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Submerged low-crested structures in front of coastal structures

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Abstract

How to adapt coastal structures to climate change has become an important topic of study, particularly given the fact that sea level rise can also increase wave loading on coastal structures that were designed under depth-limited wave conditions. One of the climate adaptation measures to ensure that existing coastal structures continue to perform their function after a magnitude of sea level rise that was unforeseen at the time of design, is to reduce the wave load before the waves reach the existing coastal structure. This can be achieved by constructing a low-crested structure in front of the existing structure. Between the two structures, structure-induced wave set-up occurs. This structure-induced wave set-up has been studied based on wave flume tests. The effects of structure-induced wave set-up on wave transmission at the low-crested structures and the effects on wave overtopping at the emerged coastal structures were also measured and analyzed.

The structure-induced wave set-up depends on the freeboard, wave steepness, and permeability of the low-crested structure. For configurations with impermeable low-crested structures, this wave-set-up does not depend on the distance between the two structures. Empirical expressions to estimate structure-induced wave set-up are derived for impermeable and permeable low-crested structures.

The measurements indicate that the effect of structure-induced wave set-up on the wave transmission coefficients is negligibly small.

The structure-induced wave set-up increases the wave overtopping discharges at the emerged coastal structure. This effect can be taken into account in wave overtopping estimates by reducing the freeboard with the structure-induced wave set-up.

Keywords

Set-up, Wave transmission, Wave overtopping, Coastal structures, Rubble mound breakwaters, Dikes, Wave flume tests

1 Introduction

How to adapt coastal structures to climate change has become an important topic of study, particularly given the fact that sea level rise can also increase wave loading on coastal structures that were designed under depth-limited wave conditions. One of the climate adaptation measures to ensure that existing coastal structures fulfill their function also after a magnitude of sea level rise that was unforeseen at the time of design, is to reduce the wave load before the waves reach the existing coastal structure (see for instance Van Gent, 2019, and Van Gent and Teng, 2023). This can be achieved by increasing the foreshore (*e.g.* sand nourishment) or by constructing a low-crested structure in front of the coastal structure. In the present study the climate adaptation measure to add a submerged low-crested structure in front of an existing coastal structures was investigated.

Besides serving as adaptation solution against climate change, submerged low-crested structures can also be designed as artificial reefs to enhance marine life and aquatic biodiversity. Besides enhancing marine life, artificial reefs can also be designed to reduce wave loading on the coast. For this purpose, estimates of wave transmission at the artificial reefs are essential.

Wave transmission at coastal structures has been studied extensively. However, most of the studies have focused on wave transmission at the low-crested coastal structure without considering another structure behind it (see Figure 1).

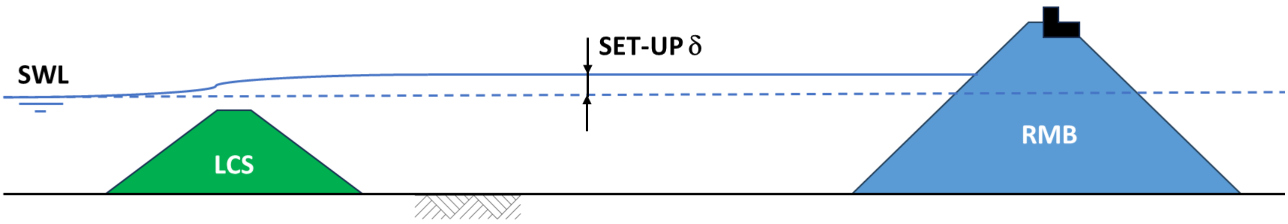


Figure 1: Submerged low-crested structure (LCS) in front of an (emerged) coastal structure (RMB).

A low-crested structure (LCS) in front of another (emerged) coastal structure can cause the mean water level in between them to increase (see Figure 1). This structure-induced wave set-up δ is expected to be at its maximum if the water between the two structures cannot flow sideways, for instance for a continuous LCS along the (emerged) coastal structure, or for a coastal system with segmented low-crested structures for which the lateral flow is blocked or reduced by another LCS (see left part of Figure 2). Blocking or reducing the lateral flow can reduce seabed scouring compared to a coastal system without structures to block or reduce the lateral flow (middle and right part of Figure 2).

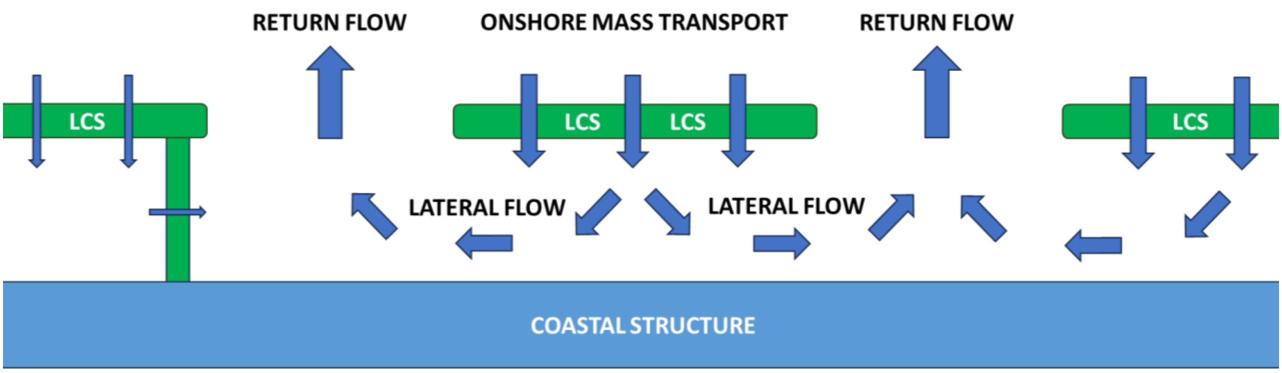


Figure 2: Top view of a segmented system of submerged low-crested structures (LCS) in front of an emerged coastal structure (dike or breakwater), with a blocked or reduced lateral flow on the left side.

The present 2D study is focused on a system of coastal structures where the lateral flow is blocked, leading to an upper limit of the potential effects of the structure-induced wave set-up between the submerged LCS and the emerged coastal structure. The following research questions are dealt with:

1) What is the magnitude of the structure-induced wave set-up between the submerged LCS and the (emerged) coastal structure, and is this mean water level set-up affected by the permeability of the structures and by the distance between the structures?

2) Is the structure-induced wave set-up affecting the amount of wave transmission at the submerged low-crested structure?

3) How does the structure-induced wave set-up affect the wave overtopping discharge at the (emerged) coastal structure?

To answer above research questions, physical model tests have been performed in a wave flume at Deltares, Delft. While wave transmission tests by Van Gent *et al*. (2023) serve as reference tests without an emerged coastal structure behind the submerged LCS, the following configurations with a combination of structures were tested:

- Impermeable submerged LCS in front of an impermeable slope with a *long* distance in between them.
- Impermeable submerged LCS in front of an impermeable slope with a *short* distance in between them.
- Impermeable submerged LCS in front of a *permeable* rubble mound breakwater.
- *Permeable* submerged LCS in front of a permeable rubble mound breakwater.

The physical model tests are described in Section 2. In Section 3 the test results are analyzed. Section 4 provides a discussion of results. The conclusions and recommendations are described in Section 5.

2 Physical model tests

The physical model tests were performed in a 55 m long section of the Scheldt Flume (110 m long, 1 m wide, and 1.2 m high) at Deltares, Delft. The wave generator is equipped with active reflection compensation, accounting for short-waves and long-waves effects. This means that the motion of the wave paddle compensates for the waves reflected by the structure, preventing them from being re-reflected at the wave paddle and propagating towards the model. Second-order wave generation was applied.

A horizontal foreshore was constructed on which the structures were placed. A transition slope was made between the bottom of the flume and the horizontal foreshore. At deep water, seaward of the submerged low-crested structure, and between the LCS and the (emerged) structure, wave gauges were positioned to measure the structure-induced wave set-up and to separate incident and reflected waves from the measured surface elevations (based on Zelt and Skjelbreia, 1992, and De Ridder *et al*., 2023).

