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Wave transmission at submerged coastal structures and artificial reefs

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ABSTRACT

Wave transmission at low-crested coastal structures has been studied, based on physical model tests with trapezoidal impermeable, permeable and perforated structures. The differences between wave transmission at impermeable and permeable structures are relatively limited. For a perforated hollow structure with an impermeable vertical screen in the middle, the wave transmission is significantly less than for perforated structures without an impermeable vertical screen; the blocking of the orbital motion by the screen significantly reduces wave transmission. The effectiveness of an impermeable vertical screen to block the orbital motion and consequently reduce wave transmission assists designers of artificial reefs to design structures that reduce wave transmission. Empirical expressions based on a hyperbolic tangent function have been derived to describe the test results. For permeable structures also available data for emerged structures has been used in the analysis, and the newly introduced expression appears to be accurate for both submerged and emerged permeable structures.

1. Introduction

Aquatic biodiversity is under threat by for instance ocean warming, acidification, local overexploitation of fisheries and locally declining water quality. The increase of atmospheric carbon dioxide concentrations threatens coral-dominated reef systems (see *e.g.* Hoegh-Guldberg et al., 2007, and Hoegh-Guldberg, 2010). To enhance marine life and improve aquatic biodiversity, artificial reefs have been proposed. Some of the proposed artificial reefs primarily focus on enhancing marine life and stimulating biodiversity. Other artificial reefs combine the function of enhancing marine life with reducing the wave loading on the coast by wave dissipation on the reef. Systems and coastal structures that have the goal to stimulate marine life can have a significantly different shape than traditional submerged coastal structures (see for instance Fig. 1 and Van den Brekel, 2021, and Van Diederen, 2022).

Climate adaptation of existing coastal structures has become more important due to climate change, the resulting sea level rise and increased wave loading for structures with depth-limited wave loading. In case sea level rise causes wave loading that becomes too severe, one of the options is to reduce the wave loading before the waves reach the existing coastal structure (see for instance Van Gent, 2019, and Hogeveen, 2021). This can be achieved by increasing the foreshore (*e.g.* sand nourishment) or by constructing a low-crested or submerged structure in front of the existing structure such that the wave loading on the existing structure reduces. The submerged structure can be a traditional coastal structure, but the function of dissipating wave energy can also be combined with the function of enhancing marine life by creating an artificial reef as discussed before. The construction of an artificial reef could be a measure against the consequences of climate change for coastal protection and contribute to diminishing the negative consequences of climate change for (the biodiversity of) marine life.

Since the primary interest with respect to the hydraulic performance of traditional submerged structures often is the reduction in wave loading on the coast, the 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; Goda and Ahrens, 2008; Tomasicchio et al., 2011; Mahmoudi et al., 2017; Lokesha et al., 2019; Brancasi et al., 2022; Le Xuan et al., 2022). Many of those studies resulted in empirical expressions to estimate wave transmission over low-crested structures, although wave transmission was also studied by means of numerical modelling (*e.g.* Van Gent, 1995;

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Metallinos et al., 2016) and machine-learning techniques (*e.g.* Van Oosten et al., 2006; Panizzo and Briganti, 2007). Since the characteristics of artificial reefs such as overall shape, permeability and roughness can be quite different from traditional submerged coastal structures, it is unknown whether existing methods to estimate wave transmission can be applied to submerged structures with other characteristics. To improve the understanding of wave transmission at submerged artificial reefs, new physical model tests have been performed.

In the present study, the primary focus is on assessing the wave transmission over submerged coastal structures, with the aim to generate knowledge on wave transmission that can be used for a variety of artificial reefs. For that purpose, physical model tests are performed in a wave flume, for a traditional trapezoidal impermeable submerged structure, a traditional trapezoidal permeable submerged structure, and three trapezoidal configurations with a non-standard submerged reef structure to obtain information on the performance with respect to wave transmission. The aim is not primarily to propose a new shape of an artificial reef but to generate knowledge that can be used in the design of other (non-tested) artificial reefs with respect to wave transmission.

The structure of the paper is as follows. In Section 2 earlier studies on wave transmission are discussed. In Section 3 the physical model tests are described. In Section 4 the test results are analysed, compared to existing empirical expressions, and a new expression is proposed. Section 5 describes the conclusions and recommendations.

2. Literature on wave transmission

Wave transmission is defined as $K_t = H_{m0\text{-}t}/H_{m0}$ where H_{m0} is the spectral significant wave height of the incident waves in front of the structure ($H_{m0} = 4\sqrt{m_0}$) and $H_{m0\text{-}t}$ is the spectral significant wave height of the waves at the rear side of the structure. In the present study the focus is on wave transmission at trapezoidal coastal structures or artificial reefs. Many studies have been performed on wave transmission at submerged (freeboard $R_c < 0$) and emerged low-crested coastal structures (freeboard $R_c > 0$). For traditional submerged structures the transmission of wave energy primarily occurs over the structure, while for emerged structures the contribution of wave transmission through permeable structures increases for higher crests. Obviously for non-overtopped structures only the wave transmission through the permeable structure is of importance. Wave transmission depends heavily on the freeboard (R_c). Sollitt and Cross (1972) studied the wave transmission for emerged low-crested rubble mound structures with wave transmission coefficients in the range of $K_t = 0.2$ to 0.5. Based on theoretical considerations and wave flume tests with regular waves, Sollitt and Cross (1972) concluded that the wave transmission depends for instance on the wave height, wave steepness (or wave length), the width of the structure, and permeability of the structure. Hamer and Hamer (1982) studied wave transmission for an emerged impermeable structure and found that, besides the wave height, wave steepness and height of the structure, also the structure slope affects the wave transmission. In addition, they found that compared to the incident waves the transmitted waves contain more energy in the higher frequencies. This indicates that the spectral shape changes which would lead to a shorter wave period at the rear side than at the front side.

Daemen (1991) analysed wave transmission at submerged and emerged low-crested rubble mound structures with irregular waves. Daemen (1991) confirmed that wave transmission depends on the freeboard (R_c), wave height (H_{m0}), wave steepness (s) and crest width (B). Daemen (1991) concluded that the slope angle has no or minor influence within the studied ranges of the available data-sets. Daemen (1991) also derived an empirical expression for trapezoidal rubble mound breakwaters with $1 < H_{m0}/D_{n50} < 6$, $-2 < R_c/H_{m0} < 2$ and a wave steepness based on the peak wave period of $0.01 < s_{op} < 0.05$ ($s_{op} = 2\pi\, H_{m0}/gT_p^2$), where D_{n50} is the stone diameter:

$$K_t = \left(0.031\left(\frac{H_{m0}}{D_{n50}}\right) - 0.024\right)\left(\frac{R_c}{D_{n50}}\right) + \left(0.51 - 5.42 s_{op} + 0.0323\left(\frac{H_{m0}}{D_{n50}}\right) - 0.0017\left(\frac{B}{D_{n50}}\right)^{1.84}\right) \quad (1)$$

with a maximum of $K_t = 0.75$ and a minimum of $K_t = 0.075$.

d'Angremond et al. (1996) proposed expressions for impermeable and permeable structures:

$$K_t = -0.4\left(\frac{R_c}{H_{m0}}\right) + c\left(1 - \exp\left[-0.5\xi_{op}\right]\right)\left(\frac{B}{H_{m0}}\right)^{-0.31} \quad (2)$$

where ξ_{op} is the surf-similarity parameter (or Iribarren parameter) based

Fig. 1. Examples of artificial reef units: Upper: Reef enhancing breakwater by Reefy in wave flume (source: Van den Brekel, 2021); Lower: Moses by ReefSystems (Lower left: model tests by Van Diederen, 2022; Lower-right:application in practice).

on H_{m0} and the peak wave period T_p of the incident waves ($\xi_{op} = \tan\alpha/s_{op}^{0.5}$); $c = 0.8$ for impermeable structures and $c = 0.64$ for permeable structures, both with a maximum of $K_t = 0.8$ and a minimum of $K_t = 0.075$.

Briganti et al. (2003) proposed to replace the expression by d'Angremond et al. (1996) for permeable structures with a wide crest ($B/H_{m0} > 10$) by:

$$K_t = -0.35\left(\frac{R_c}{H_{m0}}\right) + 0.51\left(1-\exp\left[-0.41\ \xi_{op}\right]\right)\left(\frac{B}{H_{m0}}\right)^{-0.65} \text{ for } \xi_{op} < 3 \tag{3}$$

with a maximum of $K_t = 0.8$ and a minimum of $K_t = 0.075$.

Van der Meer et al. (2005) proposed to replace the expression by d'Angremond et al. (1996) for permeable structures with a very wide crest ($B/H_{m0} > 12$) by:

$$K_t = -0.3\left(\frac{R_c}{H_{m0}}\right) + 0.75\left(1-\exp\left[-0.5\xi_{op}\right]\right) \text{ for } \xi_{op} < 3 \tag{4}$$

with a maximum of $K_t = 0.8$ and a minimum of $K_t = 0.075$, and to use d'Angremond et al. (1996) for normal crest widths ($B/H_{m0} < 8$), and to interpolate between Eq. (2) and Eq. (4) for intermediate crest widths ($8 < B/H_{m0} < 12$).

