



Modeling studies on the behavior of single and double rubble mound breakwaters using genetic programming tool

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Experimental investigation on wave transmission, reflection and dissipation characteristics of rubble mound breakwater models are time consuming and expensive. However, such studies are required for designing the rubble mound breakwaters for marine structures in an optimal condition. In order to overcome such problems many researchers used various soft computing techniques such as Artificial Neural Network (ANN), Adaptive Neuro Fuzzy Interference System (ANFIS), Genetic Programming (GP), Support Vector Machine (SVM) etc, in order to predict the design factors in the field of coastal engineering. The current work proposes Genetic Programming (GP) as a modeling tool to evolve mathematical models for the behavior of single and double breakwaters. Based on the detailed experimental data, GP models were performed to predict the reflected wave height (H_r), wave height on the breakwater (H_s) and transmitted wave height (H_t) by considering with and without trigonometric effects of those breakwaters. The quality of predictability of the present model is measured by the statistical parameter, RMSE (Root Mean Square Error). Since the waves were more complex in nature, it is very essential in considering the trigonometric function's effect in the modeling aspects. It is evident that, the GP model accurately described the non linear complex effects.

[Keywords: Genetic programming, Modeling, Rubble mound breakwater, RMSE]

Introduction

Breakwaters are generally called as wave breakers or wave barriers, which are designed to protect the sea shore areas from erosion and for the construction of ports, harbors and marinas from the wave disturbances. It functions by absorbing/dissipating the wave energies of the gravity waves generated by winds. The choice of breakwaters relies on the factors like height of waves and time domain of the receding waves. The floating breakwaters can be chosen for smaller wave heights and wave periods; whereas rubble mound breakwaters are used for larger wave heights and wave periods. As construction of breakwater involves huge investment, it is recommended to do model studies to simulate the functioning of the breakwaters, and identify design variables which can be best optimized.

Physical model study on rubble mound breakwaters for the assessment of its stability, wave transmission/reflection/dissipation characteristics is an important research aspect for optimized design of such marine structures. Such model studies have been carried out by many researchers in the past¹⁻⁵.

Physical modeling is becoming more expensive and more time consuming. Therefore, an alternative technique needs to be used for predicting design parameters, which are needed for overall optimized design of rubble mound breakwaters. For better understanding of the performance of the physical models, mathematical modeling can be done on the data obtained from such model studies. In the past research works, soft computing techniques including ANN, ANFIS, SVM, and GP has been widely used in the domain of marine engineering⁶⁻⁹. Most of these modeling techniques were focused on the prediction of some variables with a set of input variables and the results were compared with conventional methods. For instance, ANN is used for forecasting the level of damages and stability conditions of a rubble mound breakwater¹⁰. However, a better performance by ANN when compared to conventional empirical methods is noticed¹¹. Furthermore, in order to minimize the error, optimization techniques such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are also used¹². Such hybrid models are used in predicting the

scour depth on the mid portion of breakwater considering non-breaking waves. This has provided more accurate and realistic results. Analytical models use the parameters such as non-breaking wave steepness, toe mean water depth, reflection coefficient, shield parametric factors etc., as input variables and predict scour depth as output¹³. Based on the value of the statistical parameters obtained, GP model outperformed ANN model in scour depth prediction. Apart from the accuracy desired in the prediction of the output variable, it will be more useful if the information on the behavior of the model itself can be understood better.

This study recommends Genetic Programming as a modeling tool to evolve mathematical models, the analysis of whose structure is expected to yield more meaningful information. The parameters such as Incident wave height (H_i), Length of the wave (L) and Water depth (d) obtained from the experimental test is used as a input parameters in the GP for modeling reflected wave height (H_r), wave height on the breakwater (H_5) and transmitted wave height (H_t) equations.

