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AN EFFICIENCY TEST ON WAVE ENERGY REDUCTION OF PILED BREAKWATERS USING PHYSICAL MODEL

การทดสอบประสิทธิภาพในการลดพลังงานคลื่นของเขื่อนสลายพลังงานคลื่น โดยใช้แบบจำลองทางกายภาพ

Ar-sawin Intasupa[1], Winai Ouypornprasert[2], Payom Ratanamanee[3],
Tanawat Jarupongsakul[4] and Pramot Sojisuporn [1*]

[1] Department of Marine Science Faculty of Science Chulalongkorn University

[2] Department of Civil Engineering College of Engineering Rangsit University

[3] Department of Civil Engineering Faculty of Engineering Prince of Songkhla University

[4] Department of Geology Faculty of Sciences Chulalongkorn University

อาศวิน อินทสุภา[1] วินัย อวยพรประเสริฐ[2] พยอม รัตนมณี[3]
ธนวัฒน์ จารุพงษ์สกุล[4] และ ปราโมทย์ โศจิศุภร[1*]

[1]ภาควิชาวิทยาศาสตร์ทางทะเล คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

[2]ภาควิชาวิศวกรรมโยธา คณะวิศวกรรมศาสตร์ มหาวิทยาลัยรังสิต

[3]ภาควิชาวิศวกรรมโยธา คณะวิศวกรรมศาสตร์ มหาวิทยาลัยสงขลานครินทร์

[4]ภาควิชาธรณีวิทยา คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

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Abstract

The physical model at Hydraulic Engineering Laboratory Unit, Prince Songkhla University was used to test the efficiency of a triangular-concrete piled breakwater. Seven parameters; namely wave height, wave period, water depth, spacing between row, spacing between pile in the same row, angle of incident wave and orientation of pile's angle in the row were selected and each parameter was tested at 3 predefined values, namely low, medium and high values. The piled breakwater was composed of either one, two, three or four rows of piles. The best arrangement which could reduce the incident wave energy for up to 53% was obtained when using short wave period and the acute angle of the triangular pile pointing outward on the 3-row piled breakwater. When comparing the cost with its effectiveness in reducing the wave energy, the best-performed piled breakwater was the one consisting of 3 rows of piles with 1.5 m spacing between each row and 1.5 m spacing between

* corresponding author
E-mail : pramot.s@chula.ac.th
Phone : + 66-2218-5405

each pile in the row. This type of piled breakwater was already constructed at Ban Khun Samut Chin, Phra Samut Chedi District, Samut Prakarn Province.

Keywords: piled breakwaters, wave energy reduction

บทคัดย่อ

การทดสอบประสิทธิภาพในการสลายพลังงานคลื่นของเขื่อนเสาคอนกรีตสามเหลี่ยมโดยใช้แบบจำลองทางกายภาพที่หน่วยปฏิบัติการวิศวกรรมชลศาสตร์ มหาวิทยาลัยสงขลานครินทร์ กำหนดค่าตัวแปรที่ทำการทดสอบจำนวน 7 ตัวแปร คือ ความสูงคลื่น คาบคลื่น ความลึกน้ำ ระยะห่างระหว่างแถว ระยะห่างระหว่างเสาในแถว ทิศทางคลื่นที่เข้าสู่แนวเขื่อน และมุมของเสาที่ทำกับแนวเขื่อน แต่ละตัวแปรใช้ค่าทดสอบ 3 ระดับ คือ ต่ำ กลาง สูง และทดสอบเขื่อน 4 แบบตามจำนวนแถวของเสา คือ 1, 2, 3 และ 4 แถวตามลำดับ พบว่าเมื่อใช้คาบคลื่นสั้นควบคู่กับมุมของเสาที่ทำกับแนวเขื่อนแคบ และมีจำนวนแถวของเสา 3 แถว สามารถลดพลังงานคลื่นสูงสุดได้ประมาณ 53 เปอร์เซ็นต์ และเมื่อเปรียบเทียบต้นทุนในการก่อสร้างเขื่อนกับประสิทธิภาพของเขื่อน พบว่า เขื่อนเสาสามเหลี่ยม 3 แถว ระยะห่างระหว่างแถว 1.5 ม. และระยะห่างระหว่างเสาในแถว 1.5 ม. ดังที่ได้ก่อสร้างขึ้นที่บ้านขุนสมุทรจีน ต.แหลมฟ้าผ่า อ.พระสมุทรเจดีย์ จ.สมุทรปราการ มีต้นทุนต่ำสุดและมีประสิทธิภาพในการลดแรงคลื่นได้ดีที่สุด

