Maritime Technology and Research 2020; 2(1): 19-32 CrossMark https://doi.org/10.33175/mtr.2019.177366

Maritime Technology and Research

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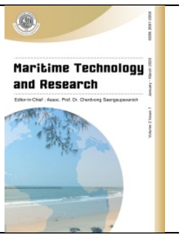

Research Article

Roughness coefficient of polyurethane-bonded revetment

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Article information
Received: March 13, 2019
Revised: April 17, 2019
Accepted: May 6, 2019

Keywords
Coastal protection structure,
Coastal erosion,
Alternative revetment,
Polyurethane revetment

Abstract

This article analyzed the roughness coefficient of polyurethane-bonded revetment (PBR) by laboratory testing. A wave basin was constructed, with a regular wave generator installed. Three types of revetment were constructed at the same time in the wave basin. Scales were painted on the revetments. Video cameras were installed to record the wave run-up. Measurments of wave height and wave period during the tests were not necessary, since a run-up estimation was entirely based on a linear relationship. The PBR's roughness coefficient could be interpolated from those of rock and concrete revetments. Three revetment slopes were tested. The roughness coefficient of the PBR was found to be in the range of 0.632 - 0.674, with a standard deviation of 0.042 - 0.053. Following this identification of the roughness coefficient of PBR, coastal engineers can now design revetment crest elevations with confidence.

1. Introduction

Coastal erosion is a problem that can be found in sea-connected nations (Cao and Wong, 2007; Cicin-Sain and Knecht, 1998; Cellone et al., 2016; Fitton et al., 2016; Houwing, 2000; Lin, 1996). Coastal protection is necessary, because it mitigates damage to buildings, infrastructures, and other facilities that are important to coastal communities (Saengsupavanich et al., 2008; Saengsupavanich, 2013). Coastal protection must rely on the understanding of physical, environmental, and social surroundings. Different locations have different environments, therefore demanding different coastal protection measures. A certain coastal protection method suitable for one site may not be appropriate for another area (US Army Corps of Engineers, 2006).

Thailand has a coastline longer than 2,600 km, 1,660 of which border the Gulf of Thailand, with the rest bordering the Andaman Sea (Sudara, 1999). Thailand's shoreline is diverse, comprising sandy, rocky, and muddy coasts. Current erosion protection measures can be divided into 2 categories: hard and soft options (Williams et al., 2019). The hard option is related to constructing engineering structures to resist wave force, such as offshore breakwaters, groins, or revetments (Saengsupavanich, 2017). The soft option deals with coastal erosion with non-structural

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measures, such as mangrove reforestation, set-back lines, and settlement retreats (Cicin-Sain & Knecht, 1998). Coastal inhabitants who suffer from coastal erosion usually prefer the structural measure, since it is effective and can protect their properties immediately. However, constructing coastal revetments may result in reduced scenic beauty. Rock quarry may not be available in some remote area or islands. As the result, a polyurethane-bonded revetment (PBR) has been developed to solve such problems.

PBR is a coastal protection structure constructed from small aggregates bonded with liquid polyurethane (**Figure 1**). Its appearance looks like pebbles on a swimming pool floor. Sand particles can be plastered on the PBR surface, making it look similar to a natural sandy beach. Although there is a lot of literature on other types of coastal revetment (US Army Corps of Engineers, 2006), there is very little about PBR. This article focuses on the surface roughness of PBR, which is one of the fundamental design parameters. The surface roughness leads to estimations of wave run-up and overtopping discharge, which will determine the revetment's crest elevation, as well as the design of the drainage system for the overtopping wave.

Figure 1 A polyurethane-bonded revetment in Thailand.

2. Methodology

This research attempted to determine the roughness coefficient (γ_r) of PBR. This section is divided into 2 parts. The first part explains related concepts about wave run-up; the second part deals with an experimental setup.