Kurdistani et al. (2022) proposed a formula for submerged homogeneous rubble mound breakwaters based on a large dataset and numerical modelling. Kurdistani et al. (2022) compared their empirical expression with expressions by d'Angremond et al. (1996), Seabrook and Hall (1998), Calabrese et al. (2002), Briganti et al. (2003), and Goda and Ahrens (2008). Kurdistani et al. (2022) concluded that their formula outperforms mentioned empirical relations:

$$K_t = 0.576\ \ln\left(0.428\ (1+\cot\alpha)^{0.042}\left(1-\frac{R_c}{H_{m0}}\right)^{0.75}\left(\frac{B_{eff}}{D_{50}}\right)^{0.125}\left(\frac{L_p}{B_{eff}}\right)^{0.39}\omega^{0.413}\ \psi^{-0.18}\right) + 0.923 \tag{5}$$

where R_c is a negative value for submerged structures, B_{eff} is defined as $B_{eff} = (4B + \text{bottom width})/5$ for submerged structures, which results in an "effective width" B_{eff} larger than the crest width B. For a trapezoidal structure: $B_{eff} = B + 0.4 \cot\alpha\ (h + R_c)$ in which h is the water depth in front of the structure and $h + R_c$ is the height of the structure. ω is a non-dimensional wave parameter $\omega = (1/2\pi)\tanh(2\pi h/L_p)$ in which the local wave length L_p is based on the peak wave period T_p and the local water depth h. For the ratio between the stone diameter D_{50} and the nominal stone diameter $D_{n50} = 0.84\ D_{50}$ has been used here. ψ is a kind of wave damping parameter to account for dissipation inside the permeable structure with porosity n: $\psi = n^{0.5}hB_{eff}/BH_{m0}$. Compared to Eqs. (1)–(4), Eq. (5) introduces the water depth in front of the structure h and the porosity n as additional independent parameters.

Note that Eqs. (2)–(4), include the surf-similarity parameter, which consists of the slope angle and the wave steepness, while Sollitt and Cross (1972) and Daemen (1991) observed a dependency on the wave steepness but not on the slope angle. Thus, the mentioned publications all confirm that the wave steepness affects wave transmission, while the dependency on the slope angle is apparently not that obvious. Besides the freeboard, also the crest width clearly affects the wave transmission since most researchers observed this dependency, except Van der Meer et al. (2005) who concluded that for very wide crests there is no dependency on the crest width. If very wide crests would not reduce the wave transmission any further, it is hard to justify the practical relevance of such more expensive structures in terms of hydraulic performance. Very wide structures for which Eq. (4) is developed are not within the scope of the present study and therefore Eq. (4) is not considered in the following. Eq. (3) was also derived for very wide crests, and therefore not considered further. In the following, expressions shown in Eq. (2) and Eq. (5) are used.

Based on the earlier studies it can be concluded that wave transmission is primarily determined by the freeboard (R_c), the crest width (B), the wave height (H_{m0}) and the wave steepness (s) while the influence of the structure slope (cot α), stone diameter (D_{n50}), porosity (n) and local water depth (h) are also included in empirical expressions by some researchers. Impermeable structures show a somewhat different performance in terms of wave transmission than permeable structures. d'Angremond et al. (1996) indicates that the same parameters affect wave transmission for impermeable and permeable structures and that differences can be accounted for by changing a coefficient in the empirical expression. In the present study the focus is on submerged structures and artificial reef structures.

To illustrate the expressions by d'Angremond et al. (1996), Fig. 2 shows Eq. (2) for impermeable and permeable structures, each for the lowest and highest wave steepness within the range of validity ($s_{op} = 0.01$ and $s_{op} = 0.05$), all with a slope of 1:2 and a crest width of $B/H_{m0} = 1.5$. It is remarkable that the transmission coefficient does not show a trend towards $K_t = 1$ for relatively low structures. This upper limit is one of the aspects investigated in present research.

d'Angremond et al. (1996) addressed the problem that available data from previous tests do not form a homogenous database. This is because model tests have been carried out by different laboratories, using different methods of wave generation and wave absorption, different methods to obtain incident waves from measured surface elevation, and different definitions of parameters. This also hampers data driven techniques based on databases from different sources, like the machine-learning method by Van Oosten et al. (2006) and other attempts to estimate wave transmission based on machine learning techniques.

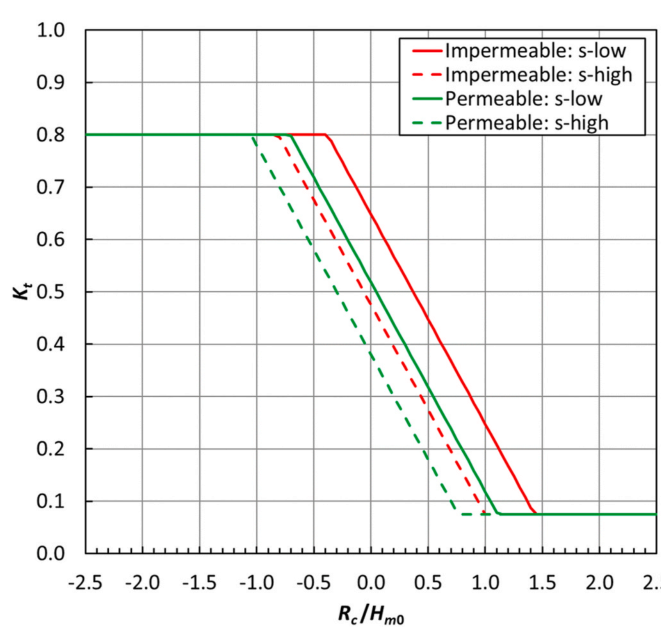

Fig. 2. Wave transmission as function of the non-dimensional freeboards as expressed by d'Angremond et al. (1996) for impermeable and permeable structures (1:2 slopes and crest width of $B/H_{m0} = 1.5$).

Modelling wave transmission using numerical models is another option but the modelling of interaction of breaking waves needs careful validation and appropriate modelling of for instance wave breaking processes and the flow in porous media. Hereafter, the focus is on physical modelling of wave transmission for various types of coastal structures in the same test set-up using the same wave conditions, the same wave generation and active wave absorption technique, and the same method to obtain incident waves from surface elevations. It is believed that these experiments provide new data to characterize wave transmission at permeable artificial reefs.

It is unknown to what extent available literature on wave transmissions can be applied for artificial reefs that have considerably different characteristics (see for instance Fig. 1). Of course, each type of artificial reef to enhance marine life can be tested to determine the wave transmission performance. However, in order to provide additional guidance to design artificial reefs, more knowledge on the dominant influence factors on wave transmission is desirable. For that purpose, the wave transmission performance of traditional low-crested structures (impermeable and permeable) is compared to those of some theoretical structures. In the test programme the focus is on effects of the surface porosity (*i.e.* the fraction of open space of the outer boundary of the structure) and the permeability of structures (*i.e.* determined by the porosity and size of the stones in the entire structure). Use will be made of perforated structures, not to develop a new type of artificial reef but to improve the understanding of wave transmission. Nevertheless, if any of the tested structures would be applied in reality as artificial reef, it is likely that the various structures could to some extent enhance marine life. However, evaluation of their performances other than comparing the wave transmission characteristics is not part of the scope of the present research. The aim is also not to provide design guidelines for specific artificial reefs as shown in Section 1, but to provide guidance that can be used to design (other) artificial reefs.

3. Physical model tests

The physical model tests were performed in the Scheldt Flume (110 m long, 1 m wide, and 1.2 m high) at Deltares. 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 to re-reflect at the wave paddle and propagate towards the model. Second-order wave generation has been applied to avoid spurious waves that occur when first-order wave generation is applied.

A horizontal foreshore was constructed on which the submerged structures and artificial reef structures were placed. Fig. 3 shows the cross-section of the foreshore in the flume. A 1:10 transition slope with a total height of 0.35 m was made between the bottom of the flume and the horizontal foreshore. The horizontal foreshore had a length of 13.9 m. At the back of the flume a passive wave absorber was placed. In front and behind the structures wave gauges were positioned to separate incident and reflected waves from the measured surface elevations (Mansard and Funke, 1980). The wave transmission is defined as $K_t = H_{m0\text{-}t}/H_{m0}$ where H_{m0} is the significant wave height of the incident waves in front of the structure and $H_{m0\text{-}t}$ is the significant wave height of the waves at the rear side of the structure, thus both wave heights are those propagating from left to right in Fig. 3.

Five trapezoidal structures were tested, all with a total height of h = 0.30 m, 1:2 slopes, and a crest width of B = 0.20 m.

A) **Impermeable structure**: Smooth impermeable structure, made of wood.
B) **Permeable structure**: Homogeneous permeable structure of stones, with D_{n50} = 0.040 m and a porosity of n = 0.436. Stones were fixed such that no displacements of stones occurred.
C) **Perforated structure**: Hollow perforated structure, made of wood, with a surface porosity of n = 0.44 (slopes n = 0.443 and crest n = 0.424). Except for a few exceptions, to enable use of velocity meters inside the structure, the circular holes all had a diameter of 0.04 m.
D) **Perforated structure with an impermeable screen**: As Structure C, but now an impermeable vertical screen was positioned in the middle of the structure.
E) **Perforated structure with a perforated screen**: As Structure D, but now the vertical screen was perforated (n = 0.425).

Fig. 4 shows the five (schematised) structures and pictures of each of the structures. For the perforated structures (C to E) electromagnetic velocity meters (EMF), with a diameter of 40 mm, were placed inside the structures. The velocity measurements have been analysed in Buis (2022) and are not further discussed here.

These configurations allow for comparing wave transmission at impermeable and permeable submerged structures under the same test conditions (Structures A and B). The first perforated structure (Structure C) was tested, not primarily to simulate real artificial reefs, but to study the influence of surface permeability and core permeability (comparing Structures A, B and C). Structure D was tested to examine the influence of blocking the orbital motion for the part within the structure while Structure E was tested to examine the effect of partly blocking the orbital motion for the part within the structure.

