                  | Water depth ($d$) = 0.4m | Water depth ($d$) = 0.5m |
|-----------------------------|---------------------------|---------------------------|
| Diameter of piles ($D$)     | 0.0335m                   | 0.0335m                   |
| Clear spacing between piles ($b$) | 0.5D                     | 0.5D                     |
| Pore diameter ($D_p$)       | 0.15D, 0.20D and 0.25D    | 0.15D, 0.20D and 0.25D    |
| Incident wave height ($H_i$)| 0.08m to 0.16m            | 0.08m to 0.16m            |
| Wave time period ($T$)      | 1.5sec and 2sec           | 1.5sec and 2sec           |

4. Results and analysis
In statistics, the degree of prediction accuracy of a forecasting method is given by the mean absolute percentage error (MAPE). It gives a percentage measure of error size. It is the most widely used method of predicting accuracy due to its scale-independency and interpretability.
The mean absolute percentage error (MAPE) of the numerical results compared with the experimental results is determined for each test case.

4.1 Grid Convergence Study
A two-dimensional rectangular wave tank 12m long is used to carry out and assess the performance of the numerical wave tank. Based on linear wave theory, waves of wave height 0.08m are generated for a water depth of 0.4m. A numerical wave probe in the working zone is used to measure the surface elevation. Mesh sizes of 0.05m, 0.025m, 0.0125m and 0.00625m are used to study the grid convergence. The results obtained for these mesh sizes are compared as illustrated in Figure 4.

It is clear from Figure 4 that the crests and troughs of the waves are damped out for 0.05m mesh and improved results are obtained for a mesh size of 0.025m. The variations are negligible in the wave profile for 0.025m and 0.0125m since both converge to a single solution and give the same result.

Figure 4. Grid convergence study results for mesh sizes of 0.05m, 0.025m, 0.0125m and 0.00625m.

From the grid convergence study, it can be concluded that the optimum grid size lies between 0.0125-0.025m and hence 0.020m grid size is used in the investigation of wave interaction with pile breakwater.

4.2 Influence of wave steepness and pile spacing on wave transmission
The wave attenuation by the structure is represented by the transmission coefficient ($K_t$) in terms of the incident wave. It is nothing but the ratio of transmitted wave height ($H_t$) to the incident wave height ($H_i$). Numerical probes are placed before and after the single row of piles to measure the height of the wave before and after interaction with the pile. The corresponding values of wave transmission coefficient ($K_t$) obtained from the simulation are plotted against the incident wave steepness ($H_i/gT^2$) for all the different experimental conditions and pile spacing.

4.2.1 Single Row of non-perforated Pile Breakwater. The variation of transmission coefficient ($K_t$) with wave steepness ($H_i/gT^2$) for the water depth of 0.4m is plotted in Figure 5 and Figure 6.
The influence of wave steepness \( (H_i/gT^2) \) on wave transmission coefficient \( (K_t) \) for a water depth of 0.4m and \( b=1D \) spacing and with a MAPE of 9.54% is shown in Figure 5.

From the above results it is observed that as the wave steepness increases, transmission coefficient decreases as pile spacing \( (b) \) decreases from 1D to 0.5D, an average of 6% reduction in \( K_t \) is observed at 0.4m water depth and 4% reduction in \( K_t \) at 0.5 m water depth. This means that closely spaced piles are more effective in increasing wave attenuation and hence are more efficient in stabilising the incident waves. Hence a clear spacing of 0.5D is adopted in the current numerical investigation and perforations are introduced to check the variation in wave attenuations.
4.2.2. Single row of perforated pile breakwater.

The variation of transmission coefficient ($K_t$) with wave steepness ($H_i/gT^2$) for the water depth of 0.4m and water depth of 0.5m is plotted in Figure 9 and Figure 10 for all the different pore diameters.

