LARGE-SCALE PHYSICAL MODEL TESTS TO DETERMINE INFLUENCE FACTOR OF ROUGHNESS FOR WAVE RUN-UP OF CHANNEL SHAPED BLOCK REVETMENTS

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ABSTRACT

To optimize the design and assessment of placed block revetments, nine different types of block revetments were tested on near-prototype scale in the Deltares Delta Flume. These tests were carried out to determine the stability under wave loading and to determine their ability to reduce the wave run-up height. This paper focuses on the wave run-up height reduction and wave overtopping discharge reduction of so-called channel shaped placed block revetment. These blocks have a specific shape which is characterised by notches at the sides of the block. By placing these blocks in a pattern, a channel pattern is created in which the wave run-up tongue is dissipated to a certain extend leading to a reduced wave run-up height and a reduced mean wave overtopping discharge. This paper describes the performed tests with channel shaped placed blocks and proposes a formula to determine the influence factor for roughness ($\gamma_f$) for a revetment consisting of these blocks. Distinction is made between an influence factor for roughness with respect to wave run-up ($\gamma_{fru}$) and an influence factor for roughness with respect to the mean wave overtopping discharge ($\gamma_{fq}$).

KEYWORDS: Wave run-up, influence factor of roughness, channel shaped placed block revetment, Delta Flume

1 INTRODUCTION

Within the framework of the ‘Comparative research of placed block revetments’, Rijkswaterstaat, three Dutch Water Boards (united in the Dutch ‘Project Overstijgende Verkenningen Waddenzeedijken’) and several commercial suppliers of placed block revetments investigate whether placed block revetments can be implemented in a more efficient way. There are several types of placed block revetments available which differ in shape and all have their own specific characteristics. The project focussed on two aspects of placed block revetments: stability and wave run-up reduction due to roughness. To this end Deltares performed large-scale physical model tests in the Deltares Delta Flume. Nine different types of placed block revetments were tested for stability. Three types of placed block revetments (Hillblock, RONA® Taille and Verkalit® GOR) were also tested to determine their ability to reduce wave run-up and wave overtopping, which is the focus of this paper. The three tested placed block revetments are all a relatively new type of placed block revetment that can be applied on a filter layer to prevent erosion of dikes and banks under hydraulic loads such as waves or currents. An impression of the tested blocks is given in Figure 1, Figure 2, and Figure 3.
1.1 Literature

To determine the wave run-up height on a slope, usually the so-called TAW (2002) formula is used.

\[
\frac{z_{2\%}}{H_{m0}} = \min \left[ a \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \xi_{m-1,0} \right] \left[ \gamma_f \cdot \gamma_\beta \cdot \left( b - \frac{1.5}{\sqrt{\xi_{m-1,0}}} \right) \right]
\]

\[
\xi_{m-1,0} = \frac{\tan \alpha}{\sqrt{s_{m-1,0}}}
\]

Where \( z_{2\%} \) is the run-up height exceeded by 2% of the incident waves, \( H_{m0} \) is the spectral significant wave height, \( \gamma_b, \gamma_f, \) and \( \gamma_\beta \) are influence factors for the presence of one or more berms, roughness and angle of wave incidence, \( \xi_{m-1,0} \) is the breaker parameter, \( \alpha \) is the slope angle, \( s_{m-1,0} \) is the wave steepness, and \( a \) and \( b \) are stochastic normal distributed parameters. The Coefficient of Variation of both \( a (\mu_a = 1.65) \) and \( b (\mu_b = 4.0) \) is equal to \( c_v = 0.07 \), where \( \mu \) is the mean value, \( \sigma \) is the standard deviation and \( c_v = \sigma / \mu \). Equation (1) is based on many research projects which are mainly performed in the 1980’s and are based on both large- and small-scale model tests. An impression of these test results is given in TAW (2002) which is reprinted as Figure 4. In that figure, Equation (1) is shown as ‘formula 5a’ and ‘formula 5b’.