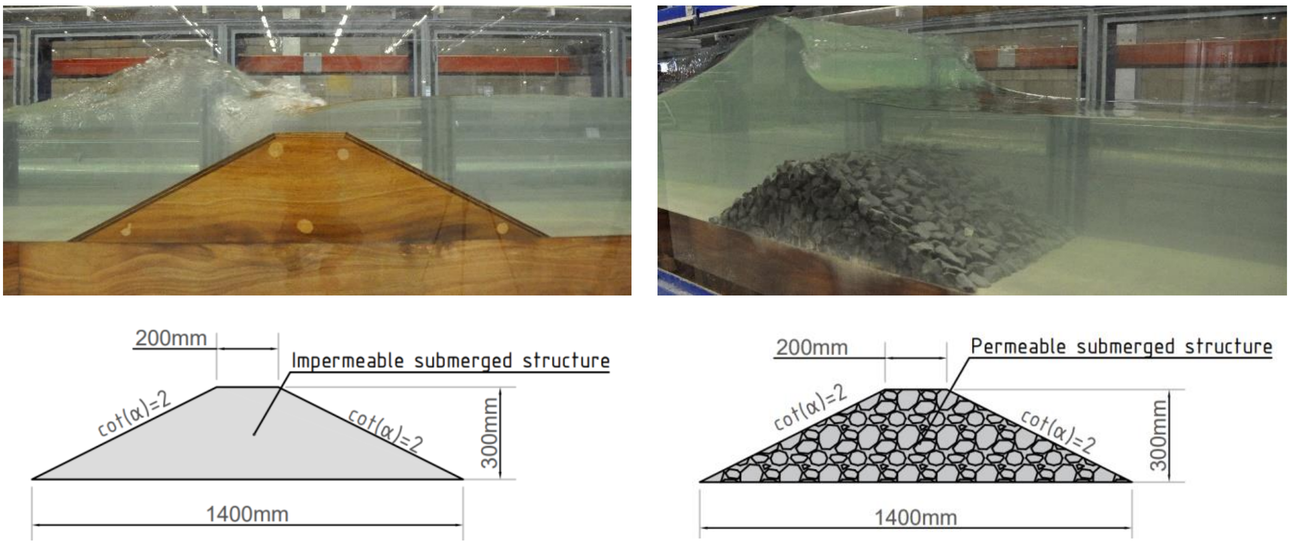


Figure 3: Tested impermeable and permeable submerged low-crested structures (pictures from Van Gent *et al*, 2023).

The submerged low-crested structures all had a trapezoidal shape with 1:2 slopes and a crest width of $B = 0.20$ m (see Figure 3). The smooth impermeable LCS had a height of $h_c = 0.30$ m. The permeable homogeneous low-crested structures had a height of either $h_c = 0.30$ m or $h_c = 0.40$ m. The permeable low-crested structures consisted of stones with a stone diameter of $D_{n50} = 0.040$ m and a porosity of $n = 0.436$. Stones were fixed such that no displacements of stones occurred. Wave transmission tests by Van Gent *et al* (2023) with an impermeable and permeable LCS with such a trapezoidal shape, but without an emerged structure behind the LCS, serve as reference tests for the analysis of wave transmission. Figure 3 shows pictures of wave interaction with the impermeable and permeable low-crested structures.

The impermeable emerged structures consisted of a smooth non-overtopped slope, with the toe of the slope either 2 m behind the rear-side edge of the submerged LCS, or 10 m behind the submerged LCS. The permeable emerged rubble mound structure (RMB) is described in the following section in more detail, but the configuration is based on a configuration tested by Van Gent *et al* (2022). Wave overtopping tests by Van Gent *et al* (2022) with a rubble mound breakwater, but without a submerged LCS in front, serve as reference tests for the analysis of wave overtopping discharges.

In all tests a JONSWAP wave spectrum was used (with the standard peak enhancement factor of 3.3). All tests consisted of about 1000 waves. Tests were performed with incident significant wave heights at the toe of the LCS between $H_{m0} = 0.085$ m and 0.212 m. Three values of the offshore wave steepness were used, leading to a wave steepness at the toe of the LCS between $s_{m-1,0} = 0.008$ and 0.040 ($s_{m-1,0} = 2\pi\ H_{m0} / gT_{m-1,0}^2$). Use is made of the spectral mean period $T_{m-1,0}$ since this wave period has shown to describe the influence of the spectral shape on for instance wave run-up, wave overtopping, and wave reflection at coastal structures (see Van Gent, 1999, 2001, and Dekker *et al*, 2007).

The physical model in the wave flume is not a scale model of an actual project. Applications of the test results are expected to be for structures in the range of about 10 to 50 times larger in reality than the tested models. Furthermore, results are expected to be used to design future model tests with structures of similar sizes.

2.1 Impermeable low-crested structure in front of impermeable structure

Two test set-ups were applied with an impermeable (trapezoidal) LCS (left panel of Figure 3) in front of an inshore impermeable slope (upper left panel of Figure 5). These tests were focused on determining the structure-induced wave set-up between the two structures (see Figure 1). To analyze the potential influence of the distance between the two structures, this distance was varied; in one set-up the distance between the two structures was 2 m in the model (measured at the seabed) and in another set-up the distances was 10 m, see Figure 4.

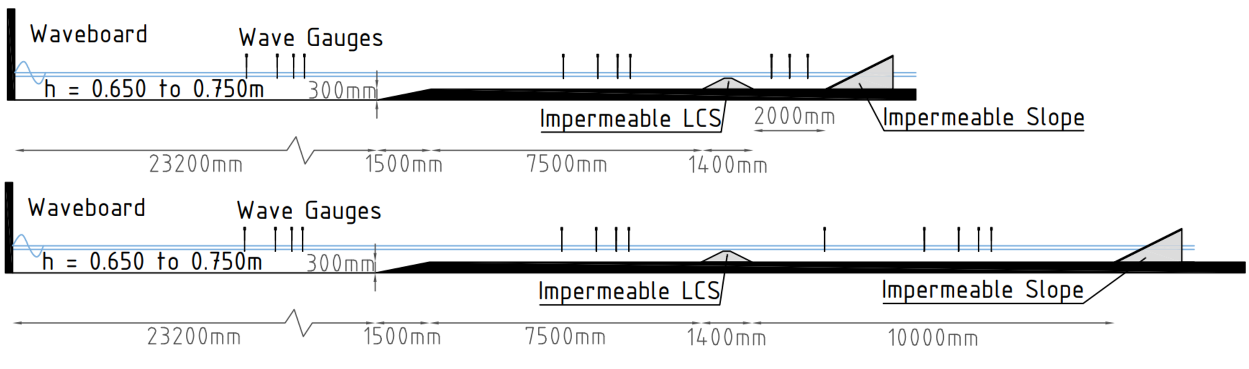


Figure 4: Test set-ups with impermeable LCS in front of impermeable slopes (resp. with 2 m and 10 m in between).

Both structures were made of wood, leading to smooth slopes. The impermeable slope of the emerged structure was non-overtopped. Wave gauges were positioned at deep water, on the horizontal part seaward of the LCS, and between the two structures. At these locations a set of wave gauges was used to measure the mean water level set-up (average of the corresponding wave gauges) and to separate incident from reflected waves (except for the set-up, where only 2 m existed between the two structures, which is not sufficient to separate incident from reflected waves). At deep water and seaward of the LCS a set of 4 wave gauges was positioned, while between the two structures 3 to 5 wave gauges were positioned.

For the tests with 2 m between the two structures, three water levels were used, leading to freeboards of the LCS of R_c = -0.150 m, -0.100 m and -0.050 m. Three wave steepnesses were tested; at deep water approximately $s_{m-1,0} = 0.015$, 0.025 and 0.040, referred to as ‘low steepness’, ‘mid steepness’ and ‘high steepness’ respectively. For each wave steepness four wave heights were tested, between H_{m0} = 0.15 m and 0.23 m at deep water. This leads to in total 36 tests for this configuration where the distance between the two structures was 2 m.

For the tests with 10 m between the two structures, five water levels were used, leading to freeboards of the LCS of R_c = -0.150 m, -0.125 m, -0.100 m, -0.075 m and -0.050 m. Three wave steepnesses were tested; at deep water approximately $s_{m-1,0}$ = 0.015, 0.025 and 0.040. For each wave steepness four wave heights were tested, between H_{m0} = 0.15 m and 0.23 m at deep water. This leads to in total 60 tests for this configuration.

Figure 5: Pictures of tested impermeable slope and (permeable) rubble mound structure.