2.1 Wave run-up theory and how to estimate the γ_r of the PBR

When waves hit a revetment, the waves flow up the revetment's slope. Wave run-up is defined as a vertical distance between a still water level and the highest point where water can reach during the wave uprush. The wave run-up level is one of the most important factors affecting the design of coastal structures, because it determines the design crest level of the structure in cases where no (or only marginal) overtopping is acceptable. Empirical formulas have been proposed by many researchers (Ahrens, 1981; Battjes, 1974; Van Oorschot and d'Angremond, 1968) in the form of linear equation with reduction factors {Eq. (1)}.

$$\frac{R_{ui\%}}{H_s} = \left(A\xi + C\right)\gamma_r\gamma_b\gamma_h\gamma_\beta \tag{1}$$

when $R_{ui\%}$ is run-up level exceeded by i percent of the incident waves, H_s is significant wave height at the top of the structure (m), ξ is a surf-similarity parameter, γ_r is a reduction factor related to the structure's surface roughness, γ_b is a reduction factor related to the structure's berm, γ_h is a reduction factor for influence of shallow-water conditions where the wave height distribution deviates from the Rayleigh distribution, and γ_β is a reduction factor for influence of angle of incidence of the waves (US Army Corps of Engineers, 2006).

The wave run-up depends on surface roughness. de Waal and van der Meer (1992) recommended the γ_r of a rock revetment of 0.5 - 0.55, while a concrete revetment has the γ_r of 1.0. It can be noticed from Eq. (1) that the run-up estimation is entirely based on a linear relationship. If both ends of the linear curve are known, it is possible to interpolate the γ_r of the PBR (**Figure 2**). This approach is valid only if all other parameters are the same.

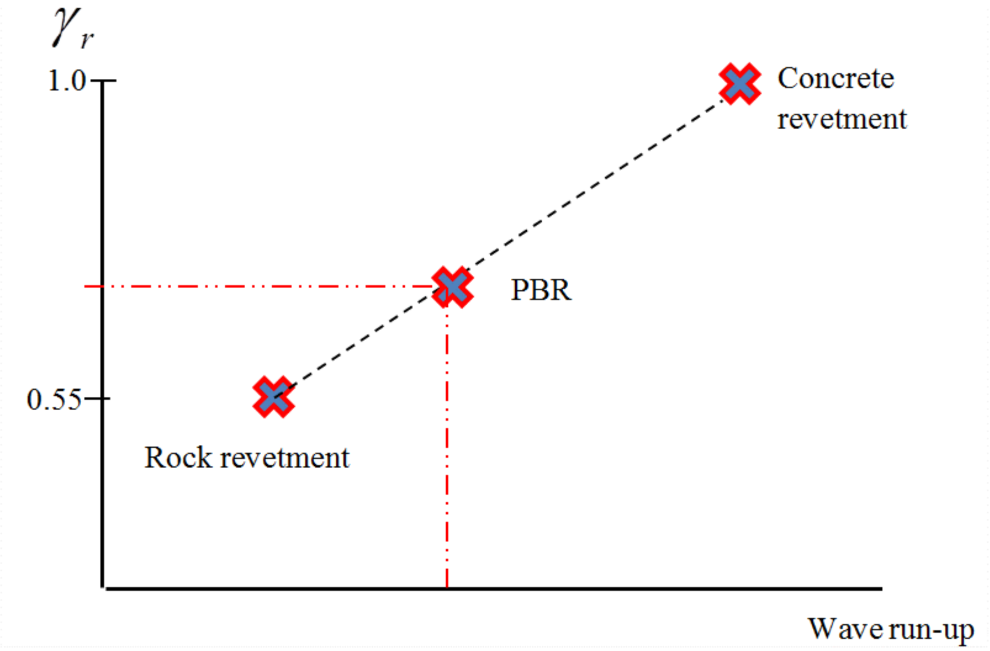

Figure 2 A concept to estimate the γ_r of the PBR.