Tests were performed with significant wave heights of H_{m0} = 0.10 m, 0.15 m, 0.20 m and 0.25 m. Two values of the wave steepness were used leading to a wave steepness at the toe of the structures of around $s_{m\text{-}1,0}$ = 0.015 and 0.03 ($s_{m\text{-}1,0} = 2\pi\ H_{m0}/gT^2_{m\text{-}1,0}$). Use is made of the spectral mean period $T_{m\text{-}1,0}$ since this wave period has shown to describe the

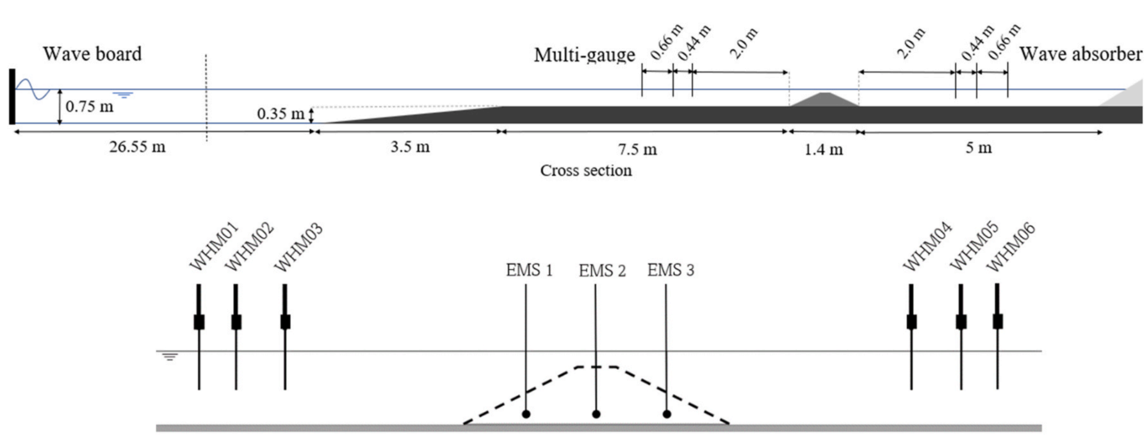

Fig. 3. Cross-section of the foreshore in the flume (upper panel) and close-up of perforated structure with positions of wave gauges WHM and velocity meters EMS (lower panel).

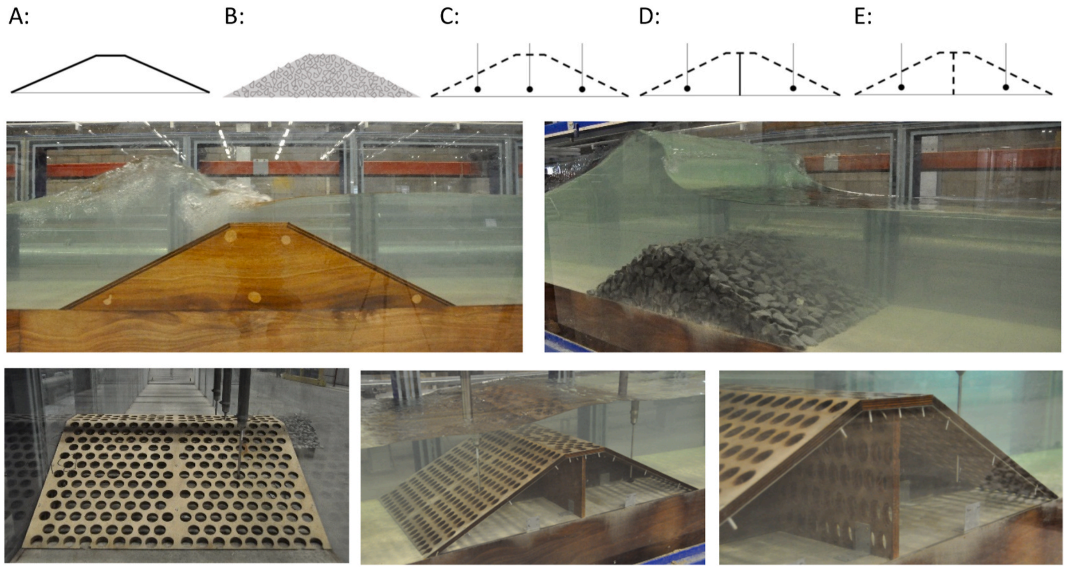

Fig. 4. Five configurations of tested structures and pictures of each of these structures.

influence of the spectral shape on for instance wave run-up, wave overtopping, and wave reflection at coastal structures (see Van Gent, 1999, 2001; Dekker et al., 2007). 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. The water depth at the toe of the structure was varied between $d = 0.25$ m–0.50 m in steps of 0.05 m, which leads to a freeboard of $R_c = -0.20$ m–0.05 m in steps of 0.05 m (negative values for R_c refer to submerged structures, positive values refer to emerged structures). For Structures C and E the highest wave height of $H_{m0} = 0.25$ m has not been tested for the two highest freeboards ($R_c = 0.05$ m and $R_c = 0$ m), while these structures are the only ones tested with $R_c = 0.05$ m and $R_c = 0$ m. Thus, for Structures A, B and D only submerged structures have been tested while for Structures C and E also some emerged low-crested structures were tested. In total 184 tests were performed (32 for Structures A, B and D and 44 for Structures C and E).

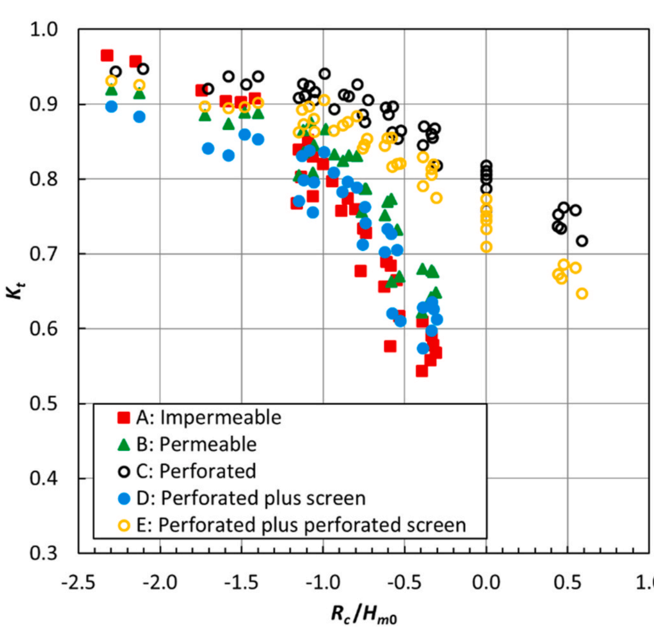

Fig. 5. Measured wave transmission for each of the five tested structures.

4. Analysis of test results

4.1. Test results

Fig. 5 shows the measured wave transmission coefficients on the vertical axis and the non-dimensional freeboard on the horizontal axis. All wave transmission coefficients are above $K_t = 0.5$ and for the conditions with the lowest relative crest, the wave transmission coefficients appear to approach asymptotically up to $K_t = 1$. Several prediction methods mentioned in Section 2 contain a maximum of $K_t = 0.75$ or $K_t = 0.80$. Such a maximum is remarkable since it is expected that wave transmission should approach to $K_t = 1$ for a very low structure or for no structure at all. The present test results show this expected trend towards $K_t = 1$.

Although other parameters than the non-dimensional freeboard R_c/H_{m0} also affect wave transmission, Fig. 5 shows systematic differences between the various structures. First observations are.

- The wave transmission for the impermeable, permeable (rubble mound breakwater), and the perforated structure with an impermeable vertical screen in the middle (Structures A, B and D) show a similar trend while the wave transmission for the perforated structure without a screen (Structure C) and the perforated structure with a perforated vertical screen in the middle (Structure E) is clearly larger than for the other structures.
- The perforated structure (Structure C) shows the largest wave transmission. The reduction in wave height due to the perforated structure is generally more than a factor two less than for the impermeable, permeable and perforated structure with a vertical screen.
- The vertical screen in the centre of the perforated structure is highly effective in reducing the wave transmission (compare Structure C and D); the wave transmission for the perforated structure with a vertical screen shows a performance that resembles those for impermeable and permeable structures (compare Structure D with Structures A and B).
- Perforating the vertical screen in the centre of the perforated structure for a large part eliminates the reducing effect of the vertical screen (compare Structure E with Structure D).

The left panel of Fig. 6 shows the differences between the wave transmission for the impermeable structure (Structure A) and the

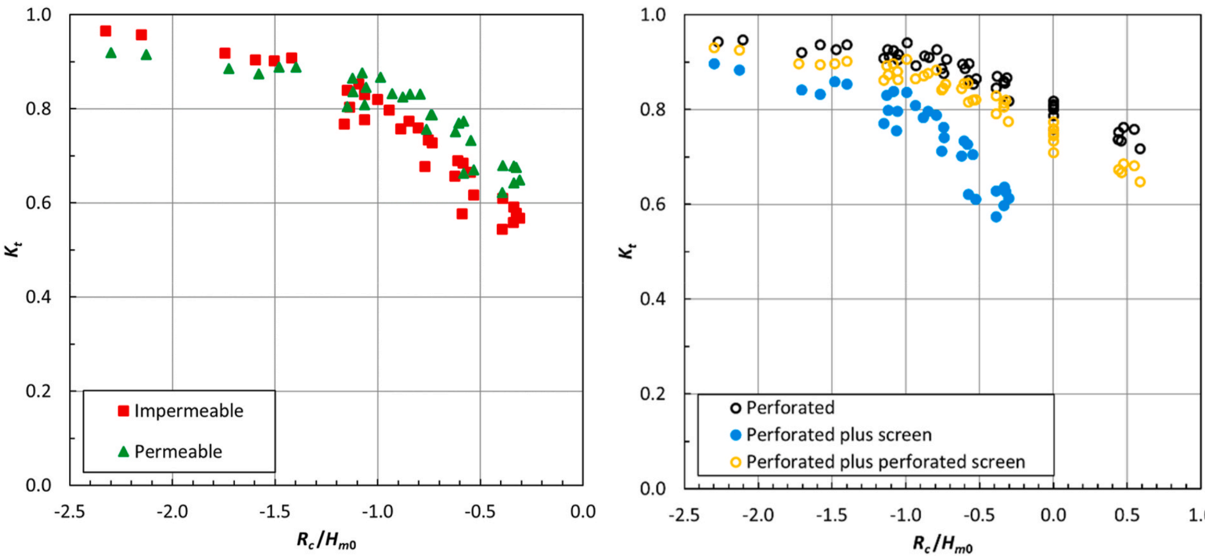

Fig. 6. Left: Comparison between impermeable and permeable (rubble mound breakwater) structures (Structures A and B). Right: Comparison between three types of perforated structures (Structures C, D and E).