คำสำคัญ: เขื่อนเสาคอนกรีตสามเหลี่ยม, การลดพลังงานคลื่น

Introduction

Ban Khun Samut Chin is located on the western side of the Chaopraya River mouth in Phra Samut Chedi District, Samut Prakarn Province. The geomorphology of the area is a tidal delta with tidal flat and mud flat with sediment brought down from the river. Mangrove forest used to cover the coastal area in this region but now is disappeared due to both natural and human causes. As a result, the coastal area experienced severed coastal erosion in the last three decades. It was estimated that about 38,000 rai (equivalent of 60.8 km^2) will be lost in the next 20 yr if no action has been done to protect the coast[1].

Many construction types and materials have been built and tried in the past 30 yr but none have been proved to effectively alleviate coastal erosion for muddy shore in the inner Gulf of Thailand. In 2006, our research team has constructed a 250-m-long piled breakwater at about 500 m out of Ban Khun Samut Chin coastline (Figure 1). The breakwater consisted of 3 rows of equilateral triangular piles which had the length of 0.5 m on each side. Each row was 1.5 m apart and each pile in the row was also 1.5 m apart. The piles were staggered such that those in the first and the third rows were aligned while those in the second row were oblique from the other rows. Ideally each pile should have about 3 m long above the ground in order for the top of the pile to stay above high water at all time. The piled breakwater has been shown to effectively reduce wave energy, especially during the south west monsoon season when wave condition was strong. Current velocity has been reduced, thus increasing sediment deposition behind the piled breakwater[2].

The triangular piled breakwater at Ban Khun Samut Chin is the first of its kind in the world. In order to prove its effectiveness on wave energy reduction, the physical model has been performed at Civil Engineering Laboratory, Prince Songkhla University (under the supervisory of Assistant Professor Payom Ratanamanee). This paper described this physical experiment and its outcome to obtain the best triangular piled breakwater arrangement that will effectively reduce the wave energy by mean of the physical model experiment.

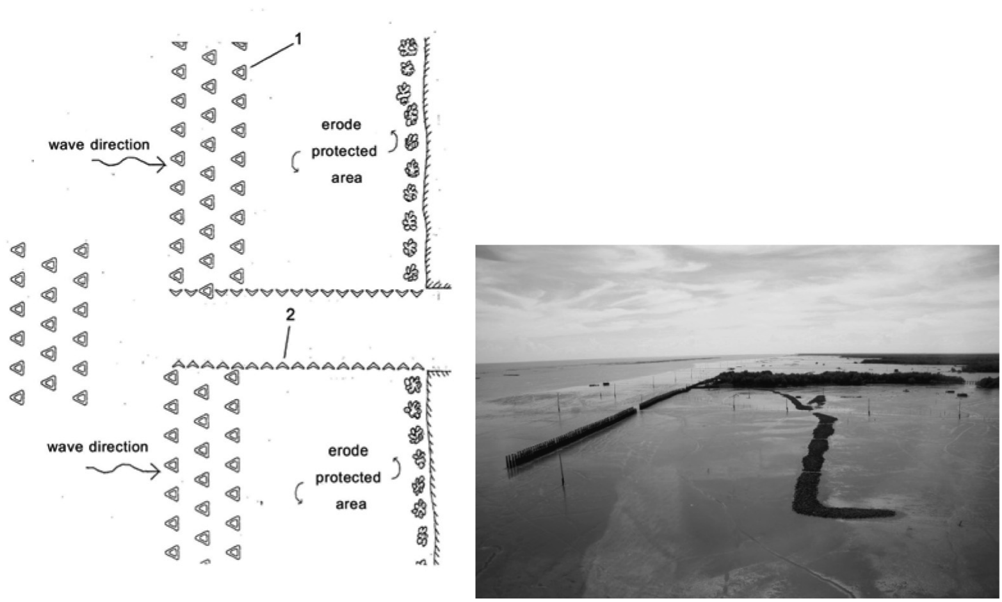


Figure 1 Sketch of 3-rows piled breakwater and the finished piled breakwater installed at Ban Khun Samut Chin, Samut Prakarn Province.