2.2 Impermeable low-crested structures in front of permeable structure

To analyze the potential influence of the structure-induced wave set-up on wave overtopping discharges, tests have been performed with an impermeable LCS in front of an inshore overtopped rubble mound breakwater (see Figure 6). The impermeable LCS is again the same structure as before (see left panels of Figure 3), while the rubble mound breakwater has a configuration based on tests by Van Gent *et al* (2022) where no LCS was present in front of the rubble mound breakwater (see right and lower-left panel of Figure 5). Since the rubble mound breakwater is now placed on a shallower foreshore while the wave loading is reduced due to the presence of the LCS, the total height and freeboard of the rubble mound breakwater were reduced compared to the structure tested by Van Gent *et al* (2022). The rubble mound breakwater consisted of a 1:2 armour layer with stones D_{n50} = 0.0317 m (layer thickness 0.060 m), a filter layer with D_{n50} = 0.0168 m (layer thickness 0.030 m), and a core with D_{n50} = 0.0065 m. At the crest, a protruding crest wall with a total height of 0.14 m was present with a protruding part of 0.05 m. Overtopping water was collected in an overtopping box using an overtopping chute starting at the crest wall. The tested cross-section is shown in Figure 7.

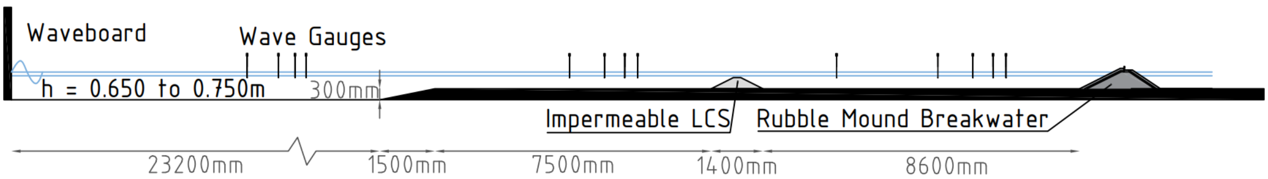


Figure 6: Test set-up with impermeable LCS in front of (permeable) rubble mound breakwater (RMB).

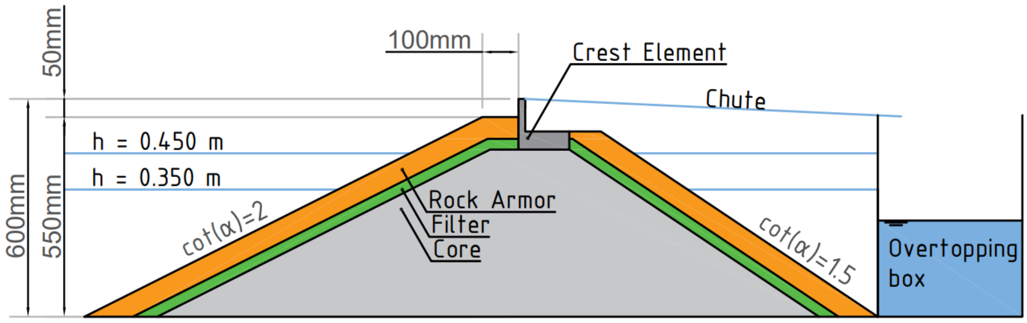


Figure 7: Cross-section of (permeable) rubble mound breakwater (RMB).

For these tests with an impermeable LCS in front of a rubble mound breakwater, two water levels were used, leading to freeboards of the low-crested structures of R_c = -0.150 m and -0.100 m. Two wave steepnesses were tested; at deep water approximately $s_{m-1,0}$ = 0.015 and 0.040, referred to as 'low-steepness' and 'high steepness' respectively. Wave heights at deep water varied between H_{m0} = 0.15 m and 0.23 m. In total 15 tests were performed for this configuration with an impermeable LCS in front of a rubble mound breakwater.

2.3 Permeable low-crested structures in front of permeable structure

It was hypothesized that the structure-induced wave set-up between the LCS and the inshore emerged coastal structure can depend on the permeability of the low-crested structure, assuming that the mean water level set-up may be reduced due to flow through the permeable LCS. Therefore, tests were performed with a permeable LCS (right panels of Figure 3) in front of a (permeable) rubble mound breakwater, as described in the previous section (see Figure 8). For the LCS two trapezoidal structures were tested, one with a height of 0.30 m and the other with a height of 0.40 m, both with the same stone size, 1:2 slopes and a crest width of 0.20 m.

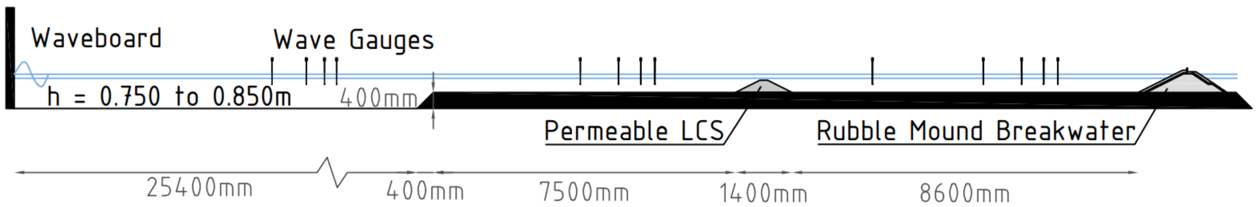


Figure 8: Test set-up with permeable LCS in front of (permeable) rubble mound breakwater (RMB).

For these tests, five water levels were used, leading to freeboards of the low-crested structures of R_c = -0.100 m, -0.075 m and -0.050 m for the LCS with a total height of h_c = 0.30 m and R_c = -0.050 m, -0.025 m and 0 m for the LCS with a total height of h_c =0.40 m. Three wave steepnesses were tested; at deep water approximately $s_{m-1,0}$ = 0.015, 0.025 and 0.040. Wave heights at deep water varied between H_{m0} = 0.15 m and 0.24 m. All tests were used to analyze the structure-induced wave set-up and wave transmission, but for 11 tests the overtopping discharges could not be used because either no overtopping occurred, too much overtopping occurred for the applied size of the overtopping box, or the overtopping tests that did not pass other quality checks. In total 69 tests were performed for this configuration, of which 58 tests for analysis of overtopping discharges.

3 Analysis of test results

3.1 Structure-induced wave set-up

The mean water level set-up induced by structures has been studied by Longuet-Higgins (1967) who provided an analytical solution for small-amplitude non-breaking monochromatic waves and frictionless structures. Obviously, the solution is not valid for structures under severe irregular wave loading, as tested in the present study. Diskin *et al* (1970) carried out physical model tests on permeable structures with monochromatic waves. Diskin *et al* (1970) derived an empirical expression in which the non-dimensional structure-induced wave set-up (δ/H) depends only on the non-dimensional freeboard (R_c / H), although they observed also an influence of the wave period.

$$\frac{\delta}{H} = 0.6\, exp\left(-\left(0.7 - \frac{R_c}{H}\right)^2\right) \tag{1}$$

Loveless *et al* (1998) tested homogeneous permeable structures with submerged and emerged crests and concluded that the structure-induced wave set-up is at its maximum for zero freeboard ($R_c = 0$), unlike Diskin *et al* (1970) who found that the set-up is at its maximum for emerged structures with $R_c / H = 0.7$. Loveless *et al* (1998) concluded that within their range of tests the set-up depends on the wave height (H), wave period (T), the local wavelength (L), water depth in front of the structure (h), freeboard (R_c), crest width (B), stone diameter (D_{n50}) and total height of the structure ($h_c = h+R_c$). Of these parameters the stone diameter and crest width have not been varied in the present test programme.

Tests with either an impermeable LCS or a permeable LCS in front of an emerged slope or rubble mound structure were performed. For the impermeable LCS three configurations were tested, two with an impermeable non-overtopped slope behind the LCS (2 m and 10 m between the structures), and one with a (permeable) rubble mound breakwater behind the LCS. The mean water level set-up between the structures causes a slight set-down in the water level seaward of the LCS due to mass balance in the flume. Although the flume is long compared to the distances between the structures, in the analysis the freeboard (R_c) is corrected for this slight set-down on the seaward side of the LCS. Legends in graphs, however, denote the initial freeboard prior to the tests.

