The performance of low crested breakwaters as a sand trap for shore protection

Fikri Aris Munandar¹, Radianta Triatmadja²*, Nur Yuwono²

¹Magister Student of Civil Engineering Program, Gadjah Mada University,
²Lecturer of Civil and Environmental Engineering Department, Gadjah Mada University.
*) Corresponding author, email : radianta@ugm.ac.id

Abstract: The low crested breakwater (LCB) is considered as a new coastal protective structure which has not been widely used compared to other coastal protection structures. LCB has more advantages than conventional ones such as breakwaters, requiring lower cost and aesthetically not disturbing nature because of its position which is below sea level so it is suitable for beach tourism.

Studies on low crested breakwaters are mostly about the ability to absorb energy waves and how beach responded to the structure. However, the study on the ability of this low crested breakwater such as a sand trip is still limited. Therefore, this study aims to observe the breakwater's performance as a sand trap for shore protection and the effect of the parameters on the performance.

This study was conducted on the plexiglass wave made with a length of 18 m, a width of 0.3 m and a depth of 0.45 m. Wave parameters (height and period) and structure parameters (height and width) were employed as a reference in this study. This research was conducted by varying the waves, height and water depth. The results indicate that the number of transport sediment tends to be increased following the wave height (Hi), the water depth at the height of the structure (Rc) and reduced wavelength (L). The type and position of a wave breaking also affect the amount of transport sediment.

Keywords: beach erosion, sediment suspension, sand trap, low crested breakwaters

1. Introduction

A low crested breakwater (LCB) is a shore protection structure built along the shoreline with its crest below water level (MSL) or slightly appears on the surface [1]. LCB serves to reduce the wave energy so that the wave energy to the coast becomes lower and causes minimum damage. Besides, it also serves to hold the sediment transport in the coastal area because the position of LCB enables the sediment transporting from the front of the structure to the backside of the structure but restraint them from returning back to the front side since the wave energy at the backside is smaller. The sediment may become salient and change the shoreline position [2].

In the early 1960s, the low crested breakwater was used to protect the harbor entrance of the harbor pool, dampen the waves and reduce sediment of the port [3]. The last few years the LCB becomes popular as the shore protector is able to provide protection well [4] without damaging the aesthetic value of the coast [5]. In Indonesia, the use of low crested breakwaters as coastal protection
is relatively new and not widely used [6]. Some places in Indonesia have used LCB as the shore protection, such as Tanjung Kait Beach and Sigandu beach [7,8].

Studies on the effects of low crested breakwater have been widely conducted [9,10] using numerical methods [11,12] or physical models [13,14]. Similarly, studies on the coast response to the low crested breakwaters [15,16] and its effectiveness [17,18]. However, studies on the performance of low crested breakwaters as a sand trap are very limited. Therefore, this study was conducted by observing the parameter effects related to the amount of transported sediment from the front to the backside of the low crested breakwater. The study is limited to the sediment transport from the sea side to the backside of the structure. This current study was conducted in the laboratory with a smaller scale but high congruency.

2. Literature review

2.1 Geometry and Degrees of the LCB

The main parameter used in describing the geometry of the LCB [7] is shown in Figure 1. In this case h is structure height, d is water depth, and Rc is water depth at the structure crest. One important parameter that determines the effectiveness of the LCB is the degree of submergence of the structure which can be explained by three parameters, namely:
1. Submergence = d / h,
2. The structure height = h / d,
3. The ratio between water depth at structure crest and water depth = Rc / d

![Figure 1. Low crested breakwaters cross-section.](image)

2.2 Wave Breaking

The waves affect the process of deposition and erosion on the coast. Iversen [19] first classified three types of wave breaking: spilling, plunging and surging. Galvin [20] then added the fourth type, namely collapsing. Spilling and plunging are the two types which are being investigated the most [21]. The spilling occurs when the wave swept to the coast with a sloping base. The crest of the breaking wave looks like bubbles or froth during spilling. Plunging occurs when the waves swept through the sloping beach. In this type of wave, a wave with a slope closer to the front beach is vertical; the wave crest then will be rolled forward, and finally plunged ahead.