permeable structure (Structure B) in more detail. Fig. 6 shows that for structures that are slightly submerged ($-1 < R_c/H_{m0} < 0$) the wave transmission for permeable structures is slightly larger than for impermeable structures. For these slightly submerged structures dissipation by wave breaking is deemed more important than wave dissipation due to roughness and friction of the permeable parts. For permeable structures, the orbital motion is slightly less disturbed than for impermeable structures; the permeable parts have a similar effect as an impermeable slope that is slightly below the actual surface of the permeable structure. As also observed for structures with a berm around the water level (see Chen et al., 2020), the wave breaking process is less intense for permeable structures than for impermeable structures (see also Metallinos et al., 2016). The flow through the permeable structure towards the wave front may reduce the intensity of the wave breaking and increase the wave transmission for permeable structures compared to impermeable structures.

The left panel of Fig. 6 shows that for structures that are much more submerged ($-2.5 < R_c/H_{m0} < -1.5$) the wave transmission for permeable structures is slightly lower than for impermeable structures. Apparently, for those low structures the dissipation by the roughness of the stones and dissipation inside the permeable structure, become relatively important compared to the influence of the permeable parts on wave breaking. This could lead to more dissipation at the permeable structure than for the smooth impermeable structure and consequently to a somewhat smaller wave transmission for permeable structures for these relatively low structures.

The right panel of Fig. 6 shows the differences between the wave transmission for the various perforated structures in more detail. The perforated (hollow) structure (Structure C) shows a relatively high amount of wave transmission. This indicates that the surface porosity, or permeability of the outer surface, contributes to the dissipation of energy but that (the absence of) a core is even more important. Apparently, the orbital motion of the waves is disturbed by the perforated outer surface but far less than for an impermeable structure or a permeable structure. Although not tested, it can be expected that if the porosity or diameter of the holes in the perforated surface would have been smaller, the permeability of the outer surface would reduce and therefore decrease the wave transmission. To increase the disturbance of the orbital motion of the passing waves, a vertical screen was placed in the centre of the perforated structure (Structure D). This proved very effective, indicating that the main reductive effect on wave transmission is due to (partly) blocking the orbital motion of the passing waves. The performance of the perforated structure with an impermeable vertical screen approaches the performance of the impermeable and permeable structures. Fig. 5 shows that the results for structures that are slightly submerged ($-1 < R_c/H_{m0} < 0$) the wave transmission for this perforated structure with a screen are between those for an impermeable structure and a permeable structure. For structures that are much more submerged ($-2.5 < R_c/H_{m0} < -1.5$) the wave transmission is even lower than for impermeable or permeable structures. Fig. 6 shows that perforating also the vertical screen in the centre of the perforated structure for a large part eliminates the reducing effect of the vertical screen. Since (almost) no material is present in the core of the perforated structures, the volumetric porosity of the core of the perforated structures is close to $n = 1.0$. Since the performance of the perforated structure with an impermeable vertical screen is rather similar to the impermeable ($n = 0$) and permeable ($n = 0.436$) structures, the results indicate that the porosity and permeability of the core play a much smaller role than the blocking of the orbital motion that is caused by the impermeable vertical screen.

The wave energy that reaches the structure is divided into transmitted wave energy, reflected wave energy and dissipation. Wave reflection is defined as $K_r = H_{m0\text{-}r}/H_{m0}$ where $H_{m0\text{-}r}$ is the spectral significant wave height of the reflected waves in front of the structure. Similar to the wave transmission coefficient K_t and the wave reflection coefficient K_r, also for the dissipation a spectral wave height can be used: $K_{dissipation} = H_{m0\text{-}dissipation}/H_{m0}$ where $H_{m0\text{-}dissipation} = 4\sqrt{m_{0\text{-}dissipated}}$ with $m_{0\text{-}dissipated}$ referring to the amount of dissipated wave energy. Using the energy balance $K_t^2+K_r^2+K_{dissipation}^2 = 1$ leads to $K_{dissipation} = (1\text{-}K_t^2\text{-}K_r^2)^{0.5}$. Thus, using the measured transmission coefficients and measured reflection coefficients a measure for the dissipation can be obtained. This dissipation is the sum of dissipation due to wave breaking, roughness and permeability of the structure.

Although other parameters than the non-dimensional freeboard R_c/H_{m0} also affect wave transmission, wave reflection and wave dissipation, the measured wave reflection is shown in Fig. 7 as function of this non-dimensional freeboard R_c/H_{m0}. The left panel of Fig. 7 indicates that the wave reflection is always larger for the impermeable structure than for the permeable structure, which corresponds to wave reflection characteristics for emerged impermeable and permeable structures. The spreading in the results indicates that the non-dimensional freeboard R_c/H_{m0} is not the only ratio affecting wave reflection. For the perforated structure with a vertical screen (Structure D) the right panel shows that the reflection is reasonable well described using the non-dimensional

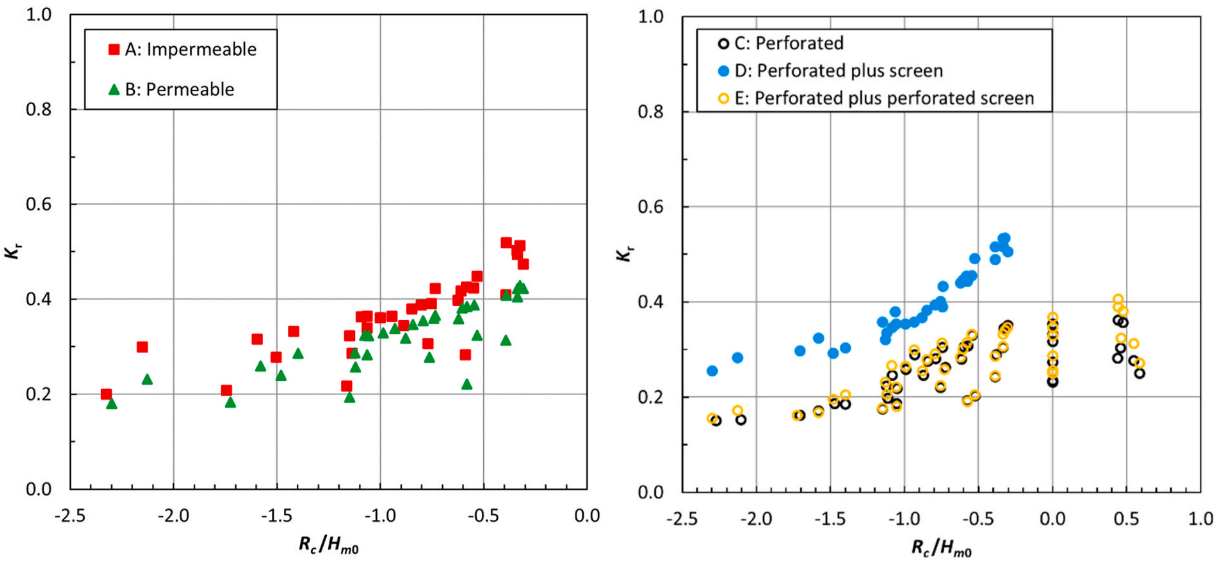

Fig. 7. Left: Wave reflection for impermeable and permeable structures (Structures A and B). Right: Wave reflection for three types of perforated structures (Structures C, D and E).

freeboard R_c/H_{m0} since the spreading around the trend is relatively small. This indicates that effects of for instance the wave steepness are relatively small for this structure type.

Comparing the wave reflection for the perforated structure with a screen (Structure D) with those for the impermeable structure (Structure A) show that these structures show similar values for the wave reflection coefficients. Note that the reflection coefficients do not reach values close to $K_r = 0$ for the tested non-dimensional freeboards. This explains why the wave transmission coefficients do not reach the value $K_t = 1$ within the tested ranges.

The reflections for the perforated structure (Structure C) and the perforated structure with a perforated screen (Structure E) are very similar, indicating that the perforated vertical screen hardly affects the wave reflection. The right panel of Fig. 7 shows a large influence of the vertical screen if the screen is impermeable (Structure D) since the reflection is clearly larger for this structure (Structure D compared to Structures C and E).

Fig. 8 shows the dissipation coefficient $K_{dissipation}$ as function of the non-dimensional freeboard R_c/H_{m0} although also other parameters affect the dissipation. The left panel of Fig. 8 indicates that for low structures ($-2.5 < R_c/H_{m0} < -1.5$) the wave energy dissipation is always larger for the permeable structure than for the impermeable structure, which confirms that for such low structures wave dissipation is dominated by friction and permeability of the structure while dissipation due to wave breaking is relatively small. Since dissipation by friction and permeability of the structure is negligible for the impermeable structure, the wave dissipation approaches zero for very submerged impermeable structures. For these low structures the wave reflection and dissipation are low, leading to relatively large wave transmission.