To determine the influence factors of roughness (\( \gamma_f \)), several research is conducted over the last decades. An overview of this research is given in Capel (2015). In TAW (2002), a list with influence factors for roughness of several top layers, which is based on DWW (2002), is given as a fixed value. With respect to the influence factor of roughness TAW (2002) makes no distinction between wave run-up and wave overtopping. For relatively high values of \( \gamma_b \xi_{m-1,0} \), TAW (2002) suggests to adapt the given influence factor of roughness \( \gamma_f \) in case \( \gamma_b \xi_{m-1,0} > 1.8 \). From \( \gamma_b \xi_{m-1,0} = 1.8 \) the influence factor of roughness is increasing linearly to a value of 1.0 for \( \gamma_b \xi_{m-1,0} = 10 \).

No literature was found that describes the roughness coefficient for wave run-up or wave overtopping discharge for channel shaped placed block revetments.
2.1 Model facility and scaling

All tests were performed in the ‘old’ Delta Flume of Deltares (location of Marknesse). This flume had a length of 235 m, a width of 5 m, and a depth of 7 m. Wave fields with a significant wave height up to $H_s = 1.6$ m could be generated in this flume. It is remarked that this flume does not exist anymore and is replaced by a new larger Delta Flume (location of Delft) which can generate higher waves. The wave board was able to create regular and irregular waves and was equipped with the so-called ‘Active Reflection Compensation System’ which minimized the re-reflections from the wave board. The research is performed on a geometric scale of 1:2 and is based on Froude scaling to obtain the same ratio between inertia and gravity. The 1:3 slope consisted of a dummy part (usually smooth concrete) and a testing part on which Hillblocks, RONA® Taille or Verkalit® GOR were placed on a filter layer.

2.2 Test program and measurement

Two test projects were carried out in 2011 and 2014. Varied parameters within the test series were the type of placed block revetment (‘Hillblocks Basic’, ‘Hillblock Slim’, ‘RONA® Taille or ‘Verkalit® GOR’ see Figure 1), the height of the used block (Hillblock: 0.15 m and 0.20 m, RONA® Taille and Verkalit® GOR: 0.15 m), the position of the blocks on the slope, the water level and the wave conditions. Reference tests were carried out with other types of block revetments (Basalton, Hydroblock, and RONA® ton) of which the influence factor of roughness is given in TAW (2002). Within each subset four to thirteen tests were carried out with different wave heights and different wave steepness. The wave conditions of the entire test program varied as follows: $0.45 \, \text{m} < H_{m0} < 1.50 \, \text{m}$ and $0.011 < s_{m-1,0} < 0.057$. The duration of most tests was approximately 1000 waves. Specific details of the test set-up and the test program are given in Van Steeg (2012, 2015a,b,c). A global overview of the test program is given in Table 1. An impression of the test set-up of Subset 1 - 4 is given in Figure 5.

During all tests wave conditions were measured using a set of three wave gauges and by applying the method of Mansard and Funke (1980) to separate incident and reflected waves. The wave run-up height was measured visually for each individual wave run-up by using lines which were drawn at the slope at every 0.5 m ($\Delta z \approx 0.16$ m), resulting in wave run-up distributions from which the $z_{25\%}$ value was derived. Since several tests were originally not intended to test wave run-up heights, no other wave run-up measurement equipment was installed. The visual measurements were in several cases performed by two independent persons resulting in the same value of $z_{25\%}$ indicating that this approach is reproducible and reliable.
### Table 1. Global overview of test program.