One of the most important factors in the process of wave breaking is the limit of the water depth in term of wave height. Approximately, in very small slope (1: 1000), the wave is breaking when h/d approximately 0.78. A higher slope leads to slightly higher ratio of breaking wave. In this study, the basic conditions of the structure was arranged to obtain the desired wave breaking by limiting the depth.

2.3 Sediment Transport by Waves

Based on the Shield theory, sediment particles will move if the driving energy in the sediment particles exceed the stabilizing force, thus sediment will begin to transport. If the external energy caused by waves and currents work on the sediment surface is strong enough, the bottom material will
move from the seabed and will be suspended and the sediment in the bottom layer of the structure will rise to the crest.

Studies in the laboratory [22,23] and field studies [24,25] point out that the majority of suspended sediments occur in the area of wave breaking. This occurs because the turbulence arising from breaking waves transport the sediments [26–28] and lift it into the sediment suspension [10,29]. This process is highly dependent on the characteristics of wave breaking, plunging type is more effective in transporting sediment than spilling types [30]. This is related to the turbulence produced, if a plunging type generates greater turbulence, it will provide greater influence on sediment than on the spilling type [21].

Van Til [28] explains that when turbulence occurs, the bottom sediment will be suspended then the sediment will be carried away by the flow of onshore-offshore arising from a wave breaking.

2.4 Scour on Low crested breakwaters

Dewi [31] describes that scour can occur because of the flow towards the shore hits the shore protection structure, causing crash around buildings that lifted sediments. The sediments are then carried by the flow. Scour depth increases as the wave steepness increases (H / L). The steeper the wave, the greater the scour depth occurred around the breakwater.

2.5 The Switching Volume of Sediment

Dewi [31] conducted a similar study by varying the bottom slope. When the value of the basic slope is 0 obtained, the tendency of sediment volume was up against the coming wave height (Hi), freeboard (Rc) and wavelength (L). Meanwhile, after a slope of coastline is included, the tendency of sediment volume decreases as the increasing wave heights (Hi), freeboard (Rc) and wavelength (L).

2.6 Non-Dimensional Parameters

The parameters that influence the process of sediment transport around the LCB is the structure height (h), the width (b), the water depth on the structure crest(Rc), the wave height (Hi), the wavelength (L), the wave period (T), water depth (d), and the sand density (ρs). These parameters are formed into a dimensionless parameter using the stepwise method. The results can be seen in Table 1.

| Repeated variables | Dimension | b | h | Rc | T | Hi | d | L | ρs |
|-------------------|-----------|---|---|----|---|----|---|----|----|
| ρs (M / L^3)      | M         | 0 | 0 | 0  | 0 | 0  | 0 | 0  | 1  |
|                   | L         | 1 | 1 | 1  | 0 | 1  | 1 | 1  | -3 |
|                   | T         | 0 | 0 | 1  | 0 | 0  | 0 | 0  | -  |
| ρs (M / L^3)      | T         | 0 | 0 | 0  | 1 | 0  | 0 | 0  | -  |
|                   | L         | 1 | 1 | 1  | -| 1  | 1 | 1  | -  |

Based on the results obtained from dimensional analysis, the parameters used for the data include b/L, h/L, Rc/L, Hi/L, d/L. In the previous study [31], the parameters Hi / L and Rc / L were combined to Hi.Rc/L^2 to present the results. These parameters are used because they can present a better and more effective result.
3. Research Methods

3.1 Research Location
This research was conducted at the Laboratory of Hydrology-Hydraulics, Center for Engineering Research Center, Gadjah Mada University. The Flume has the following specifications. The length is 18 m, the width is 0.3 m, and the depth is 0.45 m.

3.2 The LCB Shape
In this study, the LCB were made of PVC pipe with a diameter of 11.2 cm which filled with concrete as ballast. The bottom material was colored sand with a thickness of 10 cm and D50 = 0.2 mm. The use of colored sand aims to ease the researcher to observe the sediment movement either, from the seaside or from the backside. Sediment measurements was performed using sediment catchers [32,33] with a size of 60 x 30 x 5cm which were placed behind the LCB. The low crested breakwater is running for four hours each test. The duration was selected so that the volume of the sediment transported was easily measurable. However, there was as situation where no transport of sediment was observed. The 4 hours duration was enough to make sure that the transport of sediment did not occur. The parameters that were adopted for the experiment are given in the following section.