![Figure 9](image9.png) **Figure 9.** Influence of wave steepness ($H_i/gT^2$) on wave transmission co-efficient ($K_t$) for a water depth of 0.4m and $b=0.5D$ spacing.

![Figure 10](image10.png) **Figure 10.** Influence of wave steepness ($H_i/gT^2$) on wave transmission co-efficient ($K_t$) for a water depth of 0.5m and $b=0.5D$ spacing.

From the above two graphs, it is clearly seen that $K_t$ values of perforated piles are lesser than the $K_t$ values of non-perforated piles.

The streamline trace for the single row of non-perforated and perforated piles with the spacing $b=0.5D$ are shown in Figures 11 and Figure 12. The velocity of the incident waves is intercepted by the row of piles resulting in the increase of turbulence which in turn gives rise to a reduction of wave height by the loss of wave energy.

![Figure 11](image11.png) **Figure 11.** The streamline trace for a single row of non-perforated piles with $b=0.5D$ spacing
Figure 12. The streamline trace for a single row of perforated piles with b=0.5D spacing.

It is seen from Figure 11 and Figure 12 that the captivation of orbital velocity and development of turbulence is more in case of a single row of piles with perforation as compared to single rows of piles without perforation.

5. Conclusions
In the present investigation numerical model of non-perforated piles in a single row for two different clear spacing are simulated. The resultant wave characteristics are validated by comparing the transmission coefficient obtained from REEF3D with the experimental results by Subba Rao et. Al., (1999) [15]. The numerical results are in good agreement with the experimental results. It is observed that in the single row, piles with 0.5D clear spacing showed more turbulence and wave attenuation compared to piles with 1D clear spacing. It is concluded that lesser pile spacing of 0.5D gave better results and it was further adapted to study the effect of perforations on turbulence and wave attenuation.

Perforations are introduced to the single row of piles and the numerical models are simulated in REEF3D for the same test conditions as that of non-perforated piles. The resulting transmission coefficient values are compared with the coefficient values of non-perforated piles. It is observed that the transmission coefficient values of perforated piles are much lower than that of non-perforated piles. Lesser value of transmission coefficient directly implies that the transmitted wave height is less since they are directly proportional. Hence it is concluded that perforated piles create more turbulence and have more wave attenuation as compared to non-perforated piles.

This numerical investigation can be further extended to find optimum porosity of pile for maximum wave attenuation for the given wave conditions by simulating multiple cases of the single row of perforated piles with varying porosity percentage using REEF3D.

Acknowledgements
The authors would like to extend their heartfelt gratitude towards authorities of Department of Applied Mechanics and Hydraulics, NITK Surathkal and Centre for System Design (CSD), NITK Surathkal for providing the necessary resources for the study.
References