<table>
<thead>
<tr>
<th></th>
<th>type of block</th>
<th>height of block $D$ (m)</th>
<th>position on slope $Z$ (m + bottom)*</th>
<th>wave spectrum***</th>
<th>water level $Z$ (m + bottom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel shaped placed block revetment</td>
<td>Subset 1</td>
<td>Hillblock-Basic</td>
<td>0.15</td>
<td>5.5 – 8.3**</td>
<td>Pierson Moskowitz</td>
</tr>
<tr>
<td></td>
<td>Subset 2</td>
<td>Hillblock-Slim</td>
<td>0.15</td>
<td>5.5 – 8.3**</td>
<td>Pierson Moskowitz</td>
</tr>
<tr>
<td></td>
<td>Subset 3</td>
<td>Hillblock-Basic</td>
<td>0.15</td>
<td>5.5 – 8.3**</td>
<td>JONSWAP</td>
</tr>
<tr>
<td></td>
<td>Subset 4</td>
<td>Hillblock-Slim</td>
<td>0.15</td>
<td>5.5 – 8.3**</td>
<td>JONSWAP</td>
</tr>
<tr>
<td></td>
<td>Subset 5</td>
<td>Hillblock-Basic</td>
<td>0.15</td>
<td>2.0 – 8.3</td>
<td>JONSWAP</td>
</tr>
<tr>
<td></td>
<td>Subset 6</td>
<td>Hillblock-Basic</td>
<td>0.20</td>
<td>2.0 – 8.3</td>
<td>JONSWAP</td>
</tr>
<tr>
<td></td>
<td>Subset 10</td>
<td>Verkalit® GOR</td>
<td>0.15</td>
<td>2.0 – 8.3</td>
<td>JONSWAP</td>
</tr>
<tr>
<td></td>
<td>Subset 12</td>
<td>Verkalit® GOR</td>
<td>0.15</td>
<td>5.5 – 8.3</td>
<td>JONSWAP</td>
</tr>
<tr>
<td></td>
<td>Subset 14</td>
<td>Verkalit® GOR</td>
<td>0.15</td>
<td>5.5 – 8.3</td>
<td>JONSWAP</td>
</tr>
<tr>
<td></td>
<td>Subset 15</td>
<td>Verkalit® GOR</td>
<td>0.15</td>
<td>2.0 – 8.3</td>
<td>JONSWAP</td>
</tr>
<tr>
<td></td>
<td>Subset 16</td>
<td>RONA® Taille</td>
<td>0.15</td>
<td>2.0 – 8.3</td>
<td>JONSWAP</td>
</tr>
</tbody>
</table>

** The position on the slope is where the specific block is placed. The other parts of the slope consisted of smooth concrete unless indicated otherwise.

** From $Z = 2.0$ m - 5.5 m: Basalton slope, see also Figure 3.

*** The wave spectrum was varied due to requirements of the test set-up with respect to stability testing of the revetment (which is outside the scope of this paper)

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**Figure 5.** Left: Impression of test set-up of Subset 1, Subset 2, Subset 3, and Subset 4. Right: during testing.

### 3 RESULTS AND ANALYSIS

Each test resulted in a value of $z_{2\%}$ which was made dimensionless by the significant wave height $H_{\text{m0}}$. The measured dimensionless wave run-up height $z_{2\%}/H_{\text{m0}}$ is given as function of the breaker parameter $\xi_m$ in Figure 6 and Figure 7. The subsets are shown in three different graphs with each graph representing tests with a different water depth: $d = \{3.1, 4.7, 5.5\}$ m. The reference tests (Subset 7, 8, 9, 11, 13) consisted of a combination of a section with a smooth slope ($\gamma = 1.0$) and a section with a slope with some roughness. No reference tests with a water depth of 5.5 m were carried out. According to
TAW (2002) the influence factor for roughness of the used placed block revetments (Basalton, RONA®ton, and Hydroblock) at the reference sections is equal to $\gamma_l = 0.9$. The influence factor for roughness of the entire slope (combination of smooth and rough slope) is determined for each test using the software tool PC-Overtop which is based on TAW (2002) methodology. Resulting values of the influence factor for roughness of the entire reference slope are therefore $0.90 < \gamma_l < 0.95$, depending on the specific test conditions. In Figure 6 (right) it can be seen that in some cases the measured run-up height of the reference tests (black markers) are in some cases higher than according to the TAW (2002) formula (red line). The TAW (2002) is plotted for $\gamma_l = 1.0$ and ‘mean’ values for parameters $a$ and $b$ ($\mu_a = 1.65$ and $\mu_b = 4.0$, see Equation (1)). It is therefore concluded that the measurements with the reference tests do not agree with the ‘mean’ TAW formula. For these specific tests there is a need to adapt the TAW formula to agree with measured run-up heights at the reference tests. This adaptation is performed by correcting the TAW (2002) formula with a correction factor $C$ as follows:

$$\frac{z_{2m}}{h_{m0}} = C \cdot \min \left[ 1.65 \cdot \gamma_f \cdot \xi_{m-1,0} \cdot \gamma_f \cdot \left( 4.0 - \frac{1.5}{\sqrt{\xi_{m-1,0}}} \right) \right]$$  (3)

Based on a comparison between the measured wave run-up height of the reference tests and the TAW (2002) formulation, a value for $C$ is determined. Figure 6 and Figure 7 show that the discrepancy between the measured values and the TAW (2002) prediction is higher for a larger water depth. It is also remarked by Szmytkiewicz et al (1994) that larger wave run-up values were recorded for larger water depths. Reference is made to the right graph in Figure 7 where the correction factor $C$ of all reference tests is plotted as function of the water depth $d$. It can be seen that, with increasing water depth, the correction factor $C$ increases (indicating a larger wave run-up height). For the performed tests the following estimate is made to correct the TAW (2002) formula:

$$C = 0.074 \cdot d + 0.81$$  (4)

Equation (4) can only be used for the conditions which are comparable with the tests as described in this paper since the correction factor is not made dimensionless. Equation (4) is not made dimensionless since it is unknown which parameters are relevant. It is likely that water depth, significant wave height and wave period are important parameters. Now it is possible to compare the measured results with the adapted TAW formula as given in Equation (3) and Equation (4) and to derive the influence factor for roughness with respect to wave run-up, $\gamma_{l,w}$. For relatively large values of $\gamma_b \cdot \xi_{m-1,0}$ a correction is made according to the procedure as described in Section 1.1 of this paper.

![Figure 6. Test results. Left: SWL = 3.1 m + bottom flume, Right: SWL = 4.7 m + bottom flume.](image1)

![Figure 7. Test results. Left: SWL = 5.5 m + bottom flume, Right: correction factor as function of water depth for reference tests.](image2)
4.1 Wave run-up

The influence factor for roughness with respect to wave run-up $\gamma_{f,ru}$ is determined by measuring the wave run-up height and to compare this with the derived wave run-up height of a fictitious smooth slope. This is a common procedure to determine the influence factor of block revetments and is also implemented in this way in TAW (2002). The applied method is also practical since wave overtopping measurements on large-scale models is relatively difficult. The reduction of wave run-up height of the tested placed blocks revetment is due to the channel shaped characteristic of the used blocks, see also Figure 1, Figure 2, and Figure 3. It is therefore likely that the reduction of wave run-up height increases with a larger volume of these channels. In this analysis this is characterised by the total volume of the channels per m² indicated with $d_{channel}$ (unit: m³/m²). It is emphasized that only the hollow sections around the ‘neck’ of the block are taken into account and not the volume around the ‘toe’ or the ‘head’ of the block. An important condition for this approach is that the openings in the head of the blocks are large enough to allow the wave run-up tongue to enter the channels. The open volume per m² is made dimensionless with the significant wave height: $d_{channel}/H_{m0}$. The determined influence factor of roughness $\gamma_{f,ru}$ as function of the dimensionless parameter $d_{channel}/H_{m0}$ is given in Figure 8.

![Figure 8. Determined influence factor of roughness as function of the dimensionless channel volume.](image)

In Figure 8 it can be seen that, for increasing values of dimensionless channel volume ($H_{m0}/d_{channel}$), the influence factor of roughness ($\gamma_{f,ru}$) increases. The suggested formula to describe the influence factor for roughness as function of the dimensionless parameter $H_{m0}/d_{channel}$ is as follows:

$$\gamma_{f,ru} = 0.0028 \cdot \frac{H_{m0}}{d_{channel}} + f$$  \hspace{1cm} (5)

With $f = 0.69$, 0.72, and 0.75 for respectively Hillblock, RONA® Taille, and Verkalit® GOR.