3.3 Parameter Variations
Variations in parameters in this research are presented in Table 2.

| Variation | d (cm) | h (cm) | d / h | Rc / d |
|-----------|--------|--------|-------|--------|
| 1         | 20     | 11     | 1.82  | 0.45   |
| 2         | 17     | 8      | 2:13  | 0.53   |
| 3         | 14     | 5      | 2.80  | 0.64   |
| 4         | 11     | 2      | 5.50  | 0.82   |

The breaking wave conditions were determined by the wave period (T). At T =0.84 seconds there was no breaking wave. The wave starts breaking at T approximately 0.79 seconds or higher.

4. Result and Discussion

4.1 Sediment Transport
The deposited sediment is given in Table 3 as the result of four hours running duration.

- Variation 1: d = 20 cm, h = 11 cm.

| T      | H/L | H1.Rec/L² | Zmax | Zmax/h | Sediment (g) |
|--------|-----|-----------|------|--------|--------------|
| 0.84   | 0.074 | 0.007    | 0.03 | 0.27   | 0            |
| 0.79   | 0.09  | 0.009    | 0.03 | 0.27   | 0            |

Table 3 shows the result of the first variation. It was performed under two conditions, namely T = 0.84 seconds (the waves did not break) with H / L = 0.074 and T = 0.79 sec (breaking wave) with H / L = 0.12. Zmax is the maximum value of the high suspended sediment. At the end of the running sediment transport across the LCB was not found.

On the condition where the wave did not break, the bottom sediment was transported to form a ripple in front of the structure. Based on the observations, the height of the sediment suspension was 3 cm above the bottom or 27% of the LCB height. Because the the suspension was under the LCB crest, the suspended sediment could not pass through the LCB. A similar effect occurred when the low crested breakwater was run under spilling breaking wave that occurred in front of the structure. The turbulence that was caused by breaking waves was not
strong enough to lift up the sediment to pass through the LCB crest. The height of sediment suspension was also approximately 27% of the LCB height.

![Figure 2. Description of result at Run number 1. a) annotation; b) photo of experiment.](image)

- **Variation 2**: $d = 17 \text{ cm}, h = 8 \text{ cm}$

Table 4. The results of Variation 2.

| $T$ | $H/L$ | $H_i.Rc/L^2$ | $z_{max}$ | $Z_{max}/h$ | Sediment (g) |
|-----|-------|--------------|-----------|-------------|--------------|
| 0.84 | 0.080 | 0.008        | 0.03      | 0.38        | 0            |
| 0.79 | 0.083 | 0.009        | 0.04      | 0.5         | 0            |

Table 4 shows the result of the second variation. It indicated the same result as the first run. The height of suspension was below the LCB crest and hence no sediment was transported through the structure. In terms of wave breaking, the turbulence generated more impact than in the first run. The sediment suspension was found to be 4 cm or 50% of the LCB height.

- **Variation 3**: $d = 14 \text{ cm}, h = 5 \text{ cm}$

Table 5. The results of Variation 3.

| $T$ | $H/L$ | $H_i.Rc/L^2$ | $z_{max}$ | $Z_{max}/h$ | Sediment (g) |
|-----|-------|--------------|-----------|-------------|--------------|
| 0.79 | 0.079 | 0.009        | 0.03      | 0.6         | 0            |
| 0.72 | 0.120 | 0.016        | 0.05      | 1           | 1610         |

Table 5 shows the result of the third variation. In variation 3, the wave period was different from Variation 1 and 2. The wave periods at Variation 3 were $T = 0.79$ (no breaking wave) and $T = 0.72$ (wave breaking). The breaking wave was due to the water depth that was reduced by increasing the bottom elevation in front of the LCB structure thereby affecting the limit of the wave height. In this case, when the wave was not broken, the suspended sediment height was 3 cm or 60% of the LCB height. With this condition, sediment cannot be transported passing through the LCB.

The wave breaking type during Variation 3 was plunging. The turbulence arising from breaking wave have a major impact on the sediment movement. The sediment suspension height was 5 cm or equal to the LCB height. This condition enabled the sediment transport across the structure. The movement of sediment mechanisms is described in Figure 3 below.