The main parameter affecting the structure-induced wave set-up (δ) is the freeboard (R_c). In Figure 9 the measured non-dimensional set-up (δ/H_{m0}) is shown versus the non-dimensional freeboard (R_c /H_{m0}). The left panel shows all tests with an impermeable LCS and the right panel all tests with a permeable LCS.

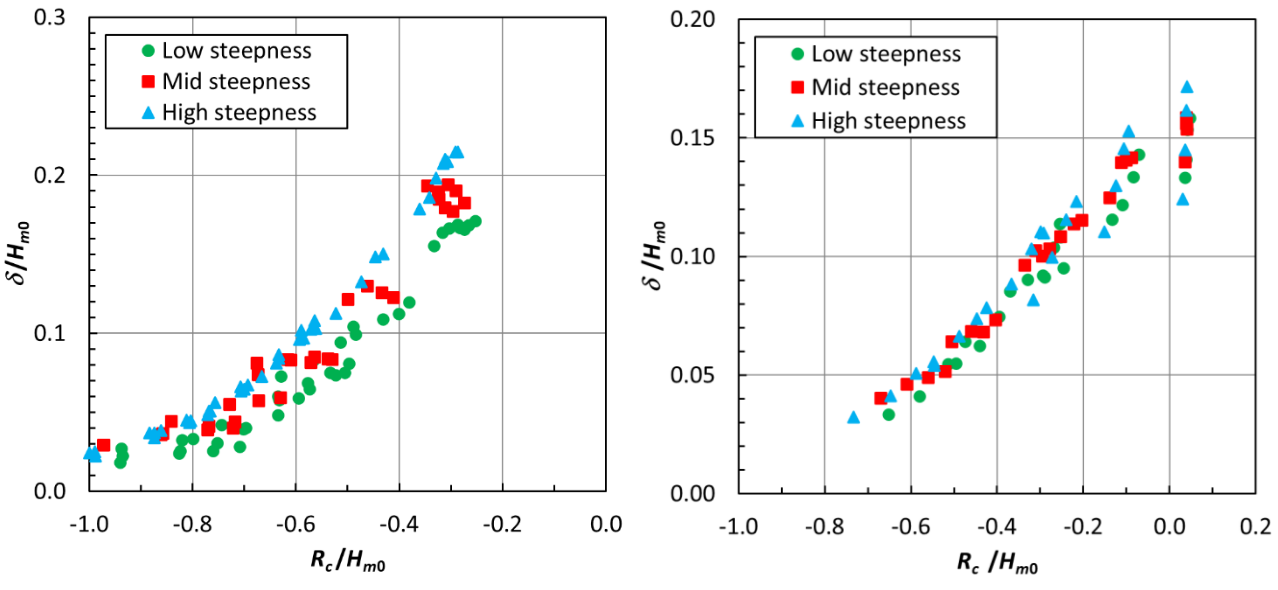


Figure 9: Measured non-dimensional wave set-up (δ/H_{m0}) versus the non-dimensional freeboard (R_c /H_{m0}); Left panel: All tests with an *impermeable* LCS; Right panel: All tests with a *permeable* LCS.

Figure 9 shows that for both types of structures the wave set-up clearly depends on the non-dimensional freeboard. Figure 9 also shows that for the impermeable LCS there is also a clear dependency on the wave steepness (*i.e.* larger wave set-up for larger wave steepnesses), while for the permeable LCS this dependency is less clear. Comparing the left and right panels shows that the set-up is larger for the impermeable LCS. This is expected to be due to the seaward flow through the permeable LCS that reduces the wave set-up. If the seaward flow through the permeable LCS is affecting the wave set-up, the height of the permeable LCS may play a role. Besides the height of the structure, a lower permeability resulting from a smaller stone size, smaller porosity, or wider structure may increase the wave set-up, but this was not examined in the present test programme.

Two heights of the permeable LCS have been tested for the configuration with a rubble mound breakwater inshore of the permeable LCS, referred to as ‘low LCS (permeable)’ and ‘high LCS (permeable)’ in the right panel of Figure 10. Although the tests with a high LCS were performed with higher water levels than the tests with a low permeable LCS, there is an overlap in the tests for crest levels in the range between $-0.4 < R_c / H_{m0} < -0.2$. The right panel of Figure 10 indicates that there is a slight influence of the height of the structure, leading to wave set-up values that were slightly larger for the low permeable LCS.

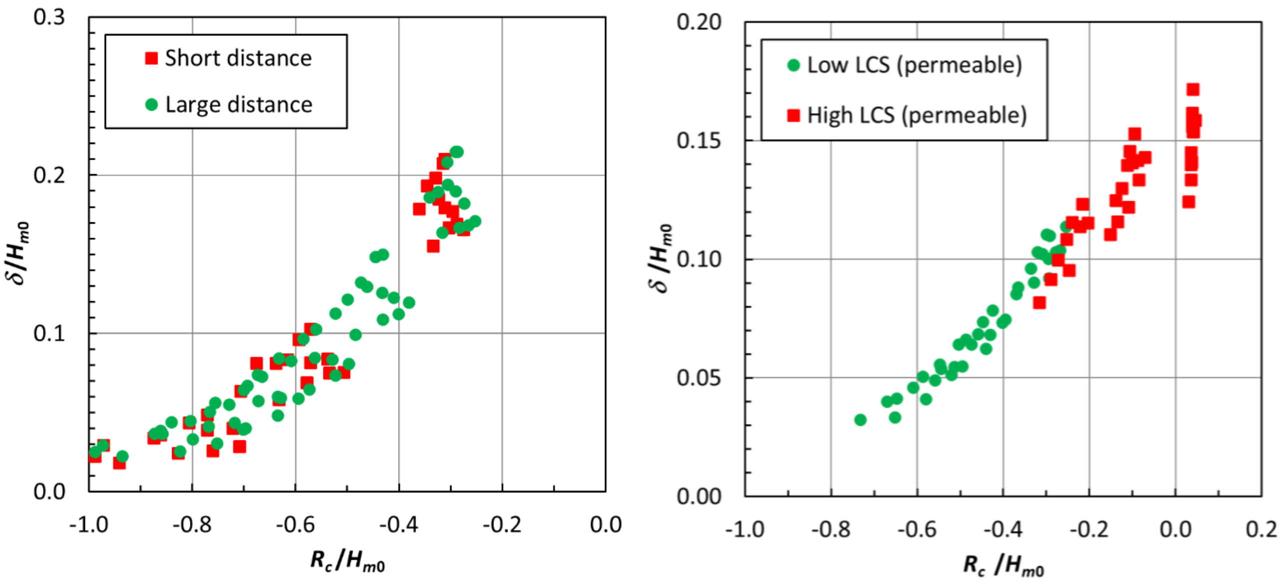


Figure 10: Measured non-dimensional wave set-up (δ/H_{m0}) versus the non-dimensional freeboard (R_c / H_{m0}); Left panel: Impermeable LCS with short and long distances between LCS and slopes (2 m and 10 m respectively); Right panel: Permeable LCS with a low and high LCS.

For the impermeable LCS, the distance between the LCS and the impermeable non-overtopped slope was varied. The left panel in Figure 10 shows all data for the short distance between the two structures (2 m) and the same tests plus a few additional series for the configuration with a large distance between the two structures (10 m). The left panel of Figure 10 indicates that for these impermeable structures the influence of the distance between the structures is negligibly small.

This first part of the analysis of the structure-induced wave set-up shows that for impermeable low-crested structures the wave set-up is dominated by the freeboard and the wave steepness. For permeable low-crested structures the height of the structure also seems to play a role, indicating that there may be an influence of the stone size, porosity and width of the LCS as well.

For an impermeable submerged LCS in front of another structure an empirical expression for the wave set-up has been derived using the non-dimensional freeboard (R_c / H) and the wave steepness (for $0.01 \le s_{m-1,0} \le 0.04$ and $-1 \le R_c / H_{m0} \le 0$):

$$\frac{\delta}{H_{m0}} = 0.34\, s_{m-1,0}{}^{0.4} \left(\frac{R_c}{H_{m0}} + 1.6\right)^{3.5} \tag{2}$$

The left panel of Figure 11 shows all data with impermeable low-crested structures in front of three types of emerged structures. The right panel shows the same data but with the symbols denoting the tests with different wave steepnesses. Figure 11 shows that Equation 2 provides an accurate description of the measured structure-induced wave set-ups, for each of the configurations with an impermeable LCS and for each wave steepness. The RMSE value based on the non-dimensional set-up is 0.0082.