[1] Mani J S and Jayakumar S 1995 Wave Transmission by Suspended Pipe Breakwater J. Waterw. Port, Coastal, Ocean Eng. 121 335–8
[2] Rao S, Shirlal K G and Rao N B S 2002 Wave Transmission and Reflection for Two Rows of Perforated Hollow Piles Indian J. Mar. Sci. 31 283–9
[3] Suh K D, Ji C H and Kim B H 2011 Closed-Form Solutions for Wave Reflection and Transmission by Vertical Slotted Barrier Coast. Eng. 58 1089–96
[4] Hutchinson P S and Raudkivi A J 1984 Case History of a Spaced Pile Breakwater at Half Moon Bay Marina Auckland, New Zealand 19th International Conference on Coastal Engineering (Houston, Texas, United States: ASCE) pp 2530–5
[5] Hagiwara K 1984 Analysis of Upright Structure for Wave Dissipation Using Integral Equation Coast. Eng. 7908 1488–506
[6] Hayashi T and Masataro H 1968 Closely Spaced Pile Breakwater as a Protection Structure against Beach Erosion Coast. Eng. Japan 11 606–21
[7] Truitt C L and Herbich J B 1986 Transmission of Random Waves Through Pile Breakwaters Proc. 20th Coastal Engineering Conference (Taipei, Taiwan: ASCE, NewYork, N. Y) pp 2303–13
[8] Rao S, Rao N B S and Sathyanarayana V S 1999 Laboratory investigation on wave transmission through two rows of perforated hollow piles Ocean Eng. 26 675–99
[9] Rao S and Rao N B S 2001 Laboratory Investigation on Wave Transmission Through Suspended Perforated Pipes ISH J. Hydraul. Eng. 7 23–32
[10] Bovin R 1964 Comments on vertical breakwaters with low co-efficients of reflection Dock and Harbour Auth. 45 56-61
[11] Kakuno S and Liu P L-F 1993 Scattering of Water Waves by Vertical Cylinders J. Waterw. Port, Coastal, Ocean Eng. 119 302–22
[12] Koraim A S 2014 Hydraulic Characteristics of Pile-Supported L-Shaped Bars Used as a Screen Breakwater Ocean Eng. 83 36–51
[13] Liu H, Ghidaoui M S, Huang Z, Yuan Z and Wang J 2011 Numerical Investigation of the Interactions between Solitary Waves and Pile Breakwaters Using BGK-Based Methods Comput. Math. with Appl. 61 3668–77
[14] Weele B J Van and Herbich J B 1972 Wave Reflection and Transmission for Pile Arrays 13th International Conference on Coastal Engineering (Vancouver, British Columbia, Canada: ASCE, New York, N.Y.) pp 1935–53
[15] Rao S and Rao N B S 1999 Laboratory Investigation on Wave Reflection Characteristics of Suspended Perforated Pipe Breakwater ISH J. Hydraul. Eng. 5 22–32
[16] Kamath A, Chella M A, Bihs H and Arntsen Ø A 2015 CFD Investigations of Wave Interaction with a Pair of Large Tandem Cylinders Ocean Eng. 108 738–48
[17] Bihs H, Kamath A, Alagan Chella M and Arntsen Ø A 2016 Breaking-Wave Interaction with Tandem Cylinders under Different Impact Scenarios J. Waterw. Port, Coastal, Ocean Eng. 142
04016005-1–14

[18] Arunakumar H S, Suvarna P, Abhijith P A, Prabhu A S, Pruthviraj U and Kamath A 2019 Effect of emerged coastal vegetation on wave attenuation using open source CFD tool: REEF3D Proceedings of the Fourth International Conference in Ocean Engineering (ICOE2018) vol 1 (Chennai, India: Springer Nature Singapore Pte Ltd.) pp 591–603

[19] Bihs H, Kamath A, Alagan Chella M, Aggarwal A and Arntsen Ø A 2016 A New Level Set Numerical Wave Tank with Improved Density Interpolation for Complex Wave Hydrodynamics Comput. Fluids 140 191–208

[20] Bihs H and Kamath A 2017 A Combined Level Set/Ghost Cell Immersed Boundary Representation for Floating Body Simulations Int. J. Numer. Methods Fluids 83 905–16

[21] Alagan Chella M, Bihs H, Myrhaug D and Muskulus M 2017 Breaking solitary waves and breaking wave forces on a vertically mounted slender cylinder over an impermeable sloping seabed J. Ocean Eng. Mar. Energy 3

[22] Kamath A, Bihs H, Chella M A and Arntsen Ø A 2015 CFD simulations to determine wave forces on a row of cylinders Procedia Eng. 116 623–30

[23] Jiang G-S and Peng D 2003 Weighted ENO Schemes for Hamilton--Jacobi Equations SIAM J. Sci. Comput. 21 2126–43

[24] Shu C-W and Osher S 1988 Efficient Implementation of Essentially Non-oscillatory Shock-Capturing Schemes J. Comput. Phys. 77 439–71

[25] Sussman Mark, Peter S and Stanley O 1994 A level set approach for computing solutions to incompressible two-phase flow J. Comput. Phys. 114 146–59