Materials and Methods

Experimental set up and tools used

Experimental set-up

A series of large experimental investigations were carried out in the rectangular wave flume tank (54.5 m long x 0.6 m wide x 1.15 m deep) of the coastal engineering laboratory at Kuwait Institute for Scientific Research (KISR), Kuwait. Waves were generated in the wave flume using computer controlled piston type wave generator. Regular types of waves were created by the periodic movement of the piston type (paddle) wave generator with single frequency and constant amplitude. The wave maker was installed in the upstream closing part of the flume and was connected to a host computer to generate regular type's of waves with different wave heights and wave periods. For random type's waves, the piston movement is also random since the signal generated by computer is from mathematical spectrum like JONSWAP and is also random. The wave maker is active absorption type. Any reflected wave from the model section is absorbed by the wave maker and hence the quality of data collected at model section is much better than the conventional wave flumes without active wave absorption system. The standard capacitance type of wave probe's having

the range of 60 cm and resolution of 0.15 mm are kept positioned in the wave flume at six different locations to measure the water surface variations resulting from the wave-structure interaction. Three water depth conditions 0.5, 0.6 and 0.7 m (which corresponds to emerged condition, water level at crest level of breakwater and submerged condition of the breakwater) are considered for testing. The breakwater models are kept positioned of 15 m distance apart from the wave generator. The breakwater models of both single and double permeable types are constructed with the same type and size of rubbles. The breakwater height 'h' is kept constant at 0.6 m. The use of one layered structure is beneficial in reducing construction time and cost as well as simplifying the construction process. In the field construction of rubble mound breakwaters, slope varying from 25 to 40 degree is used in general, depends upon the predominant armor stone weight available from the quarry. The sea side and rear side slopes is selected as both 30° for the single (Study 1) and Double breakwater (Study 2) models.

Both the breakwater models are having equal in total volume of stones (i.e., the volume of stone used in single breakwater is equal to the sum of volume of stones used in the twin breakwater); however, each model had a different shape. The single and double breakwaters are of trapezoidal type and triangular type, respectively. One wave probe (WP1) is placed in front of the wave generator at a distance similar to a wave length of the largest wave to be generated during the experiments, to estimate the heights of incident waves. The other three wave probes (WP2, WP3 and WP4) are fixed in the frontage of the breakwater model to estimate an envelope created by the wave heights of the reflected waves and the incident waves. The fifth wave probe (WP5) is partially immersed inside the breakwater model when a single structure is being tested (to measure the water surface fluctuation at the mid section of the breakwater), whereas in the case of double breakwaters, the fifth probe is positioned in the middle between the structures, to measure the wave variations in the water pool formed in the area between the double breakwaters. Wave probe WP6 is placed in the lee side of the breakwater model to estimate the height of the transmitted waves. The positions of wave probes in single breakwater and double break water are shown in Figures 1 & 2.

The regular waves were generated for a whole time interval of 90 s for every run. The wave heights