For structures that are slightly submerged ($-1 < R_c/H_{m0} < 0$) the wave dissipation for the permeable structure (Structure B) is generally smaller than for the impermeable structure (Structure A). This confirms that for slightly submerged structures dissipation by wave breaking is more important than wave dissipation due to roughness and friction of the permeable parts.

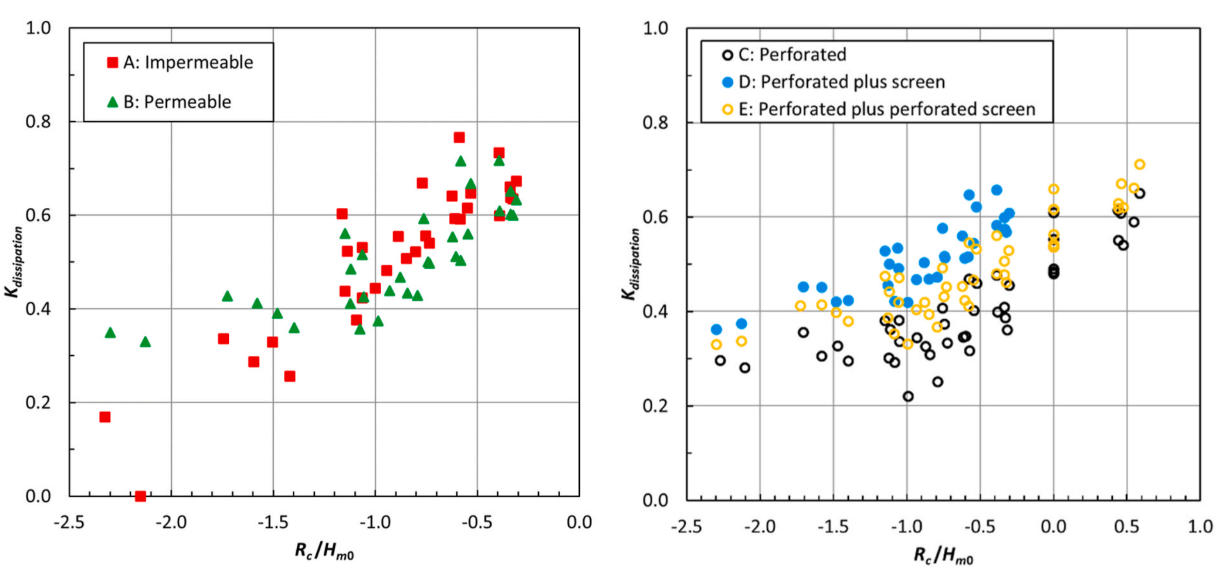

Fig. 8. Left: Wave energy dissipation for impermeable and permeable structures (Structures A and B). Right: Wave energy dissipation for three types of perforated structures (Structures C, D and E).

The right panel of Fig. 8 shows that wave dissipation for the perforated structure (Structure C) is lower than for the perforated structure with a perforated vertical screen (Structure E). For the structure with an impermeable vertical screen (Structure D) the dissipation is the largest of these three perforated structures. The wave dissipation values for this structure (Structure D) are comparable to those of the permeable structure (Structure B), while the wave reflection values for this structure (Structure D) are comparable to those of the impermeable structure (Structure A). This leads to wave transmission coefficients for Structure D that are similar to those of the permeable structure for relatively low structures (dissipation dominated by roughness/permeability) and similar to those of the impermeable structure for slightly submerged structures (dissipation dominated by wave breaking). The impermeable vertical screen in the perforated structure (Structure D) increases both the reflection and the dissipation compared to the other perforated structures (Structures C and E), leading to significantly lower wave

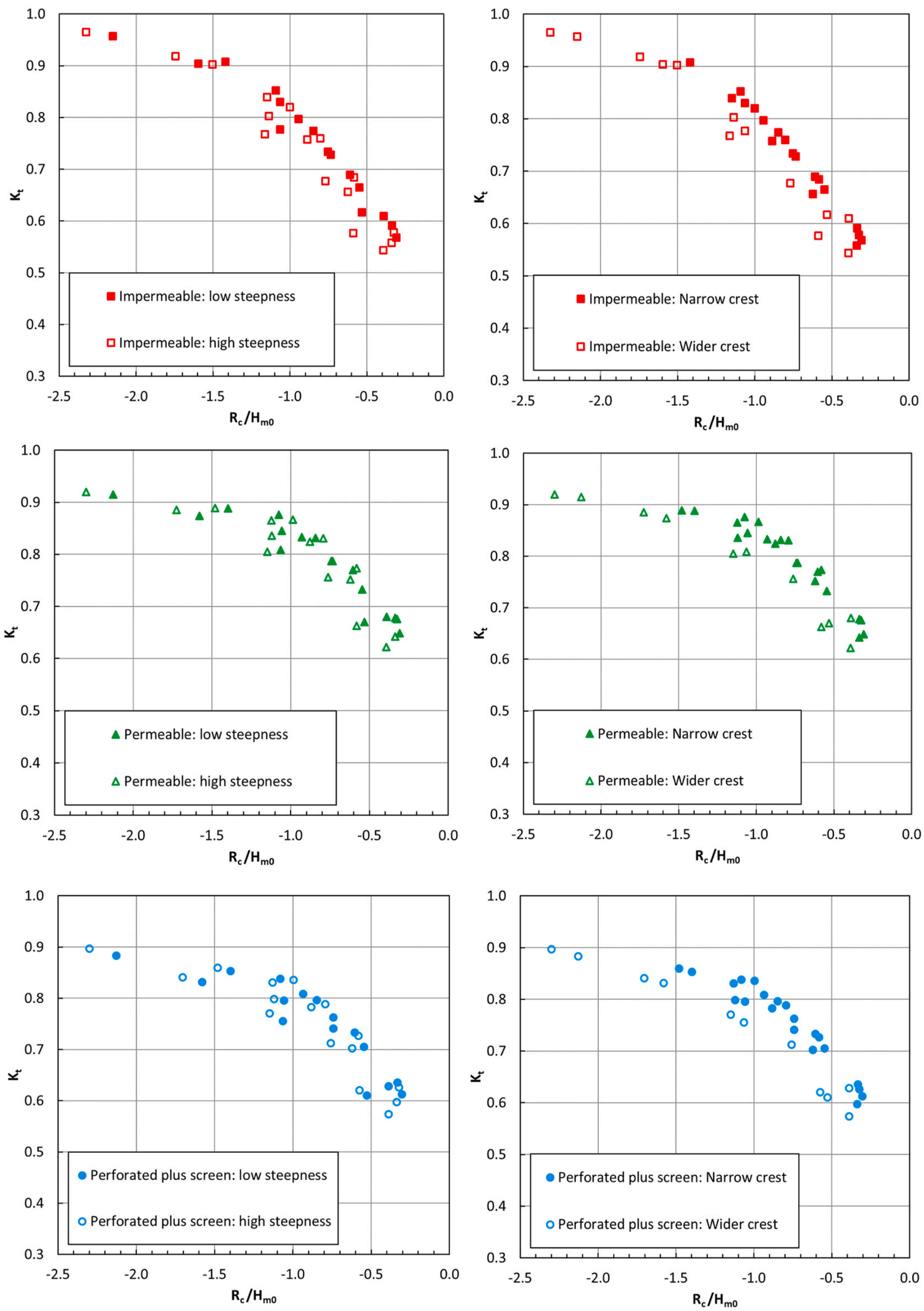

Fig. 9. Influence of wave steepness (left panels) and crest width (right panels) on wave transmission: Upper panel for impermeable structure, mid panel for permeable structure and lower panel for perforated structure (Structures A, B and D).

transmission for this Structure D compared to the other perforated structures.

The test results show that in order to limit wave transmission, the perforated structure with an impermeable vertical screen (Structure D) is preferred over the other perforated structures (Structures C and E). Therefore, the main focus of further analysis is on the performance of the impermeable structure, the permeable structure, and the perforated structure with a screen (Structures A, B and D).

Fig. 9 indicates the influence of the wave steepness (left panels) and the influence of the crest width (right panels) for the impermeable, permeable and perforated structures (Structures A, B and D). In Fig. 9 'low steepness waves' refers to a wave steepness of the incident waves in front of the structures of $s_{m-1,0} < 0.022$ ($s_{m-1,0} = 2\pi\, H_{m0}/gT^2_{m-1,0}$) and 'high steepness waves' refers to a wave steepness of $s_{m-1,0} > 0.022$. 'Narrow crest' refers to a crest with of $B < 1.5\ H_{m0}$ and 'wider crest' refers to a crest width of $B > 1.5\ H_{m0}$.

Fig. 9 shows that both the wave steepness and crest width affect the wave transmission. For each of the structures the wider crests clearly lead to lower wave transmission coefficients than the narrow crests. Note that only one crest width was tested such that the variation in the non-dimensional crest width is due to the variation in wave conditions. For each of the structures the conditions with a lower wave steepness on average lead to higher wave transmission coefficients than the conditions with a higher wave steepness. The influence of the wave steepness is relatively pronounced for the impermeable structure. The influence of the wave steepness is present for slightly submerged structures but for more submerged structures no or negligible effects of the wave steepness are observed in the wave transmission. This indicates that the wave steepness affects the wave breaking, which is more important for slightly submerged structures than for more submerged structures.

For the perforated structure (Structure D) the right panel of Fig. 7 showed that the wave reflection does not depend on the wave steepness of the structure. For the dissipation (right panel of Fig. 8) the variations around the trend due to variations in the wave steepness seem to decrease for more submerged structures, which again indicates that the influence of wave steepness reduces for more submerged structures.

For each of these structures the test results confirm the outcome of earlier studies that wave transmission depends on the wave height, the wave steepness (or wave length), the freeboard, and the crest width.