4.2 Mean wave overtopping discharge

Nowadays the wave run-up height is not much used anymore and the mean wave overtopping discharge is usually used as a key design parameter. According to TAW (2002) the influence factor for roughness of wave run-up can also be used in the wave overtopping formulas. However, no foundation to support this was found in literature. Capel (2015) showed that the influence factor of roughness for wave overtopping may be different for different wave overtopping discharges. However, the theory of Capel (2015) was based on data obtained by experiments with block revetments which are characterized by protruding parts and not characterised by channel shaped placed blocks. Therefore an alternative theory is given in this section to study how channel shaped placed block revetments will influence the mean wave overtopping. No overtopping measurements were performed but a theoretical approach is developed which is described in this section. The basic idea of the developed theory is that a part of the volume of every wave run-up tongue is sinking into the channels of the blocks and does not overtop. The wave overtopping volume of each individual wave overtopping event is therefore decreased by the total volume of the hollow sections at the entire slope above the still water line. This is illustrated with a fictitious revetment with crest height $R_c$ (m) and a slope with a steepness of $\cot \alpha$ (°) which is covered completely by channel shaped placed blocks with a channel volume per m² of $d_{channel}$ (m³/m²). The storage volume $V_{storage}$ per m width (m³/m) of the revetment is equal to:
\[ V_{storage} = L_{slope} \cdot d_{channel} = R_c \cdot \sqrt{1 + \cot \alpha} \cdot d_{channel} \] (6)

The following assumptions are made when applying Equation (6):
- The channels are completely empty at the moment the wave run-up tongue is above the blocks;
- The layer thickness is larger than the storing thickness \(d_{channel}\);
- The openings in the head of the blocks are large enough allowing the water to enter the channels;
- The water layer does not ‘overshoot’ the open areas of the head of the blocks.

Now, the storage volume, \(V_{storage}\), of each individual wave run-up event can be determined. The mean wave overtopping discharge is formed by individual wave overtopping volumes which are described by:

\[ P_v = 1 - e^{-\left(\frac{V}{a}\right)^b} \]  
\[ P_{ov} = e^{-\left(\frac{(\sqrt{\cdot m0.02}) R_c}{V_{wave}}\right)^2} \]  

With \(a\) is the scale factor \((a = 0.84 \cdot T_m \cdot q/P_{ov})\), \(b\) is the shape factor \((b = 0.73 + 0.5 \cdot (q/g \cdot H_{n0} \cdot T_{m-1.0})^{0.8}\) according to Zanuttigh et al (2013) and \(b = 0.75\) according to TAW (2002)), \(P_v\) is the probability that wave overtopping volume per wave is greater than or same as \(V\), \(V\) is wave overtopping volume per wave, \(T_m\) is the average wave period, \(T_{m-1.0}\) is the spectral wave period, \(q\) is the mean wave overtopping discharge, \(P_{ov} = (N_{ov}/N_u)\) is the probability of overtopping per wave, \(N_{ov}\) is the number of overtopping waves, \(N_u\) is the number of incoming waves during storm, \(H_{n0}\) is the spectral significant wave height and \(g\) is acceleration due to gravity. It is noted that this approach does not include the influence of the water depth. It is assumed that the mean wave period and the spectral wave period are related as follows:

\[ T_m = 0.91 \cdot T_{m-1.0} \]  