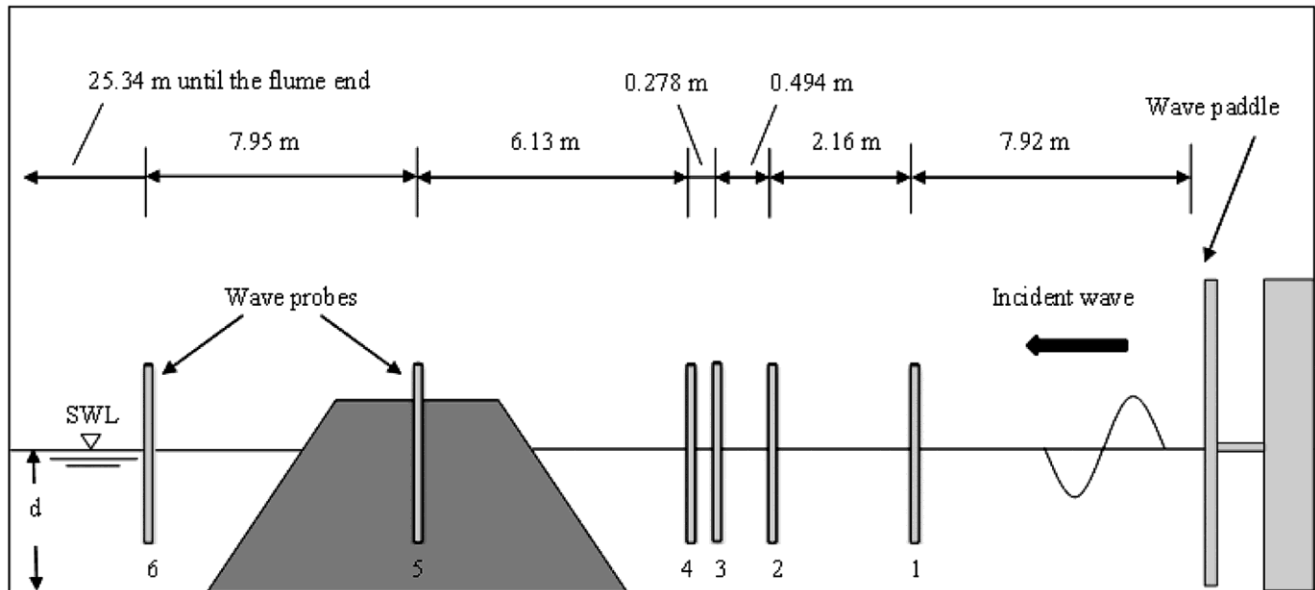


Fig. 1 — Single breakwater model and wave probes positions

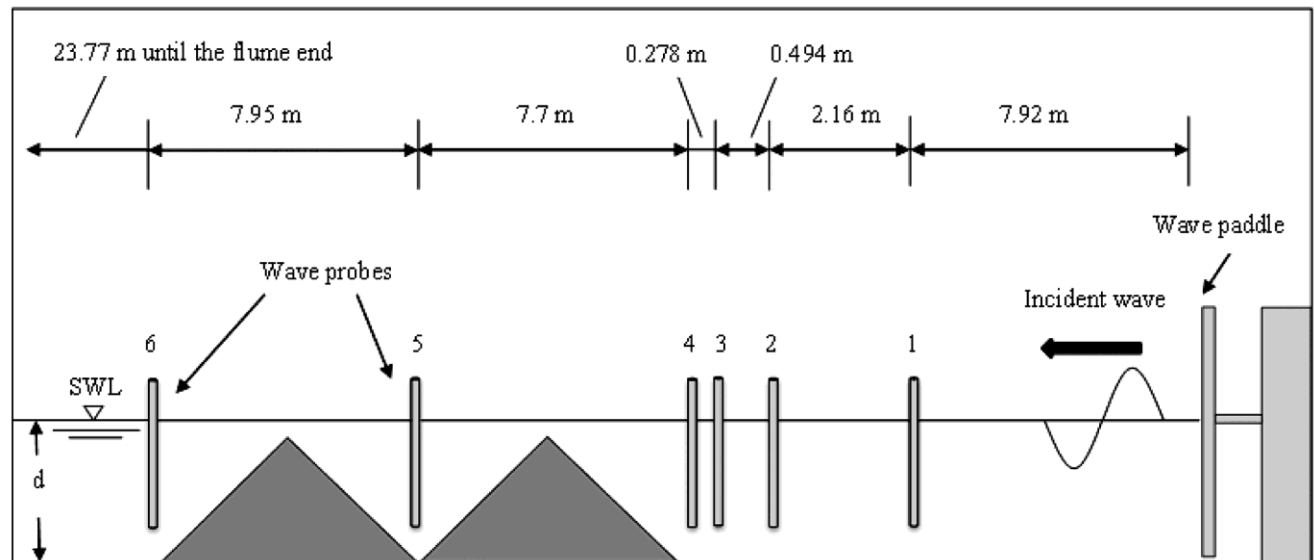


Fig. 2 — Double breakwater model and wave probes positions

generated are 10 and 20 cm and the wave periods ranged from 1 to 3 s. Data collection from all channels is initiated at least 20 s after the start of wave generation with a total duration of 30 s in order to guarantee the beginning of the repeatability of the same wave heights at the model location and take into account the short period waves ($T = 1$ s) which travel slower than the long period waves. After the completion of each run, the resulted real time series for water surface elevations measured by wave gauges were initially checked for the data collection accuracy. The adopted starting time for data

collection was based on trial runs with different wave periods, while the data collection duration and ending time were appropriately selected in a way that avoids any possibility of non categorized reflected waves from the wave maker which is affecting the measurements around the test section.