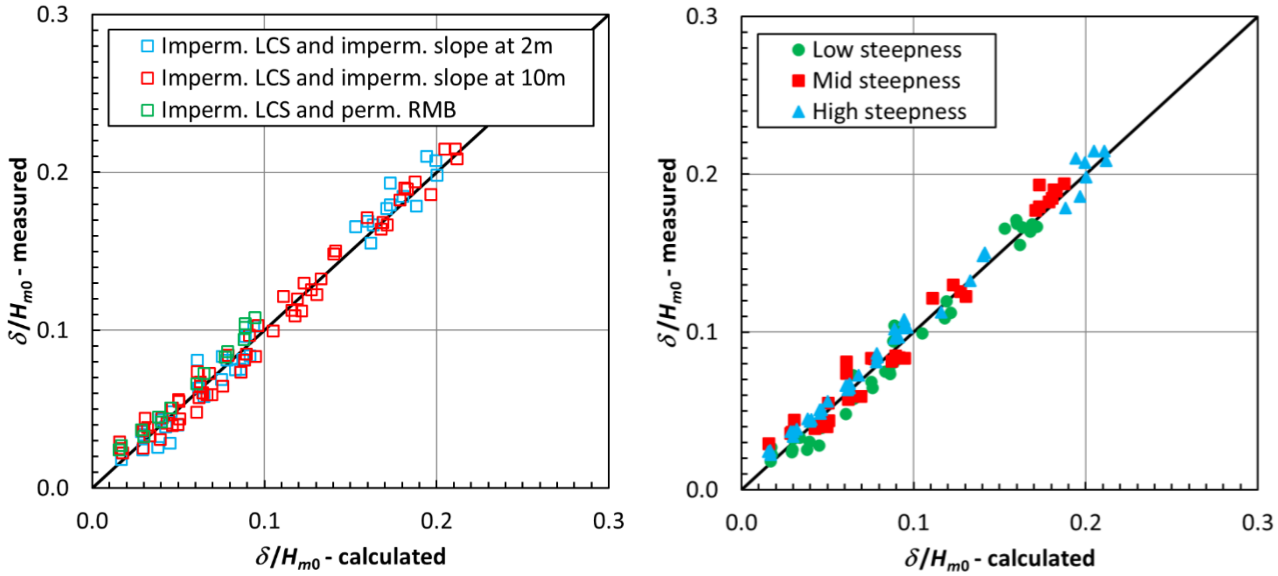


Figure 11: Measured versus calculated wave set-up for an impermeable LCS in front of other structures, using Equation 2; both panels with the same data but with different legends.

For permeable low-crested structures Diskin *et al* (1970) proposed Equation 1. This expression was derived for monochromatic waves. Nevertheless, the expression has been used here but the coefficient 0.6 has been calibrated to reduce the bias to zero. Using $H = H_{m0}$ in Equation 1 by Diskin *et al* (1970) and replacing the coefficient 0.6 by 0.25 leads to a RMSE=0.0102 for the non-dimensional set-up. The left panel of Figure 12 shows a rather good match between the data and the calibrated expression. Low values of the wave set-up are characterized accurately by the expression while for the large values the deviations between the expression and the data increase.

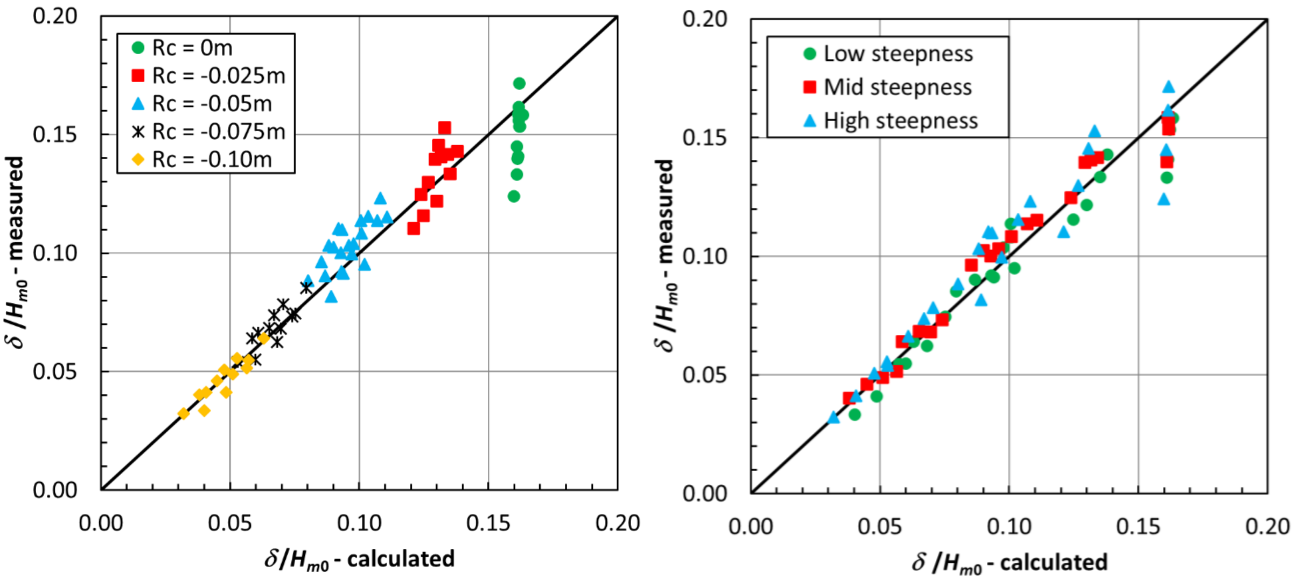


Figure 12: Measured versus calculated wave set-up using a calibrated version of the empirical expression by Diskin *et al* (1970) for a permeable LCS in front of a permeable rubble mound breakwater; both panels same data but with different legends.

As Equation 1 does not take the influence of the wave steepness and the height of the permeable structure into account, an empirical expression is derived taking these parameters into account. For a permeable homogeneous submerged LCS in front of an emerged coastal structure (impermeable or permeable) the following expression is proposed (for

$0.008 \leq s_{m-1,0} \leq 0.04$ and $1.5 \leq h_c /H_{m0} \leq 3$, $-0.8 \leq R_c /H_{m0} \leq 0$, $0.94 \leq B /H_{m0} \leq 2.35$ and $0.19 \leq D_{n50} /H_{m0} \leq 0.47$ based on the conditions of the incident waves in front of the LCS):

$$\frac{\delta}{H_{m0}} = 0.22\, s_{m-1,0}{}^{0.2} \left(\frac{h_c}{H_{m0}}\right)^{-0.7} \left(\frac{R_c}{H_{m0}} + 1.5\right)^{1.5} \tag{3}$$

Figure 13 shows all data with a permeable LCS in front of a rubble mound structure. Both panels show the same data but in the left panel the symbols denote the freeboard at the start of the tests, and in the right panel the symbols denote the different wave steepnesses. Figure 13 shows that Equation 3 provides an accurate description of the measured structure-induced wave set-up, although for the structures that are initially at the waterline (green dots), but are emerged during the tests (taking the set-down on the seaward side of the LCS into account), clearly contribute to the deviations. The RMSE value based on the non-dimensional wave set-up is 0.0071. Excluding the emerged structures leads to a RMSE value of 0.0061. Since these RMSE values are about a factor 1.5 smaller than those for Equation 1, in the remainder of the analysis in this document preference is given to Equation 3 for a permeable LCS in front of a rubble mound breakwater.