In the theoretical model, a number of waves are generated resulting in 2000 overtopping waves. Based on Equation (6) – Equation (9), the wave overtopping volume per wave \(V\) is determined and sorted from small to large. An example is given for the following conditions: \(\cot \alpha = 3\), \(R_c = 1.59\) m, \(T_{m-1.0} = 4.8\) s, \(H_{n0} = 1.0\) m, \(N_u = 6284\), \(d_{channel} = 0.0447\) m (based on Hillblock – Basic with \(D = 0.15\) m). The shape parameter \(b\) is based on Zanuttigh et al (2013) (it is noted that this gives a small discrepancy with TAW (2002) since TAW (2002) uses a value of \(b = 0.75\)). The mean wave overtopping discharge \(q\) is determined using the TAW (2002) formula and is equal to \(q = 10\) l/s/m. The wave overtopping volume per wave overtopping event as function of the probability of exceedance for a smooth slope and a slope with channel shaped placed blocks are given in the left graph of Figure 9. The cumulative volume as function of the exceedance probability (with waves sorted from small to large) is given in the right graph of Figure 9.

![Figure 9](image)

Figure 9. Left: overtopping volume per wave. Right: cumulative volume. Overtopping events are sorted from small to large. The graphs are only applicable for the given conditions.

It can be seen that, for the given conditions and according to this theoretical model, the revetment with channel shaped placed blocks reduces the wave overtopping discharge significantly. The total overtopping volume is reduced to 26% (red dot in right graph of Figure 7) of the volume that should have occurred in case of a smooth slope and according to TAW (2002). Approximately 80% (blue dot) of the waves that were overtopping in case of a smooth slope do not overtop at all when channel shaped placed blocks are applied. Using the TAW (2002) formulas, the corresponding influence factor of roughness can now be calculated for this specific example. The same analysis is carried out for other cases where the significant wave height \((H_{n0} = \{1.0; 2.0\})\) m was varied as well as the mean wave overtopping discharge \((q = \{1; 10; 50\})\) l/s/m by varying the crest height \(R_c\). The breaker parameter \(\xi_{m-1.0}\) and the spectral wave steepness \(s_{m-1.0}\) were kept constant by adapting the spectral wave period \(T_{m-1.0}\). All other parameters are equal to the example given above. Results of this
exercise are visualised in Figure 10.

![Figure 10. Comparison of derived model and Capel (2015).](image)

A comparison with Capel (2015) can now be made. Capel proposed to determine the influence factor of roughness for wave overtopping of a slope consisting of protruding elements as follows:

\[
\gamma_{f,q} = 1 + 0.585 \cdot \sqrt{0.075 - s_{m-1.0}} \cdot \sqrt{\delta} \cdot \ln \left(\frac{q}{\sqrt{g \cdot H_{mo}^3}}\right)
\]  \hspace{1cm} (10)

With \( \delta \) is a measure for the roughness characteristics of the revetment. Equation (10) is rewritten as follows

\[
\gamma_{f,q} = a \cdot \ln \left(\frac{q}{\sqrt{g \cdot H_{mo}^3}}\right) + b
\]  \hspace{1cm} (11)

Where \( a \) and \( b \) are constants. Equation (10) is shown in Figure 10 as a green line where the wave steepness is equal to \( s_{m-1.0} = 0.028 \) and the roughness characteristic is equal to \( \delta = 0.08 \). It is assumed that the gradient of Equation (10) (green line in Figure 10) is equal to the gradient of the theoretical case with \( H_{mo} = 2.0 \) m and \( \xi_{m-1.0} = 2 \) (red line in Figure 10). It is also assumed that the derived influence factors for roughness for wave run-up, based on the measurements in the Delta Flume, are applicable to situations with a significant wave height of \( H_{mo} = 1 \) m and a crest height at a level which results in a wave overtopping discharge at a smooth slope of \( q = 1 \) l/s/m or:

\[
\gamma_{f,q} = \gamma_{f,ru} \quad \text{for } q = 1 \text{ l/s/m and } H_{mo} = 1.0 \text{ m}
\]  \hspace{1cm} (12)

The given approach leads to values of \( a \) and \( b \) of:

\[
a = 0.0333
\]  \hspace{1cm} (13)

\[
b = 0.27 + \gamma_{f,ru}
\]  \hspace{1cm} (14)