2.2 Laboratory experiment

A wave basin of 8.94×19.94×1.5 m^3 (wide×long×deep) was constructed with a regular wave generator installed (**Figure 3**). Three types of revetment were constructed at the same time in the wave basin. Since the wave basin's width was 8.94 m, each type of revetment was 2.98 m (**Figure 4**), big enough to allow the authors to clearly record the run-up data. Scales were painted on the revetments. Three video cameras were installed along each side of the basin to record the wave run-up. Three revetment slopes, being 1:1, 1:1.5, and 1:2 (vertical:horizontal), were tested. One hundred regular waves were generated for each slope to anyayze the run-up (**Figure 5**).

Figure 3 A wave basin of 8.94×19.94×1.5 m^3 (wide×long×deep) (picture taken 1 November 2018).

Figure 4 Three types of revetment in the same wave basin (picture taken 13 November 2018).

Figure 5 Wave run-up on different revetments at the same time (picture taken 25 November 2018).

3. Results

The concept of testing 3 types of revetment at the same time was to neglect other parameters in Eq. (1). It was not necessary to know wave height in the wave basin, since the wave parameters were similar. What was different was only the roughness coefficient. The results are shown in **Table 1**. Recorded data can be found in **Appendixs 1 - 3**.

It was revealed that the wave run-up of the PBR was greater than that of the rock revetment, but less than that of the concrete surface. This led to an implication that the roughness of the polyurethane-bonded aggregate was able to reduce the run-up almost as much as the rock surface.The mean value of γ_r of the PBR was in the range of 0.632 - 0.674, with the standard deviation of 0.042 - 0.053.

Table 1 Mean value of γ_r of the PBR.

Slope	**Mean value of γ_r of the PBR**	**Standard deviation**
1:1	0.632	0.049
1:1.5	0.632	0.053
1:2	0.674	0.042

4. Discussion

Polyurethane-bonded revetment (PBR) is an alternative coastal protection structure to common revetments constructed from rocks or concrete. Its advantages include easy constructibility and an appearance that, when covered with sand, looks similar to a natural sandy beach. Its application is still limited. One of the reasons that it has not been applied is the lack of related research. Various design parameters of the PBR are still being assessed. This research focuses on the roughness coefficient of PBR.

The design of coastal revetment involves many structural components. Crest elevation plays an important role in limiting damage that may occur to properties on shore. The rougher the revetment surface, the lesser the roughness coefficient, and the lower the crest elevation. Many researchers have also proposed roughness coefficients for alternative revetments (van Steeg et al., 2016; van Steeg et al., 2018). Liebisch et al. (2012) studied the effect of the porosity of revetments on wave run-up and run-down, wave-induced loads on and beneath the revetment, and wave-induced pore pressures in the sand core under the revetment. Their results found that, with increasing porosity, the wave run-up height decreases significantly, due to the infiltration of the up-running water mass into the porous structure and the corresponding higher turbulences and energy dissipation. The highest wave run-up for the impermeable revetment was reduced by more than 20 % on the high porous revetment. The results of this study revealed that the roughness of the PBR is less than that of rock revetment, but greater than concrete revetment. Therefore, the crest elevation of the PBR can be lowered, compared to the concrete structure. The roughness coefficient of the PBR is found to be in the range of 0.632 - 0.674, with a standard deviation of 0.042 - 0.053, while the roughness coefficient of the rock revetment is theoretically 0.55, and the roughness coefficient of the concrete revetment is theoretically 1.0 (de Waal & van der Meer, 1992). In some areas where there is no rock quarry, big rocks may not be possible to obtain. A PBR may be preferred to a concrete revetment, based on the criteria of wave dissipation effectiveness and Nature-like beauty. Future research on PBR is still needed, such as its durability in tropical areas, ultraviolet and salinity resistance, microplastic dissolution, and toxicity to marine animals and plants.

This reseach focuses only on the wave run-up, which is only one of the design components. Succesful coastal protection must fullfil engineering, social, environmental, and financial criteria. When choosing what type of revetment is suitable for a certain site, other factors may come into consideration. Construction costs, stakeholders' acceptance, environmental impacts, maintenance availability, and other factors should be considered as well. Coastal engineers must select the most appropriate coastal protection structure that can fulfill most requirements. Sometimes, the most suitable coastal protection structure may not be the cheapest structure, nor the most hydraulically effective one.