Materials and Methods

1. Identify 7 parameters that could influence the effectiveness of piled breakwater; namely wave height, wave period, water depth, spacing between rows, spacing between pile in the same row, angle of incident wave, and orientation of pile's acute angle with the row of pile. Each parameter would be tested for 3 chosen levels only; namely low, medium, and high value (Table 1). The parameter values were chosen in such a way that they

covered the possible range found in nature.

2. Model piled breakwater for experiment in the wave tank (Figure 2) using 5:1 ratio between the actual pile and the model pile. The model piles were 0.9 m long and each side of the triangle x-section was 0.1 m width. A long hole ran through the center of the piles so that an iron rod could be placed inside the hole. The iron rod was used to fix each pile to a steel plate on the floor and a plank of wood on the top of the piled breakwater.

3. Run the experiment in July 2008 by first using medium values for all parameters. Wave forms were generated at one end of the wave tank. The wave then traveled pass the piled breakwater and was absorbed almost entirely at the other end of the wave tank. Wave heights were measured in front of the breakwater, at the breakwater and behind the breakwater by using laser beams emitting above the water surface. These experimental results would be the common results for 1-, 2-, 3- and 4-row piled breakwater respectively. In the following experiments, only one parameter was switched to either low or high value at a time while keeping the rest of the parameters at the medium values. These experiments would be called “test for single variable”. There would be a total of 13 experiments for 1-row piled breakwater and 15 experiments for each 2-row, 3-row and 4-row piled breakwater respectively.

Figure 2 Wave tank at Civil Engineering Laboratory, Prince Songkhla University. Below were triangular piles and their arrangement in the wave tank.

Table 1 Parameters and their values used in the physical model. The actual:model ratio for distance was 5:1 while the ratio for time was $\sqrt{5}:1$

Parameter	Low	Medium	High
Wave height	0.05 m	0.10 m	0.15 m
Wave period	0.9 s	1.5 s	2.1 s
Water depth	0.2 m	0.4 m	0.6 m
Spacing between rows*	0.2 m	0.3 m	0.4 m
Spacing between pile in the same row	0.2 m	0.3 m	0.4 m
Angle of incident wave	0 deg.	22.5 deg.	45 deg.
orientation of pile's acute angle with the row of pile	0 deg.	22.5 deg.	45 deg.

* For case of one-row piled breakwater, spacing between rows is not available.

4. Compute the total wave energy in front of and behind the piled breakwater using the equation, $E = \frac{1}{8}\rho g h^2$, where *E* is total wave energy in Joule, ρ is water density, *g* is gravity and *H* is wave height. Then compute percentage of wave energy reduction for each experiment.

5. Plot 2nd order polynomial curves over the wave energy reduction data of each parameter. Attention was paid to whether the minima/maxima lied close to the low or high value of the parameter because this low or high value would be chosen for “test for a pair of variables” experiment.