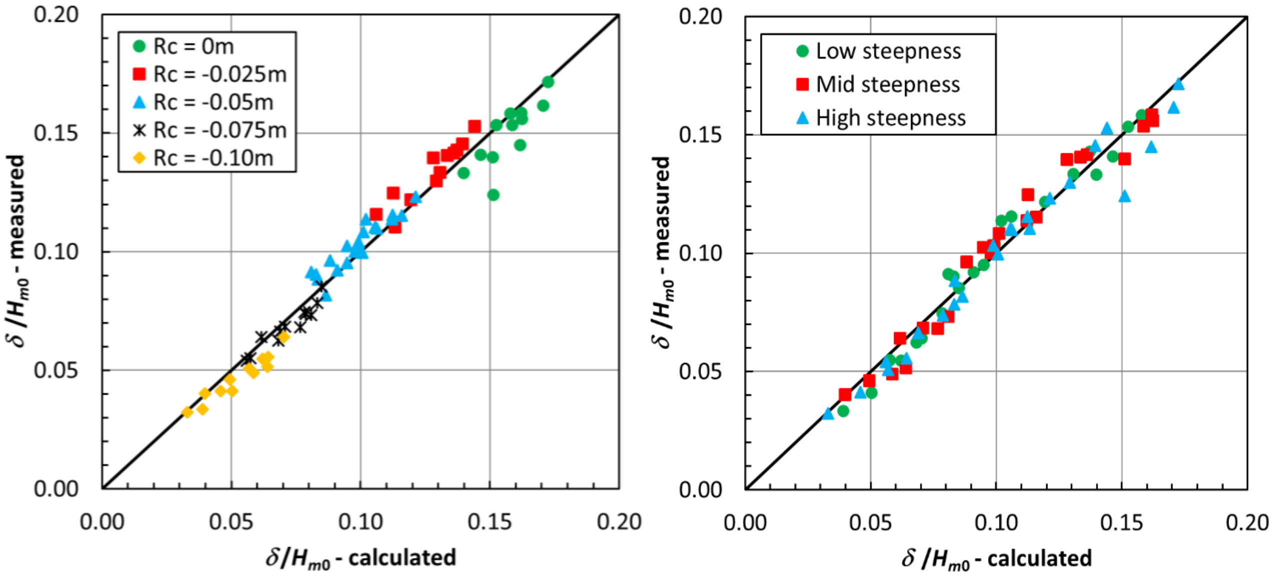


Figure 13: Measured versus calculated wave set-up for a permeable LCS in front of a rubble mound breakwater, using Equation 3; both panels with the same data but with different legends.

The analysis of the structure-induced wave set-up showed that for the performed tests the structure-induced wave set-up reached levels up to 21% of the incident significant wave height, that the wave set-up is dominated by the freeboard of the LCS, and that for an impermeable LCS the wave set-up is clearly larger than for a permeable LCS. For an impermeable LCS in front of an emerged impermeable slope, the distance between the two structures does not affect the wave set-up. For a submerged LCS in front of an emerged structure, the structure-induced wave set-up can be described by empirical expressions with reasonably good accuracy.

3.2 Wave transmission

Wave transmission at coastal structures has been studied by a large number of researchers (*e.g.* Sollitt and Cross, 1972; Daemen, 1991; d'Angremond *et al*, 1996; Seabrook and Hall, 1998; Bleck and Oumeraci, 2001; Calabrese *et al*, 2002; Briganti *et al*, 2003; Van der Meer *et al*, 2005; Van Oosten *et al*, 2006; Koutandos *et al*, 2006; Buccino and Calabrese, 2007; Makris and Memos, 2007; Panizzo and Briganti, 2007; Goda and Ahrens, 2008; Tomasicchio *et al*, 2011; Metallinos *et al*, 2016; Mahmoudi *et al*, 2017; Lokesha *et al*, 2019; Brancasi *et al*, 2022; Le Xuan *et al*, 2022; Kurdistani *et al*, 2022; Van Gent *et al*, 2023). For a discussion of the various wave transmission studies see the latter two studies. Many of those studies resulted in methods to estimate wave transmission at low-crested structures. However, most of the research was focused on wave transmission at coastal structures without another structure behind these low-crested structures. In the present study the tested LCS configurations correspond to those tested by Van Gent *et al* (2023) and therefore the derived empirical expression based on those tests is applied here:

$$K_t = c_1 \tanh\left(-\left(\frac{R_c}{H_{m0}} + c_2\left(\frac{B}{L_{m-1,0}}\right)^{c_3} + c_4\right)\right) + c_5 \tag{4}$$

where the freeboard R_c is made non-dimensional using the wave height H_{m0} and the crest width B is made non-dimensional using the wavelength based on the spectral wave period: $L_{m-1,0} = (g/2\pi)\, T_{m-1,0}^2$. The coefficients in Equation 4 depend on the type of structure. The coefficients for smooth impermeable and permeable homogeneous trapezoidal low-crested structures are shown in Table 1.

Table 1: Coefficients in Equation 4 for impermeable and permeable low-crested structures.

Structure type	c_1	c_2	c_3	c_4	c_5
A: Impermeable structure	0.47	3.1	0.75	0	0.5
B: Permeable structure	0.43	3.1	0.75	-0.25	0.5

The left panel of Figure 14 shows all data with an impermeable LCS in front of a structure (tests with an impermeable slope 10 m behind the LCS and tests with a rubble mound structure behind the LCS) together with the test conditions by Van Gent *et al* (2023) without a structure behind the LCS (red filled squares). The graph shows that the measured wave transmission from the tests with impermeable slopes behind the LCS (red open squares) are on average slightly higher than Equation 4 predicts, but still the match between the data and Equation 4 is rather good: RMSE=0.0322. The graph shows that the measured wave transmission from the tests with a permeable rubble mound structure behind the LCS (green filled squares) are on average equal to those obtained using Equation 4. The spreading around the trend is also small: RMSE=0.0153. Note that the data on which Equation 4 was based (red filled squares) lead to RMSE=0.0166.

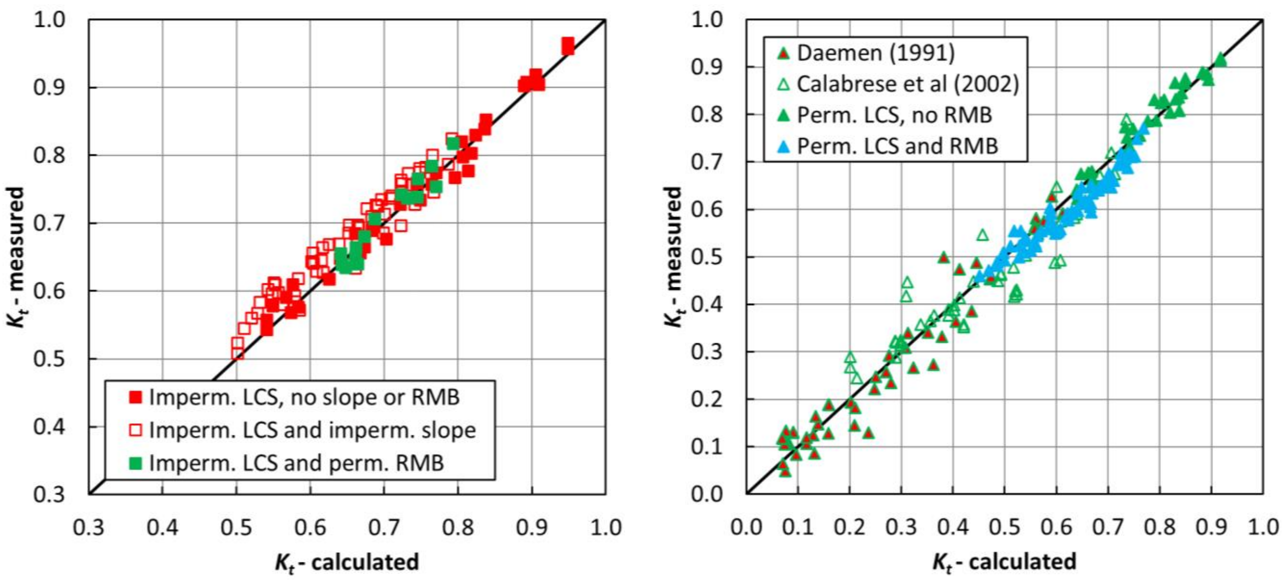


Figure 14: Measured wave transmission coefficients (K_t) versus Equation 4; Left panel: *Impermeable* LCS with and without an inshore structure; Right panel: *Permeable* LCS with and without an inshore structure.

The right panel of Figure 14 shows the new data with a permeable LCS in front of a rubble mound structure (blue triangles) together with the test conditions by Daemen (1991), Calabrese *et al* (2002) and Van Gent *et al* (2023) without a structure behind the LCS (green triangles). The graph shows that the measured wave transmission from the tests with a structure behind the permeable LCS are on average slightly lower than Equation 4 predicts, but still the differences between the data and Equation 4 are rather small: RMSE=0.0332. Note that the data on which Equation 4 was based (Van Gent *et al*, 2023) lead to RMSE=0.0198.