5. Conclusions

Polyurethane-bonded revetment (PBR) can be useful when coastal engineers must design a coastal protection structure at a remote location where other construction materials are unavailable. PBR's capability to reduce wave run-up is better than that of concrete revetment. Other advantages of PBR include its appearance, its constructability, its material availability, and its transportability. After the roughness coefficient of PBR is found, coastal engineers can now design revetment crest elevations with confidence.

Acknowledgment

The authors are grateful for all supporting staff. The research was funded by the "Talent Mobility" program in 2017 (3rd round), under the Office of the Higher Education Commission and the National Science Technology and Innovation Policy Office, Thailand. The funded project name was "Coastal protection structure from Polyurethane; effectiveness, durability, and environment".

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Appendix 1 Run-up heights of different types of revetments (slope 1.2).

ID	Wave run-up of concrete revetment (cm)	Wave run-up of PBR (cm)	Wave run-up of rock revetment (cm)	Calculated γ_r
1	73.292	55.464	45.560	0.711
2	71.311	54.473	46.550	0.694
3	72.301	55.464	47.540	0.694
4	76.263	53.483	46.550	0.655
5	73.292	53.483	49.521	0.625
6	77.253	53.483	51.502	0.585
7	75.272	52.493	51.502	0.569
8	70.320	52.493	48.531	0.632
9	72.301	54.473	46.550	0.688
10	78.244	53.483	46.550	0.648
11	69.330	55.464	45.560	0.738
12	71.311	52.493	48.531	0.628
13	73.292	52.493	50.512	0.589
14	68.339	54.473	52.493	0.606
15	73.292	53.483	50.512	0.609
16	77.253	56.454	49.521	0.663
17	78.244	57.445	47.540	0.695
18	77.253	55.464	48.531	0.659
19	73.292	54.473	49.521	0.644
20	70.320	56.454	47.540	0.726
21	73.292	57.445	50.512	0.687
22	75.272	56.454	47.540	0.695
23	71.311	57.445	49.521	0.714
24	77.253	57.445	51.502	0.654
25	73.292	54.473	48.531	0.658
26	71.311	53.483	50.512	0.614
27	75.272	53.483	47.540	0.646
28	74.282	52.493	49.521	0.604
29	82.205	53.483	49.521	0.605
30	78.244	53.483	48.531	0.625
31	79.234	53.483	49.521	0.610
32	76.263	55.464	50.512	0.637
33	69.330	56.454	47.540	0.734
34	77.253	55.464	48.531	0.659
35	76.263	55.464	46.550	0.685
36	74.282	56.454	45.560	0.721
37	73.292	57.445	47.540	0.723
38	79.234	59.426	47.540	0.719
39	78.244	58.435	49.521	0.690
40	79.234	56.454	50.512	0.643
41	75.272	57.445	48.531	0.700
42	74.282	56.454	47.540	0.700
43	76.263	57.445	48.531	0.695
44	77.253	54.473	50.512	0.617
45	82.205	53.483	51.502	0.579
46	77.253	54.473	49.521	0.630