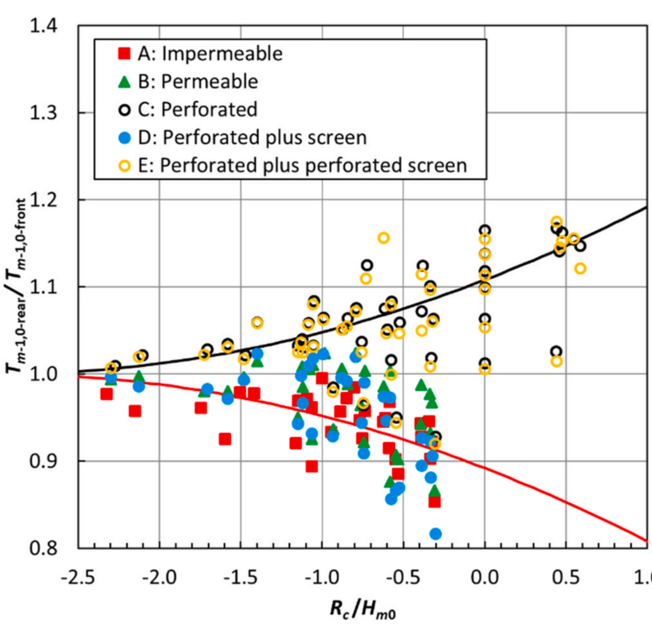

Fig. 10. Ratios of the wave period at the rear side and at the front of the structures with empirical expressions for Structures A, B and D in red and for Structures C and E in black.

The wave transmission is expressed as the ratio between the wave heights at the rear side and at the front of the structure. Besides changes in the wave height, also some changes can be observed in the wave period, although these changes are less pronounced than for the wave height. Within the present test programme, for the impermeable structure the ratio is on average $T_{m\text{-}1,0\text{-}t}/T_{m\text{-}1,0} = 0.94$, for the permeable structure 0.97, for the perforated structure 1.04, for the perforated structure with a vertical screen 0.95 and for the perforated structure with a perforated screen 1.04.

Fig. 10 shows this ratio of the wave periods versus the non-dimensional freeboard. The figure shows that the more the structure is submerged, the more the ratio of the wave periods tends towards one. For crest elevations closer to the still waterline, which corresponds to conditions with a lower wave transmission, the ratios deviate more from one. For the impermeable, permeable structure and the perforated structure with a vertical screen (Structures A, B and D), the wave periods at the rear side on average reduce slightly; the amount of energy in frequencies around the peak of the wave energy spectrum reduces slightly more than the energy at frequencies higher than the peak of the wave energy spectrum (see left panel of Fig. 11), leading to a slight decrease of the wave period $T_{m\text{-}1,0\text{-}t}$ compared to the wave period in front of the structure ($T_{m\text{-}1,0}$). Note that the wave spectra in front of the structure, as shown in Fig. 11, have a clear second-order peak at the double frequency of the peak. For the structures with relatively less wave dissipation, the perforated structure and the perforated structure with a perforated screen (Structures C and E), the wave periods at the rear side on average increase slightly; the amount of energy in frequencies higher than the peak of the wave energy spectrum reduces more than the energy around the peak of the spectrum (see right panel of Fig. 11), leading to a slight increase of the wave period $T_{m\text{-}1,0\text{-}t}$ compared to the wave period in front of the structure ($T_{m\text{-}1,0}$). Apparently, the primary wave is hardly affected by the perforated structures (Structures C and E) while the second-order peak, corresponding to shorter wave lengths, clearly is.

Fig. 10 shows trendlines with the expression $T_{m\text{-}1,0\text{-}t}/T_{m\text{-}1,0} = 1–0.012\ (3\text{-}R_c/H_{m0})^2$ in red (Structures A, B and D) and $T_{m\text{-}1,0\text{-}t}/T_{m\text{-}1,0} = 1 + 0.012\ (3\text{-}R_c/H_{m0})^2$ in black (Structures C and E).

4.2. *Empirical expressions to estimate wave transmission*

4.2.1. *Existing expressions*

Comparing the expressions by d'Angremond et al. (1996) shown in Eq. (2) and Fig. 2 with the test results shown in Fig. 5, indicates that the present test results do not confirm the upper limit of $K_t = 0.8$. Replacing the upper limit $K_t = 0.8$ by $K_t = 1.0$ in Eq. (2) enables to compare Eq. (2) with those test results for which the predictions are below $K_t = 1.0$. The upper left panel of Fig. 12 shows the comparison. For the permeable structure the match is rather good (on average a bias of $K_t = 0.02$ with RMSE = 0.0604) but for the impermeable structure there is a systematic overestimate of the wave transmission (bias of $K_t = 0.15$ with RMSE = 0.1587). Replacing $c = 0.64$ in Eq. (2) for permeable structures by $c = 0.61$ would remove the bias for the permeable structure while replacing $c = 0.8$ in Eq. (2) for impermeable structures by $c = 0.54$ would remove the bias for the impermeable structure. However, then the wave transmission for values larger than about $K_t = 0.8$ would be overestimated while those for smaller values would be underestimated.

Note that in the present tests for slightly submerged structures ($-1 < R_c/H_{m0} < 0$) the permeable structure showed less wave transmission than the impermeable structure, while the expressions by d'Angremond et al. (1996) predict the opposite for slightly submerged structures. For the more submerged structures ($-2.5 < R_c/H_{m0} < -1$) the expressions do not provide accurate estimates due to the upper limit (either $K_t = 0.8$ or $K_t = 1.0$).

The upper right panel of Fig. 12 shows the comparison between the data and the expression by Goda and Ahrens (2008) for permeable structures. The comparison shows a systematic overestimation of the

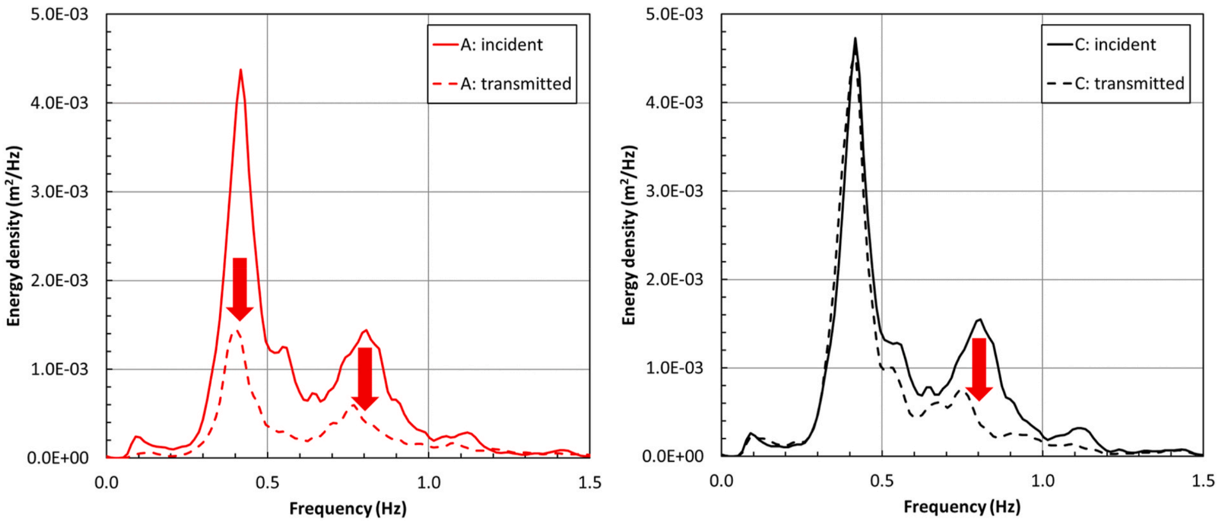

Fig. 11. Changes in spectral shape for the impermeable structure (Structure A: left) with considerable wave dissipation and for the perforated structure (Structure C: right) with relatively limited wave dissipation, for the same offshore wave condition.