Genetic Programming

Genetic Programming (GP) is nothing but a progressive algorithm based approach following Darwinian Theory on focusing the concept of selection and fittest survival elements. However, GP

evaluates an approximate of the model equation that describes how the output and input variables are getting correlated in a best manner. The algorithmic part comprises of an unsystematically created equations, which are drawn from the arbitrary grouping of input variables, arbitrary numbers and its functions, consisting of some basic arithmetic operators (+, -, X, %), mathematical advanced expressions (sin, cos, exp, log), logical/ comparison functions (OR/AND) etc., has to be suitably selected based on the functioning of this process. This population of capable outputs is then subjected to a progressive method and its 'fitness' (problem solving approach in best possible way) are assessed and best fit data's are then picked out from raw data group. Genetic Programming with their remarkable ability to derive equations from complicated or imprecise data, can be used to extract patterns that are too multifaceted to be identified either by operating persons or even computation techniques. Based on the simulated models, it can be used to provide projections for given new situation of interest. They are better than conventional algorithms in that they are more robust¹⁴⁻¹⁷.

Evolving GP models

Out of 48 experimental trials, a total of 50, 35 and 15 % data's have been taken for the category of training, testing and validation, respectively for arriving the GP Model. Rather than arithmetic functions, it also have the trigonometric functions, since the waves are a complex combination of sine or cosine nature of pattern. The optimal values of GP parameters are arrived at after trial and error viz., cross over frequency of 50 %, mutation frequency of 95 %, population size of 500 and number of generation as 1000. This optimal value is assumed to be fixed for each trial.

Performance measure

The effectiveness of the model developed is evaluated from the values of statistical parameters namely Root Mean Square Error (RMSE).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n [(X_m)_i - (X_s)_i]^2}$$

where, X – any variable that is being modeled; the observed values and hypothetical model values are represented by subscripts m and s.

RMSE estimates the variation in the values obtained from a hypothetical model and the observed

ones. It mainly relates the quality of the fit between those values.

Results and Discussions

Experimental studies

In this experiment, totally 48 trials are conducted for three water depth conditions viz. 0.5, 0.6 and 0.7 m. The parameters such as 'H_i' (Incident wave height), 'L' (length of the wave), 'H_r' (Reflected wave height), 'H_s' (Wave height on the breakwater crest for single breakwater; wave height in between the breakwater for twin breakwater) and 'H_t' (Transmitted wave height) are found for single and double breakwater and all those parameters are tabulated in Table 1. It is noticed that for the water depth of 0.5, 0.6 and 0.7 m, the wave length of the incident waves calculated using dispersion relation {L=1.56 T² [tan h(kd)]} are in the ranges from 1.51 to 6.39 m, 1.54 to 6.95 m, and 1.55 to 7.45 m, respectively; where, 'T' is the wave period, 'k' is the wave number and 'd' is the water depth. In general, for a selected water depth (Table 1), for d = 0.5 m, and for single breakwater, it is found that increase in wave length increases the wave transmission. The reason for this is that longer waves have less wave steepness and hence they move smoothly through the pores of breakwaters and results in increasing wave transmission. Steeper waves experience less transmission, since the rate of energy dissipation is more through breaking.

In comparison, the behavior of single and double breakwaters is quite different. The single breakwater dissipates more energy than double breakwater. Therefore, the single breakwater showed better hydrodynamic performance than the double breakwaters, since the single breakwater has wide width at the free surface, whereas the twin breakwater has almost no width since it is triangular in shape. The waves interacting with breakwater of wider width dissipate more energy since it interacts with more units of materials. Single rubble mound breakwater dissipates energy by turbulence, wave breaking and overtopping induced actions. In addition to these, in the twin breakwater the oscillation in between the breakwater creates wave energy dissipation depends on the mode of oscillation. Experimental data's are validated by the analytical modeling on GP.