Thus, for one configuration Equation 4 slightly underestimates the wave transmission, for another Equation 4 slightly overestimates the wave transmission, and for another Equation 4 provides a very accurate estimate of the wave transmission. These rather small differences between the test results and the calculated transmission coefficients using Equation 4 are not considered to be due to the presence of the inshore structures behind the LCS, since the differences are small and within the spreading that is observed using other datasets. Therefore, it is concluded that for a LCS in front of an inshore structure, the influence of the inshore structures on the wave transmission is negligible, despite that the inshore structure leads to structure-induced wave set-up.

3.3 Wave overtopping

Wave overtopping tests on rubble mound structures without a LCS in front have been analyzed by Van Gent *et al* (2022), including structures similar to those tested in the present programme. Therefore, the empirical expressions derived based on those tests without a structure in front of the rubble mound breakwater have been used here as reference:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.016\ s_{m-1,0}^{-1}\ exp\left[-\frac{2.4R_c}{\gamma_f\gamma_b\ \gamma_\beta\ \gamma_v\ \gamma_p H_{m0}}\right] \tag{5}$$

where q (m^3/s/m) is the mean wave overtopping discharge, g is the acceleration due to gravity (m/s^2), $s_{m\text{-}1,0}$ is the wave steepness of the incident waves at the toe of the structure, and the influence factors are denoted by γ. Of the influence factors for roughness (γ_f), a protruding crest wall (γ_v), a berm in the seaward slope (γ_b), and oblique waves (γ_β), only those for roughness and a protruding crest wall are relevant for the present tests:

$$\gamma_f = 1 - 0.7\ \left(\frac{D_{n50}}{H_{m0}}\right)^{0.1} \tag{6}$$

$$\gamma_v = 1 + 0.45\ \left(\frac{R_c - A_c}{R_c}\right) \tag{7}$$

where A_c denotes the level of the armor in front of the crest wall (R_c-A_c is the protruding part of the crest wall). Within the present test programme the influence factor for roughness varied between γ_f = 0.35 and γ_f = 0.40, while the influence factor for the protruding crest wall varied between γ_v = 1.11 and γ_v = 1.17. To evaluate the performance of empirical expressions for the present tests with a LCS in front of the breakwater, the differences between the measured and calculated discharges are characterized by the bias and the RMSE values based on the logarithm of the non-dimensional discharges $Q = q/(gH_{m0}{}^3)^{0.5}$ where the BIAS and RMSE values are calculated based on:

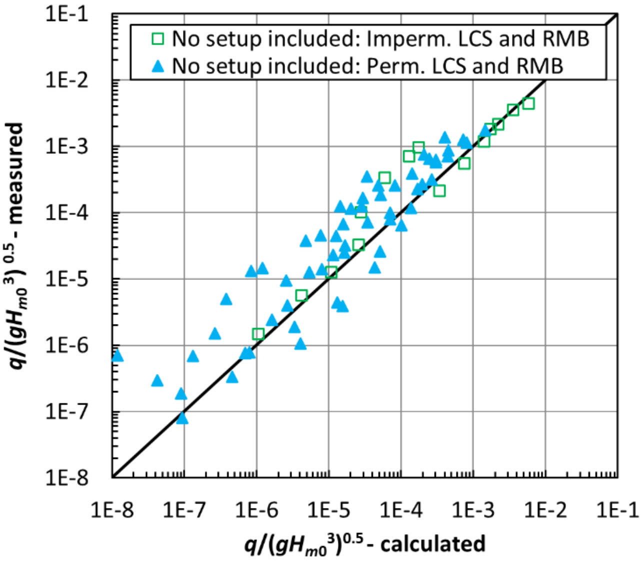
$$\text{BIAS} = \frac{\sum_{i=1}^{n_{tests}}(log(Q_{measured}) - log(Q_{calculated}))}{n_{tests}} \tag{8}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n_{tests}}(log(Q_{measured}) - log(Q_{calculated}))^2}{n_{tests}}} \tag{9}$$

The present test programme consists of two sets of wave overtopping measurements, both on the same rubble mound structure with a protruding crest element. For one set of tests the LCS was impermeable and for the other set of tests the LCS was permeable. First the analysis was based on applying Equation 5 without taking the structure-induced wave set-up into account. Thereafter Equation 5 was applied taking the structure-induced set-up δ into account by increasing the SWL with the structure included wave set-up δ, thus effectively reducing the freeboard R_c in Equation 5 by the structure-induced wave set-up δ:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.016\ s_{m-1,0}^{-1}\ exp\left[-\frac{2.4(R_c - \delta)}{\gamma_f\gamma_b\ \gamma_\beta\ \gamma_v\ \gamma_p H_{m0}}\right] \tag{10}$$

The left panel of Figure 15 shows the new measured wave overtopping data versus the calculated wave overtopping discharges, ignoring the presence of structure-induced wave set-up δ (Equation 5). The graph shows that the measured wave overtopping discharges are on average underestimated if structure-induced wave set-up is ignored (BIAS=0.3071). The measures for the spreading are RMSE=0.3745 for the impermeable LCS and RMSE=0.5473 for the permeable LCS in front of the rubble mound breakwater, taking only the discharges larger than $Q_{measured} \geq 10^{-6}$ into account since smaller values are often less relevant and scale effects may be present. Note that the data on which Equation 5 was based (Van Gent *et al*, 2022) lead to RMSE=0.2073 for structures with a protruding crest-wall and no LCS in front of the breakwater.



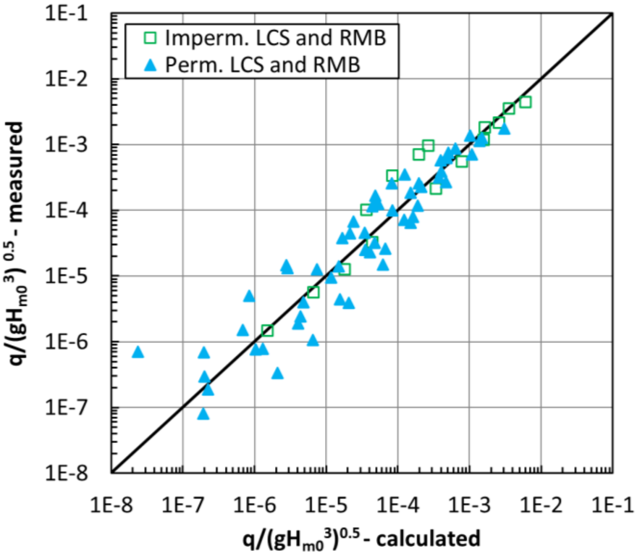


Figure 15: Measured versus calculated wave overtopping discharges, *excluding* structure-induced wave set-up (left panel) and *including* calculated structure-induced wave set-up (right panel).

If the measured structure-induced wave set-up δ is incorporated into the calculation of the mean overtopping discharge by adjusting the freeboard R_c to the freeboard after the wave set-up is included in the water level (Equation 10), this leads to a much smaller bias (BIAS=0.0293) and a reduction in the RMSE values: RMSE=0.2864 for the impermeable LCS and RMSE=0.3597 for the permeable LCS in front of the rubble mound breakwater, taking only the measured discharges larger than $Q_{measured} \geq 10^{-6}$ into account.

If the calculated structure-induced wave set-up δ (Equations 2 and 3) is incorporated in the calculation of the mean overtopping discharge by adjusting the freeboard R_c to the freeboard after wave set-up is included in the water level (Equation 10), this leads to a small bias (BIAS=0.0384) and a reduction in the RMSE values: RMSE=0.2983 for the impermeable LCS and RMSE=0.3590 for the permeable LCS in front of the rubble mound breakwater, taking only the measured discharges larger than $Q_{measured} \geq 10^{-6}$ into account. The right panel of Figure 15 shows the comparison between the measured and calculated and wave overtopping discharges taking the calculated structure-induced wave set-up δ (Equations 2 and 3) into account in the water level at the toe of the rubble mound breakwater. Comparing the left and right panels of Figure 15 shows that taking the structure-induced wave set-up into account improves the predictions of the wave overtopping discharges, reducing the bias from BIAS=0.3071 to 0.0384 and RMSE from 0.5121 to 0.3457 (*i.e.* a reduction of a factor 8 and 1.5 respectively).