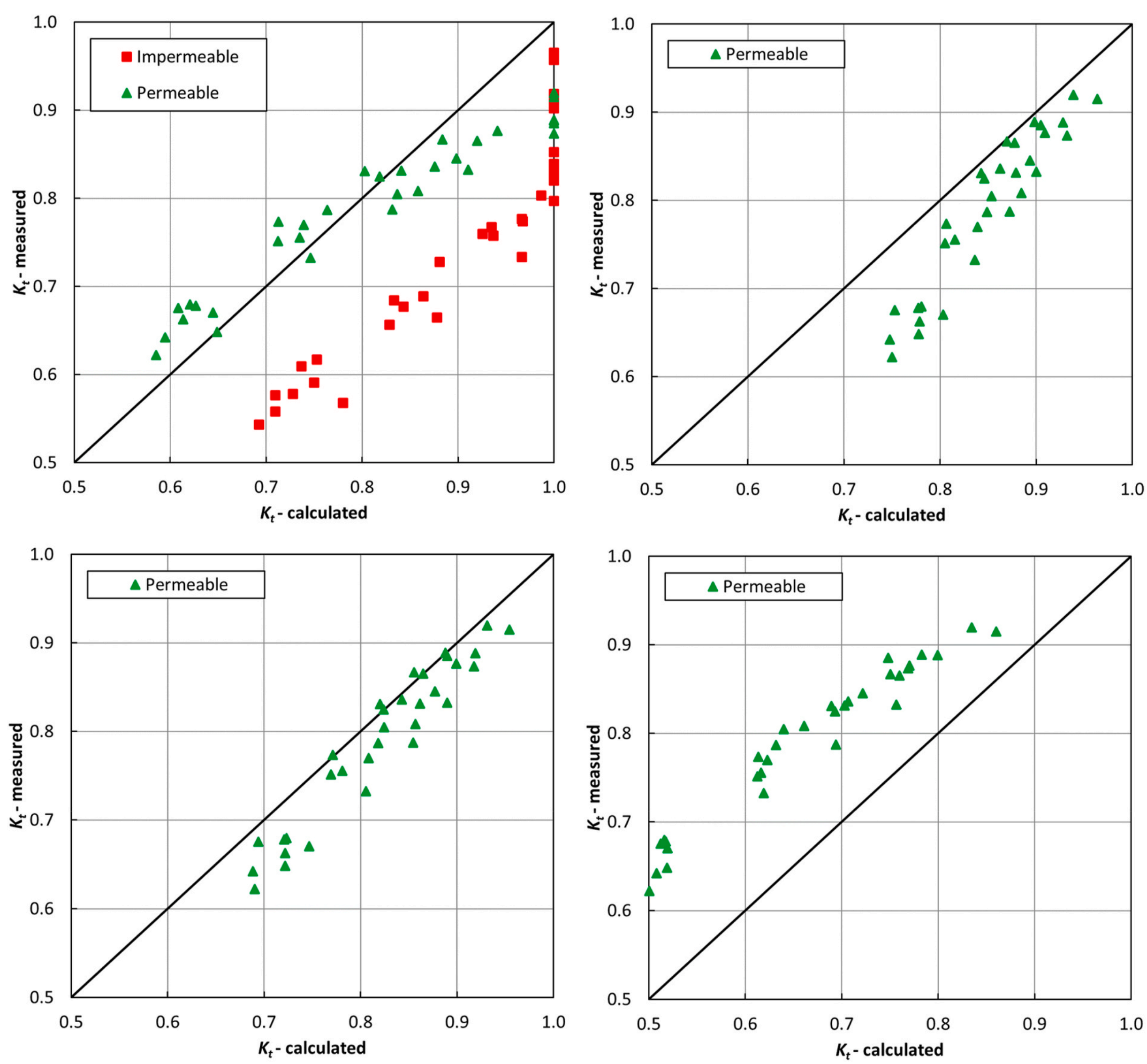

Fig. 12. Comparison between measured and predicted wave transmission coefficients; Upper left panel for d'Angremond et al. (1996) (Eq. (2)); Upper right panel for Goda and Ahrens (2008); Lower left panel for Tomasicchio et al. (2011); Lower right panel for Kurdistani et al. (2022) (Eq. (5)).

measured values (on average a bias of $K_t = 0.06$ with RMSE = 0.0604). The lower left panel of Fig. 12 shows the comparison between the data and the modified expression from Goda and Ahrens (2008) as proposed by Tomasicchio et al. (2011). The comparison shows overestimations of the measured values but the differences are clearly less than for the original expression by Goda and Ahrens (2008) (on average a bias of $K_t = 0.03$ with RMSE = 0.0405). The lower right panel of Fig. 12 shows the comparison between the expression by Kurdistani et al. (2022) for homogeneous submerged rubble mound structures as shown in Eq. (5) and the test results for permeable structures. The graph shows that the test results show a systematically higher wave transmission than those predicted using Eq. (5) (on average a bias of $K_t = 0.13$ with RMSE = 0.1304). Replacing the coefficient 0.428 in Eq. (5) by the value 0.53 would remove the bias. However, then the wave transmission for values larger than about $K_t = 0.85$ would be overestimated while those for values smaller than about $K_t = 0.7$ would be underestimated. Note that the expression by Kurdistani et al. (2022) for homogeneous submerged rubble mound structures as shown in Eq. (5), was derived based on a larger data-set of permeable structures, including variations of for instance the porosity ($0.40 \le n \le 0.60$) and stone diameter (0.017 m $\le D_{n50} \le$ 0.193 m).

4.2.2. New expression

Since the mentioned existing empirical expressions show bias and other systematic deviations, while also for the perforated structures no expression exists, a new empirical expression is developed that summarize the present test results. For this purpose, the following expression is used:

$$K_t = c_1 \tanh\left(-\frac{R_c}{H_{m0}} + c_2\left(\frac{B}{L_{m-1,0}}\right)^{c_3} + c_4\right) + c_5 \quad (6)$$

where the crest height is made non-dimensional using the wave height and the crest width is made non-dimensional using the wave length based on the spectral wave period: $L_{m\text{-}1,0} = (g/2\pi)\, T_{m\text{-}1,0}^2$. This means that the influence of the wave steepness and crest width are combined in one ratio (*i.e.* $B/L_{m\text{-}1,0}$). The coefficients in Eq. (6) vary to some extent for each of the five structures. These coefficients are shown in Table 1 together with the values for the RMSE.

Fig. 13 illustrates the shape of Eq. (6). The curves in Fig. 13 are extrapolated (dashed parts of the curves) to higher structures than tested in the present test programme. As will be explained in the next section, the (extrapolated) curve for permeable structures (Structure B) is confirmed by other data. For the impermeable structure (Structure A) and for the perforated structure with an impermeable screen (Structure D), the deviations from the coefficients for the permeable structure (Structure B) are based on the present data (only coefficients c_1 and c_4 are different). For the other two structures (Structures C and E) test results are available also for (slightly) emerged structures. The test results indicate that for these structures (C and E) the wave transmission is likely not to reach such low transmission values for (non-tested) structures that are more emerged since for these structures (C and E), the waves can relatively easily propagate through the structure, even if they are emerged. Therefore, coefficients c_1 and c_5 that determine the asymptotic values for very high and very low freeboards, are different for these structures (Structures C and E). Nevertheless, the validity of the expressions for emerged structures still needs to be examined.

Table 1
Coefficients in Eq. (6).

Structure type	c_1	c_2	c_3	c_4	c_5	RMSE
A: Impermeable structure	0.47	3.1	0.75	0	0.5	0.0166
B: Permeable structure (rubble mound structure)	0.43	3.1	0.75	−0.25	0.5	0.0198
C: Perforated structure	0.13	3.1	0.75	−0.15	0.82	0.0149
D: Perforated structure with screen	0.40	3.1	0.75	−0.15	0.5	0.0229
E: Perforated structure with perforated screen	0.17	3.1	0.75	−0.15	0.76	0.0137

Fig. 14 shows the measured versus calculated wave transmission using Eq. (6). This figure shows that the empirical expression summarizes the data accurately (note that Eq. (6) is calibrated based on these data), and accounts for effects of the wave height, the wave steepness (or wave length), the freeboard and the crest width. Note that Eq. (6) does not include (potential) influences by the local water depth, porosity and stone diameter; within the tested range the influence of the local water depth is not clearly present while for the rubble mound structure (Structure B) the porosity and stone diameter have not been varied. The expression is based on data for submerged impermeable, permeable and perforated structures ($-2.5 < R_c/H_{m0} < 0$). For two perforated structures (Structures C and E) some emerged structures have been tested up to structures ($R_c/H_{m0} = 0.5$). The wave steepness was in the range between $s_{m\text{-}1,0} = 0.015$ and 0.033. The non-dimensional crest width varied between $B/L_{m\text{-}1,0} = 0.017$ and 0.075, or $B/H_{m0} = 0.9$ and 2.3. Only trapezoidal-shaped structures with slope angles of 1:2 have been examined.

4.3. Comparison of new expression with other data

For permeable low-crested structures available data by Daemen (1991) and Calabrese et al. (2002) has been compared to Eq. (6) using the coefficients in Table 1 for permeable structures. Tests by Daemen (1991) were with trapezoidal rubble mound structures with 1:1.38 slopes and a permeable core, and Calabrese et al. (2002) were with trapezoidal rubble mound structures with 1:2 slopes. Calabrese et al. (2002) varied the crest width. Note that those data-sets cover a somewhat different range of conditions and structure geometries since a considerable portion of those tests are for emerged structures (up to $R_c/H_{m0} = 4$) and cover a wider range of the crest width (up to $B/L_{m\text{-}1,0} = 0.27$ or $B/H_{m0} = 10.6$).

Fig. 15 shows the comparison between Eq. (6) and the available data by Daemen (1991) and Calabrese et al. (2002). The relative freeboard (R_c/H_{m0}) is the most important ratio to estimate wave transmission (on the horizontal axis of the left panel), but also the relative crest width ($B/L_{m\text{-}1,0}$) affects wave transmission (not on the horizontal axis of the left panel), the two curves in the left panel of Fig. 15 are obtained using Eq. (6) with two different values of the relative crest width, to illustrate the range of influence of the relative crest width for the shown data points. These curves in the left panel of Fig. 15 are for a relative crest width of $B/L_{m\text{-}1,0} = 0.02$ and $B/L_{m\text{-}1,0} = 0.2$ since most of the tests are within that range of crest widths. The RMSE value for the data by Daemen (1991) is RMSE = 0.0397 for the data by Calabrese et al. (2002) RMSE = 0.0577 (the bias is less than $K_t = 0.01$ for each of the three subsets). The match between the measured and calculated wave transmission is good, as illustrated in the right panel of Fig. 15.

5. Conclusions and recommendations

The wave transmission at low-crested structures has been investigated by means of physical model testing in a wave flume. The trapezoidal structures were either impermeable, permeable (homogenous rubble mound structure) or hollow with a perforated surface. Three types of the latter were tested. The perforated structures can be seen as artificial reef structures but in the performed test programme they primarily serve as structures to investigate processes related to wave transmission. In the performed tests, the low-crested structures were mostly submerged. The study provides the following insights.