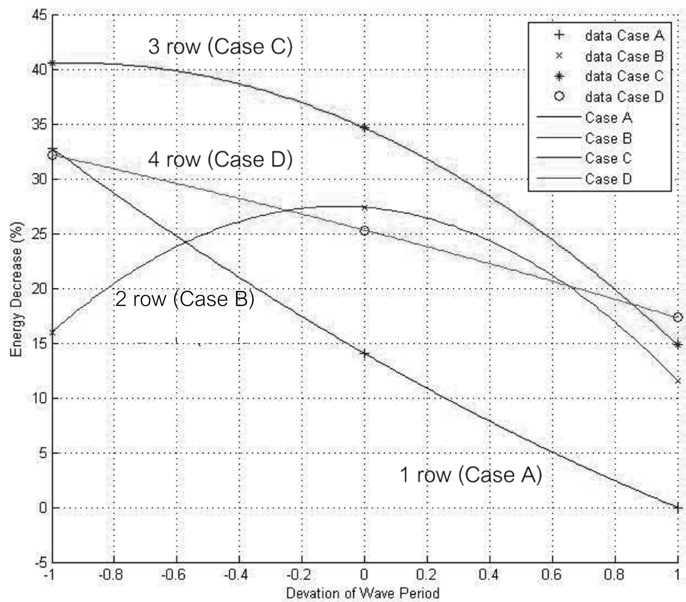
6. Test for a pair of variables was performed using information from step 5. Usually 4 tests must be carried out using low/low, low/high, high/low or high/high values of a pair of variables respectively while keeping the rest of the variables at the medium values. But to reduce a number of test runs, we chose the pair that most reduced the wave energy. For example, if percentage of wave energy reduction were high toward the low wave period and deep water, a test would be carried out using low wave period, high water depth, and medium values for the rest of the parameters. There would be a total of 15 experiments for 1-row piled breakwater and 21 experiments for each 2-row, 3-row and 4-row piled breakwater respectively. The technique that we use to design the experiment is called adaptive 2nd-order interpolating polynomial for n variables which was proposed by Ouypornprasert[(3)]. This technique was employed in order to reduce a number of experiments. For example, if we use conventional method, we need to perform a total of 1245 experiments in order to cover all the variable combination. But when we used this technique, we did only 136 experiments to come up with the optimum solution.

7. Compute and compare percentage of wave energy reduction for paired variables. The results were divided into 7 groups according to the chosen value of each parameter. The results also subdivided into groups of 1-, 2-, 3- and 4-row piled breakwaters experiments.

8. Last, construction costs and the effectiveness of the piled breakwaters were analyzed.

Result and Discussion

Figure 3 showed example of 2nd order polynomial curves for wave period variable with 1-, 2-, 3- and 4-row of piled breakwaters. The plot in the figure and the values in table indicated that 3-row piled breakwater near low wave period gave the best performance with 40% of wave energy reduction. The next best arrangements were 1-row and 4-row piled breakwaters respectively when wave period values were also near the low end. Only 2-row piled breakwater gave better performance when medium wave period value (1.5 s) was used. Other experiments which gave high wave energy reduction were 4-row breakwater with low spacing between piles in the same row (39%), 4-row breakwater with large spacing between row (39%), 4-row breakwater with high wave height (39%), and 3-row breakwater with narrow spacing between piles in the same row. It can be seen that either 3-row and 4-row piled breakwaters were more effective than the 1-row or 2-row ones.



Type of piled breakwater	Maximum point (X,Y)	2nd order polynomial
1 row	(-1,32.78)	$2.35X^2 – 16.39X + 14.04$
2 rows	(0.08,27.47)	$-13.585X^2 – 2.195X + 27.38$
3 rows	(-0.9,40.55)	$-6.955X^2 – 12.845X + 34.62$
4 rows	(-1,32.17)	$-0.56X^2 – 7.43X + 25.3$

Figure 3 2nd order polynomial curves over the experimental results when using wave periods of 0.9, 1.5 and 2.1 s respectively. There are 4 types of piled breakwater, namely 1-, 2-, 3- and 4-row piled breakwater. Table on the right gave the polynomial equations and their maximum points for each type of piled breakwaters.

Figure 4 showed percentage of wave energy reduction when pairing low wave period with either low or high values of another parameter. The results of using the medium values of all parameters were also presented (labeled “share” in the graph). The experimental results were grouped according to the type of piled breakwater (1 row, 2 rows, 3 rows, and 4 rows). Using medium values, the percentage of energy reductions varied with the type of piled breakwaters and the energy reductions were in the range of 14% - 35%. When using low wave period, the piled breakwaters performed better than the shared experiments excepted for the case of 2-row piled breakwater. And when varying wave period with another parameter, better performances were obtained at all cases for 2-row and 4-row piled breakwaters while mixed results were obtained for the cases of 1-row and 3-row piled breakwater respectively. The best performance in the figure and the best results for all experiments was achieved when combining short wave period with pile’s acute angle facing outward (0 degree alignment). There were 5 more paired combinations which could significantly reduce the wave energy as effectively as the above combination ($p \geq 0.05$, see Table 2)