RMSE value

The modeling of wave characteristics is carried out in genetic programming based on the numeric data

Table 1 — Wave parameters for different water depth conditions

S. No	d	Single breakwater					Double breakwater				
		H _i	L	H _r	H _s	H _t	H _i	L	H _r	H _s	H _t
	(m)	(cm)	(m)	(cm)	(cm)	(cm)	(cm)	(m)	(cm)	(cm)	(cm)
1	0.5	10.67	5.2386	3.0836	3.109	0.7654	9.526	5.3826	2.2862	3.509	1.646
2	0.5	11.19	4.0564	2.8423	1.965	0.5201	11.06	6.3958	3.4839	3.938	1.601
3	0.5	11.98	3.5722	3.8336	1.581	0.3423	12.09	1.513	2.1304	2.306	0.3148
4	0.5	12.07	3.0781	2.9572	1.086	0.2577	12.17	2.5712	2.7017	1.956	0.3687
5	0.5	12.18	2.5712	2.5578	0.801	0.1407	12.17	4.0564	1.5213	2.905	1.448
6	0.5	12.25	6.3958	3.8833	5.708	1.217	12.29	3.0781	2.9004	2.006	0.5295
7	0.5	12.45	2.0483	3.3864	0.0571	0.0571	12.38	3.5722	2.835	3.828	0.8788
8	0.5	12.77	1.513	2.2731	0.1964	0	12.57	2.0483	3.4819	1.597	0.2424
9	0.5	12.8	1.513	2.4192	0.1762	0.0388	12.93	1.513	3.517	0.8505	0.1612
10	0.5	14.46	2.0483	5.4659	0.4579	0.1224	13.89	6.3958	4.8615	6.056	3.981
11	0.5	15.27	6.3958	5.5125	11.49	1.704	14.93	2.0483	6.3005	2.9	0.3085
12	0.5	16.61	2.5712	3.5712	1.059	0.1566	16.99	2.5712	3.483	4.857	0.4809
13	0.5	17.26	3.5722	5.2298	3.014	0.3574	18.08	3.5722	5.3155	6.735	2.813
14	0.5	17.67	4.0564	3.9227	4.706	0.6128	18.82	4.0564	2.2584	5.239	3.649
15	0.5	18.69	5.2386	6.3359	8.719	0.9666	18.95	5.2386	4.9839	7.211	4.361
16	0.5	19.5	3.0781	5.3625	2.632	0.3057	19.72	3.0781	4.5159	5.425	1.868
17	0.6	11.35	3.2716	2.0203	2.522	1.619	12.28	3.2716	1.4245	8.362	3.04
18	0.6	11.83	5.6731	1.5497	5.579	2.074	12.35	1.5383	2.0625	4.777	3.807
19	0.6	12.3	1.5383	1.968	3.037	0.867	12.62	4.362	1.8425	5.527	5.409
20	0.6	12.43	6.9518	1.3424	7.617	3.325	12.8	2.1229	3.2768	6.206	2.754
21	0.6	12.56	4.362	2.2482	3.783	1.846	12.95	2.7051	1.9555	7.386	2.789
22	0.6	12.66	2.7051	1.8357	2.845	1.912	13.3	3.8229	1.9551	5.255	4.757
23	0.6	12.71	2.1229	3.2283	3.196	1.341	14.34	1.5383	3.4129	5.35	3.664
24	0.6	13.54	3.8229	2.6268	3.248	1.645	14.55	5.6731	5.3981	6.384	5.207
25	0.6	14.36	1.5383	2.714	2.925	1.258	16.52	6.9518	6.6906	9.638	4.909
26	0.6	19.81	2.1229	7.2901	2.847	3.253	19.88	2.1229	7.1568	6.908	4.997
27	0.6	23.88	2.7051	4.8238	4.708	3.715	23.8	2.7051	5.117	8.05	5.012
28	0.6	25.22	3.8229	8.0704	6.178	6.483	25.4	3.2716	4.8514	8.733	6.275
29	0.6	25.24	3.2716	5.4014	5.207	4.611	25.7	3.8229	8.2754	8.527	6.883
30	0.6	26.69	5.6731	7.5533	6.839	8.453	27.57	4.362	4.0804	11.33	8.099
31	0.6	27.39	4.362	3.8346	8.307	5.989	29.02	5.6731	11.6951	8.177	8.997
32	0.6	33.33	6.9518	9.5324	10.47	7.219	36.93	6.9518	11.4852	11.42	7.768
33	0.7	11.78	6.0569	1.2016	16.01	5.944	12.07	1.5506	2.3778	8.431	7.364
34	0.7	12.08	1.5506	2.5006	8.82	6.122	12.29	7.4498	4.7317	9.151	5.728
35	0.7	13.08	2.1714	2.7468	9.035	6.7	12.72	6.0569	6.0166	8.118	9.876
36	0.7	13.11	7.4498	1.7174	16.51	7.616	12.82	4.6236	2.5768	10.94	7.39
37	0.7	13.12	3.427	1.3382	11.68	4.538	12.87	3.427	1.1969	8.158	5.904
38	0.7	13.23	4.6236	1.9051	13.92	4.242	12.93	2.1714	2.961	7.478	5.306
39	0.7	13.35	2.8052	1.1882	10.3	5.588	12.95	4.0324	2.1368	9.15	8.534
40	0.7	13.57	4.0324	1.2484	9.871	5.447	13.14	2.8052	1.498	10.5	6.314
41	0.7	14.87	1.5506	3.7919	8.677	5.66	15.05	1.5506	3.597	9.106	8.047
42	0.7	21.89	6.0569	2.3422	23.89	7.66	20.14	6.0569	8.1768	23.57	14.79
43	0.7	22.72	2.1714	8.9744	9.338	7.563	22.98	2.1714	8.9392	11.27	10.08
44	0.7	25.7	4.6236	3.1868	19.28	9.888	24.32	7.4498	6.8826	17.27	11.71
45	0.7	25.8	2.8052	4.4118	10.7	8.533	25.58	4.6236	7.4694	13.31	12.75
46	0.7	26.14	3.427	3.9471	12.24	8.169	25.82	4.0324	5.2156	13.36	12.15
47	0.7	27.5	4.0324	3.3275	14.84	10.03	25.94	2.8052	3.9169	10.78	10.08
48	0.7	29.1	7.4498	7.1586	24.2	9.806	26.56	3.427	5.0995	12.44	14.07