- Wave transmission for tested hollow perforated structures is clearly larger than for impermeable and permeable structures, unless an impermeable vertical screen is placed inside the hollow structure. In that case the orbital motion of the wave is strongly affected and the impermeable screen results in much lower wave transmission,

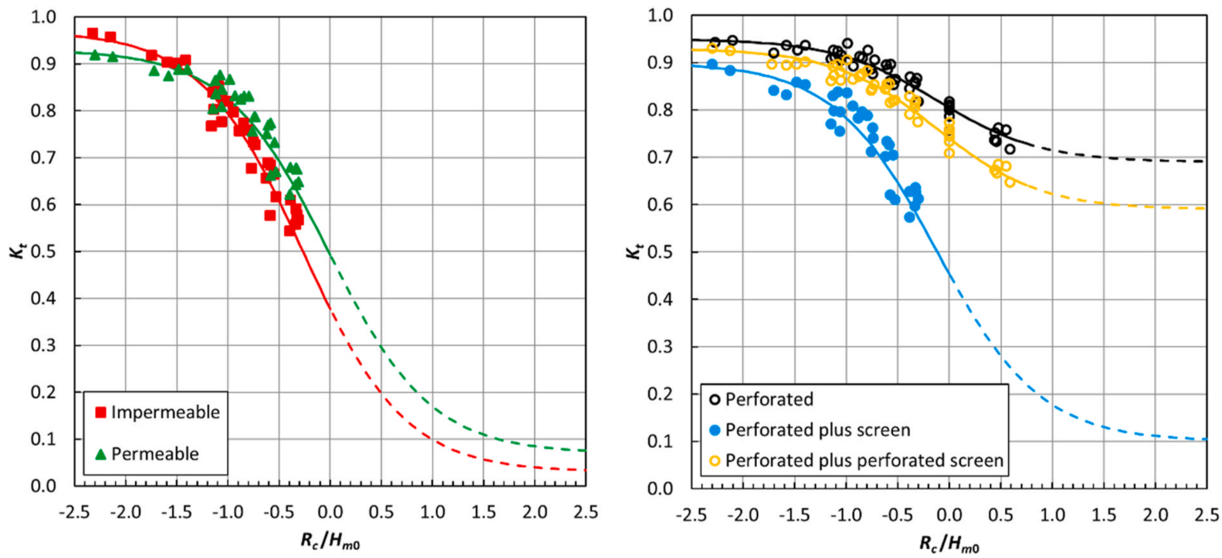

Fig. 13. Expressions to summarize the present test results (Eq. (6)); the dashed parts of the curves cover a range without tests in the present test programme (extrapolations).

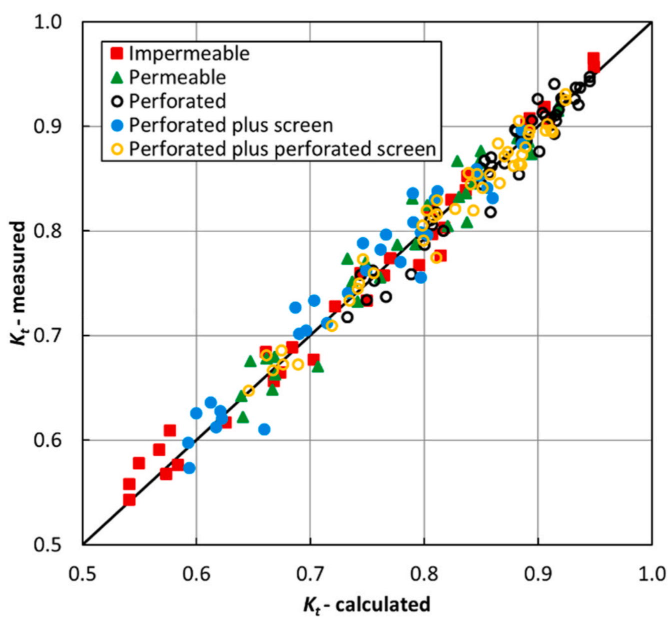

Fig. 14. Measured versus calculated wave transmission coefficients, using Eq. (6).

comparable to those for impermeable and permeable structures. For the other hollow perforated structures, the wave reflection and wave dissipation are relatively small, also if a perforated vertical screen is placed inside the hollow structure. The effectiveness of an impermeable vertical screen to reduce wave transmission assists designers of artificial reefs to design structures that reduce wave transmission.

- Wave transmission for impermeable and permeable structures is comparable but not the same. For structures that have a crest deep below the waterline, the wave transmission tends towards 100% (K_t = 1), unlike described by some existing empirical methods. For very submerged structures the wave transmission for permeable structures is somewhat less than for impermeable structures. For structures with a crest at the waterline or just below, the wave transmission is somewhat larger for permeable structures than for impermeable structures. Apparently, the wave breaking process is less intense for permeable structures than for impermeable structures. The flow through the permeable structure towards the wave front may reduce the intensity of the wave breaking and increase the wave transmission for permeable structures compared to impermeable structures.
- Obviously, the wave transmission reduces for higher structures (*i.e.* less submerged). Wave transmission for impermeable and permeable structures, as well as for the perforated structure with a vertical screen, consistently show that the wave transmission also decreases for wider crests (B/H_{m0}) and for a higher wave steepness ($s_{m-1,0}$). For these three structure types the wave periods at the rear side reduce compared to the wave periods at the front. For the perforated structures that lead to a relatively low amount of wave reflection and wave energy dissipation (*i.e.* without an impermeable vertical screen), the opposite trend was found, namely an increase in the wave period.
- Empirical expressions exist for impermeable and permeable structures. Although observed trends with respect to crest level, crest width and wave steepness are present in the applied expressions, the match between the test results and earlier empirical expressions is not very accurate, except for the expressions by d'Angremond et al. (1996) and Tomasicchio et al. (2011) that show a quite good agreement with the test results for the permeable structure. Nevertheless, a new expression (Eq. (6)) better describes the test results. The new expression matches rather well with two other available data-sets for permeable structures. The ranges of validity of this expression (Eq. (6)) for permeable structures, based on the ranges of the three applied data-sets, is characterised by crest levels between $-2.5 \leq R_c/H_{m0} \leq 2.5$ and crest widths between $0.017 \leq B/L_{m-1,0} \leq 0.27$ (or $0.9 \leq B/H_{m0} \leq 10.6$). For impermeable structures and perforated structures, the expressions are considered valid for submerged structures only. It is recommended to analyse the validity of the expression for impermeable structures also for emerged structures. Since the tests did not contain conditions where wave breaking occurred seaward of the low-crested structures, it is recommended to validate the expressions also for low-crested structures for such depth-limited wave conditions.

For applications of artificial reefs to enhance marine life and to improve the biodiversity, it is recommended to study the velocities that can cause dislodgement of underwater flora and the velocities that are too large for aquatic fauna. Artificial reefs can be designed such that the desired aquatic flora and fauna is enhanced. For that purpose, more

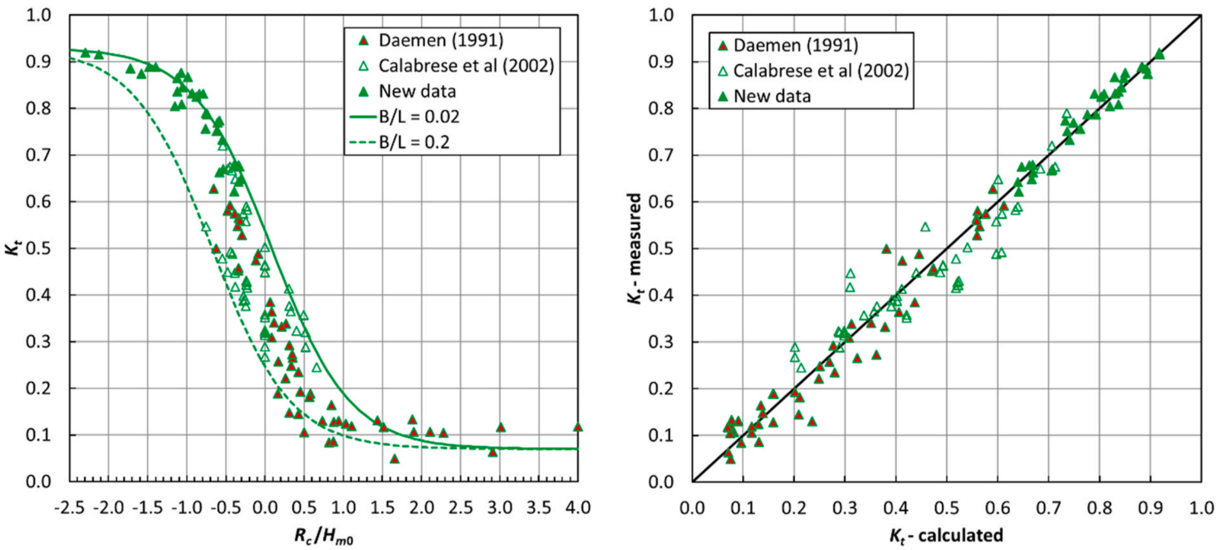

Fig. 15. Comparison between data by Daemen (1991) and Calabrese et al. (2002) for permeable structures and Eq. (6). Left panel: measured values as function of the dimensional freeboard; Right panel: measured versus calculated transmission coefficients (Eq. (6) with coefficients for permeable structures given in Table 1).

information is required on velocities that occur during storm conditions for specific shapes of artificial reefs. For estimates of velocities inside perforated structures Buis (2022) provides information. Besides velocities, also the influence of the amount of light in artificial reefs, such as inside perforated structures, needs further investigation. The amount of perforation (size of gaps and percentage of open space) is likely to affect the ecological success (in addition to for instance the material, roughness and variations of the substrate), and the effectiveness of such coastal protection structures with respect to the wave transmission.

Author statement

MvG: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Supervision, Writing-Original draft; LB: Methodology, Investigation, Formal analysis, Data curation, Visualization; JvdB: Methodology, Investigation, Review & Editing; DW: Methodology, Investigation, Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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