ID	Wave run-up of concrete revetment (cm)	Wave run-up of PBR (cm)	Wave run-up of rock revetment (cm)	Calculated γ_r
47	85.177	60.416	52.493	0.659
48	81.215	53.483	49.521	0.606
49	82.205	54.473	48.531	0.629
50	76.263	53.483	46.550	0.655
51	77.253	53.483	49.521	0.614
52	82.205	56.454	47.540	0.666
53	79.234	55.464	48.531	0.652
54	78.244	56.454	48.531	0.670
55	79.234	57.445	46.550	0.700
56	82.205	57.445	48.531	0.669
57	80.225	58.435	49.521	0.681
58	81.215	55.464	48.531	0.645
59	73.292	57.445	49.521	0.700
60	79.234	58.435	50.512	0.674
61	73.292	57.445	50.512	0.687
62	78.244	57.445	49.521	0.674
63	76.263	57.445	47.540	0.705
64	75.272	56.454	46.550	0.705
65	79.234	57.445	47.540	0.691
66	76.263	57.445	48.531	0.695
67	71.311	57.445	46.550	0.748
68	72.301	58.435	47.540	0.748
69	76.263	56.454	48.531	0.679
70	76.263	56.454	46.550	0.700
71	69.330	56.454	49.521	0.708
72	72.301	56.454	47.540	0.712
73	71.311	54.473	50.512	0.636
74	76.263	55.464	49.521	0.650
75	78.244	56.454	48.531	0.670
76	82.205	59.426	52.493	0.655
77	69.330	56.454	50.512	0.692
78	68.339	56.454	49.521	0.716
79	73.292	57.445	48.531	0.712
80	74.282	57.445	47.540	0.717
81	73.292	55.464	46.550	0.700
82	73.292	57.445	49.521	0.700
83	76.263	58.435	47.540	0.721
84	78.244	57.445	48.531	0.685
85	75.272	58.435	46.550	0.736
86	76.263	57.445	49.521	0.683
87	75.272	58.435	50.512	0.694
88	77.253	58.435	48.531	0.705
89	76.263	58.435	49.521	0.700
90	75.272	56.454	49.521	0.671
91	78.244	56.454	50.512	0.646
92	77.253	57.445	49.521	0.679
93	75.272	57.445	48.531	0.700
94	75.272	56.454	48.531	0.683

ID	Wave run-up of concrete revetment (cm)	Wave run-up of PBR (cm)	Wave run-up of rock revetment (cm)	Calculated γ_r
95	74.282	56.454	48.531	0.688
96	77.253	55.464	49.521	0.646
97	71.311	57.445	47.540	0.737
98	72.301	59.426	47.540	0.766
99	70.320	57.445	49.521	0.721
100	75.272	56.454	48.531	0.683

Appendix 2 Run-up heights of different types of revetments (slope 1.1.5).

ID	Wave run-up of concrete revetment (cm)	Wave run-up of PBR (cm)	Wave run-up of rock revetment (cm)	Calculated γ_r
1	41.948	25.169	13.728	0.732
2	40.422	25.169	11.440	0.763
3	39.660	22.881	13.728	0.709
4	40.422	23.643	14.491	0.709
5	39.660	22.881	14.491	0.700
6	40.422	25.169	16.016	0.719
7	40.422	24.406	16.779	0.695
8	38.134	23.643	15.254	0.715
9	38.134	23.643	16.016	0.705
10	38.134	25.169	16.779	0.727
11	39.660	23.643	14.491	0.714
12	39.660	24.406	16.016	0.710
13	41.185	19.067	16.016	0.605
14	41.185	25.169	17.542	0.695
15	40.422	22.118	16.016	0.663
16	41.185	23.643	16.779	0.677
17	38.897	24.406	16.016	0.715
18	38.134	20.592	16.779	0.630
19	39.660	25.931	17.542	0.721
20	39.660	24.406	16.779	0.700
21	40.422	23.643	18.304	0.659
22	41.185	23.643	15.254	0.696
23	40.422	23.643	16.016	0.691
24	40.422	22.881	16.779	0.666
25	39.660	23.643	17.542	0.674
26	39.660	23.643	16.779	0.685
27	40.422	22.881	16.016	0.677
28	38.897	22.118	16.779	0.659
29	38.897	22.118	18.304	0.633
30	39.660	23.643	19.067	0.650
31	39.660	22.881	17.542	0.659
32	41.948	22.118	18.304	0.623
33	42.710	23.643	17.542	0.659
34	39.660	22.881	16.016	0.681
35	41.185	23.643	17.542	0.666
36	41.948	25.169	19.830	0.659