obtained from the experiments. In Table 2, the comparisons of RMSE for single and double breakwaters by considering trigonometric functions and without considering trigonometric functions are tabulated.

Considering the applied data in the GP, for single breakwater, 1.655 cm and 3.538 cm are the maximum RMSE values for with and without application of trigonometric functions, respectively. For double breakwaters, the maximum RMSE values are 1.455 cm and 1.984 cm respectively. In both the types of breakwaters, the RMSE values are higher for without trigonometric functions. In general, the prediction errors are high for the water depth 0.5 m (emerged condition). For the water depth conditions, 0.6 and 0.7 m (at the crest of breakwaters and submerged condition, respectively) the model performs better, with lesser prediction error for ‘H_i’.

Modeling equation

Modeling equations was arrived with and without considering trigonometric functions.

(i) With trigonometric functions

The final form of models (Eq. 1 to 6) can be used to predict reflected wave height (H_r), wave height on the breakwater (H₅) and transmitted wave height (H_t) of single and double breakwaters with considering trigonometric functions, since length of the incident wave (L), height of the incident wave (H_i) and depth of the water (d) are known. The trigonometric shape is selected for the study as an option to see how it performs as a wave barrier. It can also be noted that, as expected, the models have sine or cosine functions. If trigonometric functions are considered in the model, there will be more than one sine or cosine functions in representing the models H_r and H₅ indicating the complex nature of the waves (Eqs. 1, 2, 4, and 5). After the waves crossed the breakwaters of any type, more energy is dissipated through breaking mechanism and hence the complexity of the wave is minimized and reflected through the presence of only

one function of sine or cosine in the model for ‘H_i’ (Eqs. 3 and 6).