Figure 3a indicates the breaking wave causes turbulence resulting in the bottom sediments to be lifted and suspended. Figure 3b indicates the suspension sediment moves towards the coast but blocked by the structure. After some time, the sediment in the front of the LCB piled up to a height of 4 cm or 80% of the LCB height as indicated by Figure 3c. The sediment continued piling up and finally reach the crest of the LCB and passed through the crest of the LCB. Figure 3d indicates the sediment that has been deposited behind the LCB. At the end of the simulation (four hours duration), the deposited sediment behind the LCB was 1610 g.
Figure 3. The Mechanism of Sediment Transport from Front to Behind the LCB.

- **Variation 4**: $d = 11 \text{ cm}$, $h = 2 \text{ cm}$.

Table 6. Results of the Variation 4.

| T    | H / L | Hi.Re / L2 | $z_{\text{max}}$ | $Z_{\text{max}} / h$ | Sediment (g) |
|------|-------|------------|-------------------|-----------------------|---------------|
| 0.79 | 0.085 | 0.009      | 0.03              | 1.5                   | 124           |
| 0.72 | 0.143 | 0.016      | 0.11              | 5.5                   | 418.4         |
| 0.72 | 0.143 | 0.017      | 0.11              | 5.5                   | 7577          |

Table 6 shows the result of the fourth variation. During Variation 4, the wave periods were the same as the Variation 3 where $T = 0.79$ (wave did not break) and $T = 0.72$ (wave breaking). In this study, we found that the sediment was deposited behind the LCB in both non-breaking wave and breaking wave. The process of sediment transport was same as during Variation 3. After the sediment was accumulated in front of the LCB, the sediment move through the crest and remained behind the LCB.

In variation 1-3 where there was no wave breaking, no sediment transports through the LCB. While in variation 4 with the same condition, it appears that sediment could pass through the LCB although the volume is far less than the breaking wave conditions. This is due to the height of the sediment suspensions ($Z_{\text{max}}$) is 3 cm or 150% higher than the height of the LCB ($h$) up to 2 cm, so that the suspended sediment from the bottom can easily pass through the LCB. For different wave periods, the wave broke in front of the LCB. The position of the breaking wave moved to 30 cm in front of the LCB. As a result, the amount of sediment transported behind the LCB almost five times the amount of sediment that on Variation 3. The shallower water depth ($d$) causes intense turbulence arising from the breaking waves which easily lift up the sediments. This promoted more sedimentation at the lee side of the LCB.

The process of sediment transport may be reported as follows. After 50 minutes of running, the LCB was fully covered with sediment. After 120 minutes, the amount of sediment was reduced and moved behind the LCB. All the sediment on the structure crest was transported behind the LCB after 180 minutes. The sediment transport caused the breaking wave position changed depending on the position of the sediment accumulation. When the LCB was fully covered with sediment, the position of breaking wave was at the LCB. After the sediment was transported and filled up the lee of the LCB, the position of a breaking wave moved behind the LCB. This process can be seen in Figure 4.

A non-dimensional graph is used to analyze the relationship between the volume of sediments deposited by influencing parameters as described in the literature review. These parameters are shown in Figure 5. The volume of sediment is expressed to be non-
dimensional, as the volume / (b.h²) with a heavy volume of sediment obtained divided by density, b is the LCB width and h is the height measured from the bottom sand LCB in front of the LCB. While Hi is the height of the incoming wave, L is the wavelength, and Rc is the average water depth at the structure crest.

Figure 4. The mechanism of sediment transport and wave breaking movement in the variation 4 (Observation Result); d) photo of experiment represent of annotation (c).

Figure 5. Referencing Parameters

Figure 6. Relationship Graph between Hi.Rc/L² and Volume/bh².

The graph shows the relationship between the volume / (b.h²) and Hi.Rc/L² in any variation of the experiment (Rc / d). It indicates that volume of deposited sediment tends to increase following the wave height (Hi), the water depth at the structure crest (Rc) and reduced wavelength (L). The higher the wave the more volume of sediment is accumulated. The transporting sediment is considerably affected by the shear velocity, which are generally associated with high amplitude of the waves. The maximum shear velocity occurs during the breaking wave [21]. The higher the wave, the greater the bed particle velocity so it is easier to move the bed sediments.