ID	Wave run-up of concrete revetment (cm)	Wave run-up of PBR (cm)	Wave run-up of rock revetment (cm)	Calculated γ_r
37	43.473	23.643	22.118	0.582
38	41.948	22.881	19.067	0.625
39	42.710	23.643	17.542	0.659
40	45.761	22.881	16.779	0.645
41	42.710	23.643	16.016	0.679
42	44.998	22.118	15.254	0.654
43	41.948	22.881	17.542	0.648
44	41.948	23.643	19.067	0.640
45	41.185	22.881	19.067	0.628
46	41.948	23.643	19.830	0.628
47	44.998	24.406	19.067	0.643
48	45.761	22.881	18.304	0.625
49	44.998	22.881	17.542	0.638
50	44.236	20.592	16.779	0.612
51	44.998	20.592	15.254	0.631
52	45.761	20.592	16.016	0.619
53	42.710	21.355	16.779	0.629
54	43.473	20.592	16.016	0.625
55	42.710	20.592	16.779	0.616
56	43.473	22.118	15.254	0.659
57	44.998	22.881	16.779	0.647
58	42.710	21.355	19.067	0.594
59	40.422	21.355	21.355	0.550
60	48.812	25.931	22.118	0.614
61	41.948	22.118	21.355	0.567
62	48.812	25.931	22.118	0.614
63	40.422	20.592	19.830	0.567
64	41.185	20.592	19.067	0.581
65	39.660	22.118	19.830	0.602
66	40.422	25.931	22.118	0.644
67	41.185	19.830	21.355	0.515
68	41.948	20.592	21.355	0.533
69	39.660	19.830	19.067	0.567
70	40.422	20.592	19.067	0.582
71	41.948	21.355	18.304	0.608
72	45.761	21.355	18.304	0.600
73	43.473	22.881	19.830	0.608
74	45.761	21.355	21.355	0.550
75	46.524	22.118	19.067	0.600
76	45.761	21.355	16.016	0.631
77	44.236	20.592	17.542	0.601
78	44.998	20.592	17.542	0.600
79	45.761	21.355	18.304	0.600
80	45.761	21.355	19.830	0.576
81	44.236	20.592	20.592	0.550
82	46.524	20.592	19.067	0.575
83	43.473	20.592	19.830	0.565
84	44.236	19.830	21.355	0.520

ID	Wave run-up of concrete revetment (cm)	Wave run-up of PBR (cm)	Wave run-up of rock revetment (cm)	Calculated γ_r
85	48.049	20.592	20.592	0.550
86	48.049	19.830	19.067	0.562
87	41.948	19.830	19.067	0.565
88	45.761	21.355	18.304	0.600
89	45.761	19.830	19.067	0.563
90	44.998	22.118	18.304	0.614
91	45.761	22.881	19.067	0.614
92	46.524	22.118	19.830	0.589
93	47.286	22.118	17.542	0.619
94	46.524	22.118	16.779	0.631
95	47.286	20.592	18.304	0.586
96	45.761	20.592	19.067	0.576
97	44.998	22.881	19.830	0.605
98	45.761	22.118	19.067	0.601
99	44.998	22.881	20.592	0.592
100	42.710	22.881	19.067	0.623

Appendix 3 Run-up heights of different types of revetments (slope 1.1).

ID	Wave run-up of concrete revetment (cm)	Wave run-up of PBR (cm)	Wave run-up of rock revetment (cm)	Calculated γ_r
1	38.291	22.124	13.615	0.705
2	23.825	13.615	12.764	0.585
3	33.185	17.869	14.465	0.632
4	32.334	17.869	11.062	0.694
5	30.633	16.167	9.360	0.694
6	30.633	15.316	11.913	0.632
7	35.738	16.167	9.360	0.666
8	31.483	17.018	11.062	0.681
9	34.036	17.018	11.913	0.654
10	33.185	15.316	14.465	0.570
11	28.080	16.167	12.764	0.650
12	28.931	14.465	14.465	0.550
13	27.229	13.615	12.764	0.576
14	28.931	15.316	11.062	0.657
15	27.229	15.316	13.615	0.606
16	26.378	15.316	14.465	0.582
17	26.378	16.167	14.465	0.614
18	25.527	16.167	13.615	0.646
19	25.527	17.018	12.764	0.700
20	24.676	15.316	12.764	0.646
21	26.378	14.465	11.913	0.629
22	27.229	14.465	14.465	0.550
23	26.378	14.465	11.062	0.650
24	24.676	13.615	12.764	0.582
25	26.378	12.764	11.913	0.576
26	27.229	11.913	11.062	0.574