For single breakwater

$$H_r = 0.372 H_i [0.072 \sin L + \sin H_i + \sin d + 0.81] - 1.07 \dots (1)$$

$$H_5 = d^4 [\cos H_i^2 - 3.078 \cos H_i - 2 \cos H_i d] + d^3 [L - 2.297] + d^2 L - dL \dots (2)$$

$$H_t = d^3 [\sin H_i + H_i + 16.82] + d^2 [L - 14.06] - d \dots (3)$$

For double breakwater

$$H_r = d^4 [2L \sin H_i + 2 H_i + 3.543] + 0.25 L \dots (4)$$

$$H_5 = d^2 [\sin^2 (H_i d) + 0.7 H_i + L + 2.835] \dots (5)$$

$$H_t = 1.73 d^4 \left[\frac{28.90}{L} \sin L - L + H_i + 14.45 \right] \dots (6)$$

The Figures 3a & 3b shows the comparison of actual H_i values with predicted H_i values for single and double breakwaters by considering trigonometric functions and it is well correlated.

(ii) Without trigonometric functions

The final form of models (Eqs. 7 to 12) can be used to predict reflected wave height (H_r), wave height on the breakwater (H₅) and transmitted wave height (H_t) of single and double breakwaters without considering the trigonometric functions. It is seen that models evolved without the use of trigonometric functions are more simple but with a penalty on prediction accuracy. The predicted errors are in the range of 15 to 25 % and 28 to 48 % for considering trigonometric and non trigonometric functions, respectively. The predicted error between the model values and observed values seems to be higher for both the types of breakwaters. In order to have a less predicted errors, the consideration of trigonometric functions are very essential in modeling the coastal structures. The Figures 3c and 3d show the comparison of actual ‘H_i’ values with predicted ‘H_i’ values for single and double breakwaters without trigonometric functions. With many peaks either under or over predicted with phase lag. For some preliminary works,

Table 2 — Comparisons of RMSE values for both breakwaters

Functions used	Output model	Single breakwater			Double breakwater		
		Training	Validation	Applied	Training	Validation	Applied
With trigonometric functions	H _r	0.881	0.9116	1.655	0.859	0.896	1.455
	H ₅	1.736	0.232	1.09	1.017	0.978	0.852
	H _t	0.788	0.749	0.709	0.831	1.101	0.837
Without trigonometric functions	H _r	1.175	0.744	1.157	0.452	0.945	1.984
	H ₅	1.294	2.203	3.538	0.27	0.282	1.122
	H _t	0.806	1.089	2.211	0.316	0.613	0.602