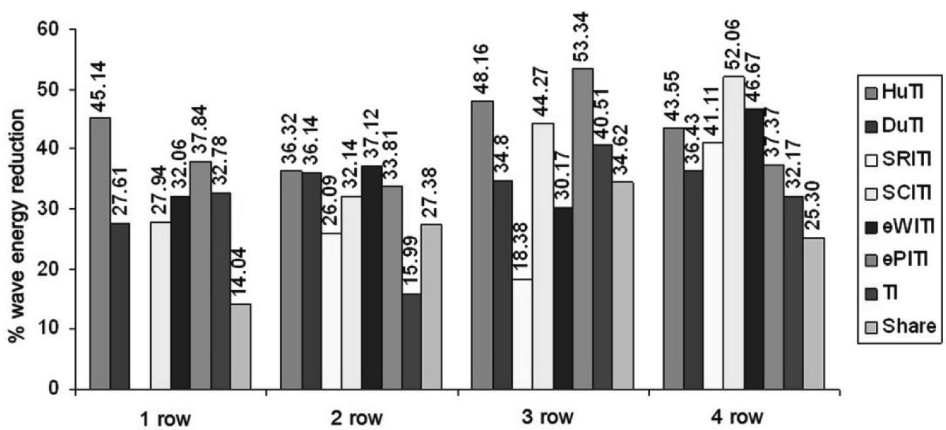


Figure 4 Percentage of wave energy reduction when combining wave period of 0.9 s with another variable. The results were grouped according to the number of row in the breakwater. (Hu = high wave height, Tl = low wave period, Du = high water depth, SRl = low spacing between row, SCl = low spacing between pile in the same row, θPl = incident wave hit perpendicular to the breakwater, θWl = pile’s acute angle facing outward, share = use medium value for every variable)

Table 2 Six paired combinations that gave high percentage of wave energy reduction. All came from 3- or 4-row piled breakwaters. Multiple comparisons have been performed on these combinations and the statistical results indicated that their effectiveness were not different (showing by drawing lines connecting mean values that were not different).

Rank	1	2	3	4	5	6
Case	3 rows	4 rows	4 rows	3 rows	4 rows	4 rows
	Tl - θWl	Du - SRl	Tl - SRl	Tl - Du	SRu - θWl	Tl - θPl
% reduction	53.34	53.27	52.06	48.16	47.90	46.67
	± 9.06	± 8.58	± 8.90	±11.86	±10.77	± 9.79

Remark: Tl = low wave period (0.9 s), θWl = pile's acute angle facing outward, Du = deep water (0.6 m), SRl = low spacing between row (0.2 m), SRu = large spacing between row (0.4 m), and θWl = incident wave hit perpendicular to the breakwater

In Table 2, 4 out of 6 experiments contained short wave period as their variable combinations. Three-row piled breakwater was more effective in reducing wave energy when using short wave period (0.9 s in the model which is equivalent to 2-s actual wave period). The wave length (λ) in the model at this wave period was about 1.2 m which was twice the thickness of the 3-row piled breakwater. Huygens-Fresnel Principle[4] stated that wave height would interfere negatively when the path lengths differ by λ/n where *n* is number of slit or opening. In this case *n* was equal to 2 and spacing between row (and spacing between pile in the same row) was equal half wave length. So there would be a chance when wave energy was lost within the breakwater (bottom scouring) beside wave reflection by the piles.

One experiment in Table 2 contained small spacing between piles (0.2 m) in the same row as variable. Friction due to the presence of pile columns would effectively reduce wave energy, especially with more rows of pile[5]. The experiment with high wave height also effectively reduced wave energy. The reason was that high wave height was not stable and tended to break when encountering the piled breakwater.