Figure 16 shows measured versus calculated wave overtopping discharges, for the new data (green open squares and blue filled triangles) and data reported in Van Gent *et al* (2022) for various types of structure without a LCS in front of the breakwater. Figure 16 illustrates that the method proposed here, to take the structure-induced wave set-up into account in the water level and thus the freeboard of the rubble mound breakwater, leads to estimates and amount of spreading that are comparable to those for structures without a LCS in front.

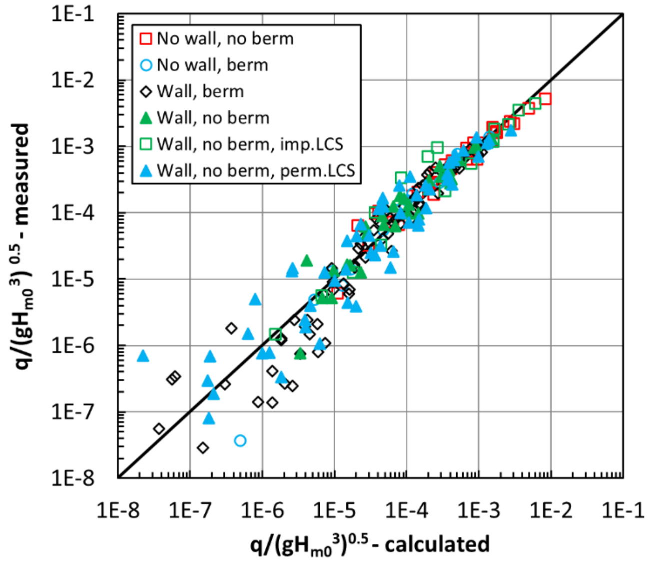


Figure 16: Measured versus calculated wave overtopping discharges for various types of structures.

Based on the analysis described in this section it is concluded that the structure-induced wave set-up δ between the LCS and the rubble mound breakwater affects the wave overtopping discharge. The effects can be taken into account by adding the structure-induced wave set-up δ, as estimated using Equations 2 and 3, to the water level in front of the rubble mound breakwater. With the modified freeboard, the existing expression to estimate wave overtopping discharges (*i.e.* Equation 10) can be applied with similar accuracy as for rubble mound breakwaters without a LCS in front.

4 Discussion

In wave flume tests the structure-induced wave set-up δ is not reduced by a lateral flow (see Figure 2). If in reality a lateral flow can occur, leading to a lower wave set-up δ, and thus tests in a wave flume can lead to larger structure-induced wave set-up and larger wave overtopping discharges than in reality. It is recommended to take these potential differences between wave flume tests and reality into account in the design of the wave flume tests and/or analysis of the test results.

If in reality a lateral flow can occur, leading to a lower wave set-up δ than without a lateral flow, the estimates of the wave set-up as given by Equations 2 and 3 can serve as upper limits for the corresponding structure configurations. Equation 2 was derived for an impermeable submerged LCS and Equation 3 for a permeable homogeneous submerged LCS. The wave set-up δ for the permeable structure is less than for an impermeable structure. It is expected that the permeability of the permeable structure affects the magnitude of wave set-up; the larger the resistance against a porous flow through the structure, the larger the wave set-up δ will be. The resistance to porous flow is affected by the size of the stones, the porosity, and the width of the permeable LCS. For instance, smaller stones or a wider structure may lead to a higher structure-induced wave set-up δ than estimated using Equation 3, with Equation 2 serving as an upper limit for a completely impermeable structure without porous flow through the structure. Also, a rubble mound LCS with relatively small core material underneath the armor stones is likely to lead to a larger wave set-up δ than a homogeneous structure with stones of the same size as the armor stones. For practical applications with other types of structures than those tested here, it is advised to analyze the magnitude of the wave set-up in dedicated physical model tests or in a validated numerical model with accurate porous media flow incorporated. Alternatively, applying the upper limit of the wave set-up δ, as described by Equation 2 in the estimates of wave overtopping discharges via Equation 10, can provide conservative (safe) estimates for coastal structures with a submerged LCS in front.

5 Conclusions and recommendations

The influence of a submerged low-crested structure in front of an emerged coastal structure were studied by means of physical model testing in a wave flume. The tested trapezoidal low-crested structures were either impermeable or permeable, while the emerged structures were also impermeable or permeable. Between the low-crested structure and emerged structure wave set-up occurs. This structure-induced wave set-up was studied, as well as the effects on wave transmission at the low-crested structures and the effects on wave overtopping at the emerged coastal structures. The study provides the following insights:

Structure-induced wave set-up:

- For the performed tests the structure-induced wave set-up reached levels up to 21% of the incident significant wave height. The wave set-up is dominated by the freeboard of the low-crested structure. The wave steepness also affects the wave set-up, while the effects of the wave steepness are more significant for an impermeable low-crested structure than for a permeable low-crested structure. For an impermeable low-crested structure the wave set-up is clearly larger than for a permeable low-crested structure. For a permeable homogeneous low-crested structure the height of the structure slightly affects the wave set-up.
- For an impermeable low-crested structure in front of an emerged impermeable slope, the distance between the two structures does not affect the structure-induced wave set-up.
- For a submerged low-crested structure in front of an emerged structure, the structure-induced wave set-up can be described by empirical expressions with reasonably good accuracy (Equations 2 and 3 for an impermeable and permeable low-crested structure, respectively).

Wave transmission:

- For a low-crested structure in front of an emerged coastal structure, the influence of structure-induced wave set-up on wave transmission is negligibly small. For the performed tests with impermeable and permeable low-crested structures, the empirical expression by Van Gent *et al* (2023) (*i.e.* Equation 4) provides reasonably accurate estimates of the wave transmission coefficients.

Wave overtopping:

- The structure-induced wave set-up between the submerged low-crested structure and the emerged structure affects the wave overtopping discharge. The effects can be taken into account by adding the structure-induced wave set-up to the water level in front of the emerged structure (rubble mound breakwater). With the modified freeboard, the existing expression to estimate wave overtopping discharges by Van Gent *et al* (2022) (*i.e.* Equation 10) can be applied with similar accuracy as for rubble mound breakwaters without a low-crested structure in front.

It is recommended to take structure-induced wave set-up into account when estimating wave overtopping discharges at coastal structures with a low-crested structure in front. For structures where a lateral flow can occur between the low-crested structure and the emerged structure, structure-induced wave set-up will be less than for situations in which this lateral flow cannot develop. For situations with a lateral flow, the presented method to estimate wave set-up and its effects on wave overtopping provides a conservative (safe) estimate of wave overtopping discharges. For situations with a lateral flow in reality, while such lateral flow obviously cannot occur in wave flume tests, special care must be taken in the analysis of wave flume tests.

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Author contributions (CRediT)

Not applicable for single-author paper.

Data access statement

The data acquired in the study will be made available on request.

Declaration of interests

The author reports no conflict of interest.

Notation

Name	Symbol	Unit
slope angle of structure	α	°
structure-induced wave set-up	δ	m
influence factor for wave overtopping	γ	-
crest level of armour at crest, relative to still water level	A_c	m
crest width of low-crested structure	B	m
stone diameter	D_{n50}	m
gravitational acceleration	g	m/s^2
significant wave height of incident waves at toe of structures, based on wave energy spectrum	H_{m0}	m
significant wave height of transmitted waves at rear of structures, based on wave energy spectrum	$H_{m0\text{-}t}$	m
water depth	h	m
structure height	h_c	m
wave transmission defined as $K_t = H_{m0\text{-}t} / H_{m0}$	K_t	-
wave length based on $T_{m-1,0}$ calculated using $L_{m-1,0} = (g/2\pi)\, T_{m-1,0}^2$	$L_{m-1,0}$	m
porosity	n	-
mean overtopping discharge	q	m^3/s/m
non-dimensional mean overtopping discharge	Q	-
freeboard (crest height relative to still water level; negative for submerged structures)	R_c	m
wave steepness calculated using $s_{m-1,0} = 2\pi\, H_{m0} / gT_{m-1,0}^2$	$s_{m-1,0}$	-
spectral mean wave period of the incident waves	$T_{m-1,0}$	s

Abbreviations

LCS	Low-crested structure
RMB	Rubble mound breakwater
RMSE	Root mean square error
SWL	Still water level

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