At the time of Rc / d = 0.45 and Rc / d = 0.53 no sediment was deposited. This was due to the water depth in front of the LCB that was not adequate so that, the water particles arising from the bottom of the wave could not carry the sediment pass through the LCB. Meanwhile,
when \( \frac{Rc}{d} = 0.64 \) and \( \frac{Rc}{d} = 0.82 \) some sediment was deposited. Along with the reduced depth and increasing wave height, the incoming wave particle velocity near the bed increased and more sediment is transported behind the LCB.

The type of breaking wave and the position also influences the amount of sediment transport. The plunging breaking wave type is the most effective because; it results in greater turbulence than the surging type and lift more bed sediment. The position of breaking wave in front of the LCB enables more sediment to move and pass through the LCB.

### 4.2 Scour on the LCB

Scour on the LCB only occurred on Variation 1 with \( d = 20 \text{ cm} \) and \( h = 11 \text{ cm} \). This was due to the initial position of the LCB which was on top of the sand bottom. This was different from other variations where the LCB was partially buried under the sand. Table 7 shows the results of scouring.

| \( H/L \) | Scour |
|---------|-------|
| 0.074   | 1.2 cm|
| 0.118   | 1.2 cm|

Scour on the LCB occurs due to the flow underneath the bottom of the LCB. This flow arises from the difference in water level in front and behind the LCB due to piling up. When the peak of the waves was in front of the LCB, the water level in front of the LCB is higher than the water level behind the LCB. The water flow eroded the sand material under the LCB towards the lee of the LCB. In other cases, as piling up has occurred behind the LCB, the water level behind the LCB is in average higher than the water level in front of the LCB. Such a difference induced the flow underneath the LCB toward the front of the LCB and scour the material under the LCB. This process continues until scouring reaches a certain depth below the LCBs and the LCB becomes stable (no scour process).

### 4.3 Sediment Analysis

Analysis of the sediment is carried by comparing the diameter of sediment deposited and the original sediment in front of the LCB. The result indicates that no difference in average diameter of the deposited sediments and the original bottom sediment, \( D_{50} = 0.106 \text{ mm} \). The suspended and transported sediment from front to behind the LCB has the same diameter.

### 4.4 Comparison with Previous Studies

In the previous study, Dewi [31] obtained when \( \frac{Rc}{d} = 0.06 \) the volume of deposited sediment tends to increase following the wave height (Hi), the water depth at the structure crest (Rc) and...
reduced wavelength (L). This is similar to the results obtained in this study. Different results obtained when the value of \( \frac{R_c}{d} = 0.11 \) and \( \frac{R_c}{d} = 0.21 \) where the volume of the deposited sediment tends to decrease following the wave height (Hi), the water depth at the structure crest (Rc) and reduced wavelength (L). The reduction of the volume of sediment when the water level in front of the LCB (d) is shallower was explained by Dewi [31] as follows. With a lower of water level, the turbulence is weaker resulting in a reduced suspended sediment that pass through the LCB. This is in contrast with the results obtained in this study in which when water level is shallower, the sediments that pass through the LCB was increase. The difference result might be due to the different of slope which modify the breaking wave position. When the breaking waves occur far away from the LCB the sediment that pass through the LCB is less. The position of a breaking wave is very important to determine the amount of sediment transport as described in the discussion above.

5. Conclusion

1. The total volume of sediment deposited tends to increase following wave height (Hi), the water depth at the structure crest (Rc) and a reduced wavelength (L).
2. Breaking wave condition is more effective to transport bed sediment than the non breaking wave. Plunging breaking wave type is the most effective because it produces greater turbulence.
3. The position of the breaking wave significantly influences the amount of sediment passing through the LCB. The breaking waves that occur in front of the LCB can lift more bed sediment than the breaking waves that occur far away from the LCB.
4. Scour occurred underneath the LCB and made the LCB to settle. Such scour was caused by the flow underneath the LCB due to water level difference between the front of and the lee sides of the LCB due to the waves action.

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