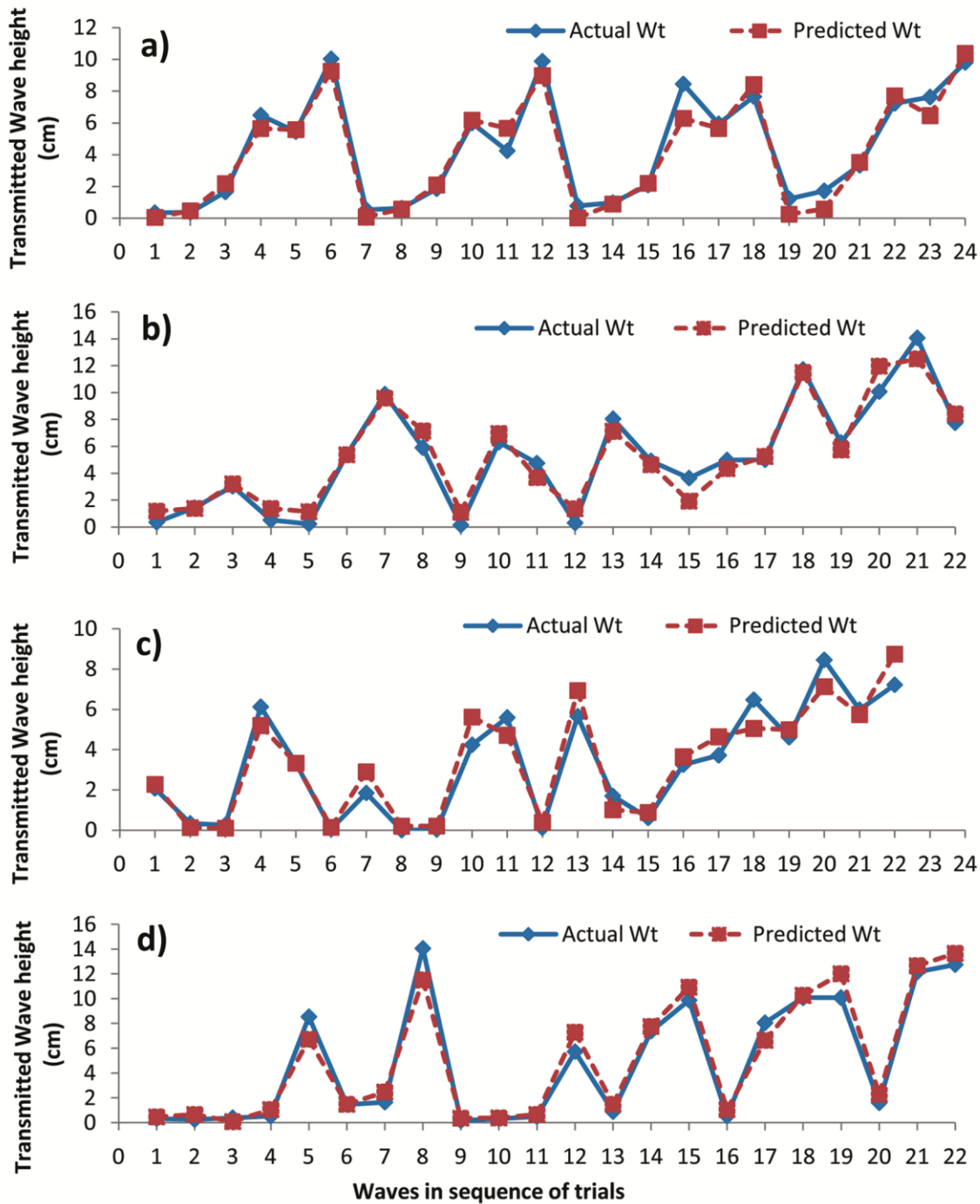


Fig. 3 — Comparison of Actual H_t vs Predicted H_t : a) for Single breakwater with trigonometric function; b) for double breakwater with trigonometric function; c) for single breakwater without trigonometric function; and d) for double breakwater without trigonometric function.

non-trigonometric models can be used when complex is not assumed to play a major role.

Single breakwater

$$H_r = \frac{0.026 L \sqrt{H_i}}{d^2} + 0.138 \frac{H_i}{d} - 2.02 \quad \dots (7)$$

$$H_5 = 2 d [-0.0026 H_i^2 - 1.063 H_i + H_i d + d] + L \dots (8)$$

$$H_t = 1.361 d^4 [H_i + L] \quad \dots (9)$$

Double breakwater

$$H_r = 0.217 [0.0022 \frac{L^4}{d^2} + H_i] \quad \dots (10)$$

$$H_5 = 0.7 d [4 d^3 - (2.07 + H_i)d^2 + L] \quad \dots (11)$$

$$H_t = d^3 [(1 + H_i) d^2 + H_i d + L] \quad \dots (12)$$

Conclusions

The following concluding remarks have been arrived based on this work: i) The transmitted wave height (H_t) on the breakwaters are directly influenced by the parameters such as water depth conditions (d), length of the wave (L) and height of the incident wave (H_i); ii) Single breakwater showed better performance than the double breakwaters in terms of high energy dissipation rates due to the design shape and thereby protection efficiency enhanced; iii) The RMSE values are high for the water depth 0.5 m (emerged condition of the breakwater) but for the water depth 0.6 and 0.7 m (breakwater crest and still water level at the same elevation and submerged condition, respectively) the RMSE values seems to be better; iv) The complexity of the wave nature is fully described by the sine or cosine functions in the developed GP models. It seems that, model ' H_t ' involves less complex nature, because of the intervention of breakwaters; and v) The prediction errors are less which are in the range of 15 to 25 % when the trigonometric functions are included in the GP modeling.

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Conflict of Interest

On behalf of all authors, the corresponding author P L Meyyappan states that there is no conflict of interest.

Author Contributions

SN, ZKA-Z & MA-K: Experimental conceptualization, model setup and run, participation in lab experiments, and draft correction; and PLM & CS: Modelling conceptualization, participation in Genetic Programming analysis, draft preparation, and editing.

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