Equation (11) can now be rewritten as follows:

\[
\gamma_{f,q} = \gamma_{f,ru} \quad \text{for } \ln \left(\frac{q_{\text{smooth}}}{\sqrt{g \cdot H_{mo}^3}}\right) < -8.05
\]  \hspace{1cm} (15)

\[
\gamma_{f,q} = \gamma_{f,ru} + 0.27 + 0.0333 \cdot \ln \left(\frac{q_{\text{smooth}}}{\sqrt{g \cdot H_{mo}^3}}\right) \quad \text{for } \ln \left(\frac{q_{\text{smooth}}}{\sqrt{g \cdot H_{mo}^3}}\right) \geq 8.05
\]  \hspace{1cm} (16)

With a maximum of \( \gamma_{f,q} = 1.0 \).

Combining Equation (5), Equation (15), and Equation (16) gives:

\[
\gamma_{f,q} = \max \left(0.0028 \cdot \frac{H_{mo}}{d_{\text{channel}}} + f + \max \left\{0; 0.27 + 0.0333 \cdot \ln \left(\frac{q_{\text{smooth}}}{\sqrt{g \cdot H_{mo}^3}}\right)\right\}; 1.0\right)
\]  \hspace{1cm} (17)

Where \( \gamma_{f,q} \) is the influence factor for roughness to determine the mean wave overtopping discharge, \( H_{mo} \) is the incident
significant wave height, $d_{\text{channel}}$ is the open volume in the channel of the placed block revetment per m$^2$, $q_{\text{smooth}}$ is the estimated mean wave overtopping discharge when no roughness is applied (can be determined using the TAW (2002) formula), $g$ is the acceleration due to gravity and $f$ is a factor depending on the type of used placed block: $f = 0.69$, $0.72$ and $0.75$ for respectively Hillblock, RONA®Taille, and Verkalit® GOR.

5 CONCLUSIONS AND RECOMMENDATIONS

Based on large-scale physical modelling and a theoretical approach, the influence factor for roughness of a revetment consisting of channel shaped placed blocks is determined. Distinction is made between an influence factor for roughness applicable to wave run-up processes (Equation (5)) and an influence factor for roughness applicable to the mean wave overtopping discharge (Equation (17)). The given formulas are based on a dataset as summarised in Table 2 and can be used in the TAW (2002) formulation. For cases outside the tested range, such as a different slope angle, additional research is recommended. For preliminary design the restrictions as given in TAW (2002) in combination with the formulas in this paper are recommended.

The results of the research indicate a significant influence of the water depth on the wave run-up height. This influence is not incorporated in common methodologies such as TAW (2002). It is recommended to study this aspect in more detail to improve wave run-up and wave overtopping formulation.

<table>
<thead>
<tr>
<th>Table 2. Overview characteristics of tests with channel shaped placed block revetments.</th>
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</thead>
<tbody>
<tr>
<td>type of placed block</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>height of placed blocks $D$ (m)</td>
</tr>
<tr>
<td>slope angle $\cot \alpha$ (-)</td>
</tr>
<tr>
<td>channel volume per m$^2$ $d_{\text{channel}}$ (m$^3$/m$^2$)</td>
</tr>
<tr>
<td>significant spectral wave height $H_{\text{ref}}$ (m)</td>
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<tr>
<td>influence factors for berms $\gamma_0$ (-)</td>
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<tr>
<td>influence factors for angle of incidence $\gamma_1$ (-)</td>
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</tbody>
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ACKNOWLEDGEMENT

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REFERENCES


DWW, 2002, Roughness factors related to wave run-up and wave overtopping for dikes (in Dutch; original title: Ruwheidsfactoren met betrekking tot golfoorloop en golfoverslag bij dijken), May 2002.


Zanuttigh, B., van der Meer, J.W., Bruce, T., and Hughes, S., Statistical characterisation of extreme overtopping wave volumes. Proc.
ICE, Coasts, Marine Structures and Breakwaters 2013, Edinburgh, UK.