ID	Wave run-up of concrete revetment (cm)	Wave run-up of PBR (cm)	Wave run-up of rock revetment (cm)	Calculated γ_r
27	24.676	11.913	9.360	0.625
28	27.229	13.615	11.913	0.600
29	26.378	14.465	12.764	0.606
30	28.931	15.316	14.465	0.576
31	28.080	15.316	15.316	0.550
32	24.676	16.167	14.465	0.625
33	37.440	18.720	16.167	0.604
34	27.229	17.018	14.465	0.640
35	28.931	17.018	13.615	0.650
36	31.483	16.167	12.764	0.632
37	31.483	16.167	11.062	0.663
38	32.334	14.465	11.913	0.606
39	29.782	14.465	13.615	0.574
40	33.185	15.316	11.913	0.622
41	34.036	15.316	11.062	0.633
42	35.738	17.018	10.211	0.670
43	33.185	15.316	11.913	0.622
44	34.036	16.167	12.764	0.622
45	33.185	15.316	14.465	0.570
46	35.738	15.316	11.913	0.614
47	**37.440**	**18.720**	**14.465**	0.633
48	33.185	15.316	11.913	0.622
49	32.334	13.615	14.465	0.529
50	**38.291**	**18.720**	**16.167**	0.602
51	28.931	14.465	15.316	0.522
52	28.931	14.465	11.913	0.618
53	29.782	14.465	12.764	0.595
54	29.782	14.465	13.615	0.574
55	27.229	13.615	11.913	0.600
56	26.378	13.615	11.062	0.625
57	25.527	14.465	11.913	0.634
58	27.229	15.316	9.360	0.700
59	31.483	15.316	12.764	0.611
60	29.782	17.018	13.615	0.645
61	27.229	18.720	14.465	0.700
62	29.782	15.316	14.465	0.575
63	28.931	16.167	15.316	0.578
64	26.378	17.018	13.615	0.670
65	27.229	15.316	14.465	0.580
66	27.229	15.316	12.764	0.629
67	28.931	15.316	11.913	0.640
68	23.825	15.316	11.062	0.700
69	25.527	14.465	9.360	0.692
70	24.676	14.465	10.211	0.682
71	27.229	15.316	9.360	0.700
72	25.527	15.316	10.211	0.700
73	28.931	14.465	11.913	0.618
74	26.378	13.615	11.062	0.625

ID	Wave run-up of concrete revetment (cm)	Wave run-up of PBR (cm)	Wave run-up of rock revetment (cm)	Calculated γ_r
75	22.974	12.764	11.062	0.614
76	23.825	13.615	11.913	0.614
77	25.527	14.465	13.615	0.582
78	27.229	15.316	13.615	0.606
79	26.378	15.316	12.764	0.634
80	25.527	14.465	13.615	0.582
81	29.782	13.615	12.764	0.573
82	27.229	14.465	11.913	0.625
83	23.825	14.465	14.465	0.550
84	25.527	14.465	11.913	0.634
85	24.676	14.465	11.062	0.663
86	25.527	15.316	11.062	0.682
87	22.124	15.316	13.615	0.640
88	22.974	15.316	13.615	0.632
89	21.273	15.316	12.764	0.685
90	23.825	17.018	11.062	0.760
91	24.676	14.465	10.211	0.682
92	26.378	15.316	9.360	0.708
93	25.527	14.465	9.360	0.692
94	27.229	14.465	10.211	0.663
95	23.825	17.018	11.062	0.760
96	25.527	15.316	11.062	0.682
97	26.378	17.018	11.913	0.709
98	25.527	15.316	13.615	0.614
99	22.124	17.018	14.465	0.700
100	22.124	16.167	12.764	0.714