When piled breakwater was constructed at Ban Khun Samut Chin, no data was available for estimation cost .vs. effectiveness of the construction. Now the results from this physical experiment can be used to assess the best piled arrangement that would effectively reduce wave energy and use less money to construct. The information from the physical experiment indicates that 3- or 4-row piled breakwater with less spacing between piles in the same row would be more effective in reducing wave energy. Thus, we will compare only 3- and 4-row piled breakwater with 1-m spacing which give the best result and 1.5-m spacing which is the actual pile spacing at Ban Khun Samut Chin. The cost of piled breakwater consists of construction and transportation of the triangular piles and hammering each pile into place. Thus, the total cost of construction depends on a number of piles used. If we assume that each pile costs X Baht to build, to transport and to put into place, and we assume that the length of the piled breakwater is 1 km. Table 3 displays no. of piles used together with estimated cost and percentage wave energy reduction from the physical experiment. It can be seen that 3-row piled breakwater with 1.5-m spacing can reduce the same level of wave energy as the 4-row piled breakwater does but use less than half the money to construct. Thus, we can summarize that 3-row piled breakwater with spacing between piles in the same row about 3 times the side width of the equilateral triangular pile would be more effective in reducing wave energy and use less money to construct. And this arrangement has been used to construct the piled breakwater at Ban Khun Samut Chin.

Table 3 Comparison of construction costs and their effectiveness in reducing wave energy for 3- and 4-row piled breakwater 1 km long. The spacing between piles in the same row either 1 m or 1.5 m.

Type of piled breakwater	No. of piles used	Cost (Baht)	Percentage of wave energy reduction
3 rows of piles, 1 m spacing	2,400	2400 X	~ 27 – 44
4 rows of piles, 1 m spacing	3,200	3200 X	~ 22 – 53
3 rows of piles, 1.5 m spacing	1,500	1500 X	~ 18 – 53
4 rows of piles, 1.5 m spacing	2,000	2000 X	~ 20 – 48

Conclusion

To assess the effectiveness of the equilateral-triangular piled breakwater, the physical model was carried out at Civil Engineering Laboratory, Prince Songkhla University. The ratio of the prototype to the actual features was 5:1. Seven parameters that would contribute to the effectiveness of the piled breakwater were chosen and tested at pre-defined values (low, mean, high). And 1-, 2-, 3- and 4-row piled breakwater were tested in the wave tank. Wave height would be measured at a point in front of and behind the piled breakwater, and percentage of wave energy reduction for each run was computed. To reduce the number of experimental runs, initially one experiment was perform for each type of the piled breakwater where mean values were used for all 7 parameters. Then, at each experiment only the value of one parameter was allowed to vary from the mean value while using mean values for the rest of the parameters. The percentage of wave energy reduction was in the range of 0 - 41 when varying only one variable. The maximum wave energy reduction was highest when using short wave period with 3-row piled breakwater. A 2^{nd} order polynomial curve was fitted on to the percentage of wave energy reduction data of each parameter, and the maximum/peak point where the energy reduction would be highest was determined. Then another experiments were performed where combination of 2 variables were allowed to vary from the mean values while keeping the rest of the parameters at mean values. To avoid carrying out the experiment at values of the variables that would not give high percentage of wave energy reduction, only the variable values near the peak points were chosen for the experiment, thus further reducing the number of experiment. The experimental results showed that the highest wave energy reduction of about 53 percent was achieved when using short wave period with pile's acute angle pointing outward over 3-row piled breakwater. Combination of short wave period with some other variables over 3- or 4-row piled breakwater also gave high percentage of wave energy reduction.

From the physical model results, we found that the efficiency of the piled breakwater increases with increasing a number of rows of pile, wave height and spacing between rows while decreasing wave period, water depth, spacing between piles in the same row. And the piled breakwater was more effective when wave traveled in parallel to the breakwater and the acute angle of the concrete pole pointing outward. However, the construction cost of the breakwater was controlled by a number of piles used and the number of piles depended on spacing between piles in the same row and a number of rows constructed. The most efficient piled breakwater with the lowest construction cost was 3-row piled breakwater with spacing between piles in the same row about 3 times the side width of the equilateral triangular pile.

Acknowledgements

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