A comparison of overtopping behaviour over a permeable and impermeable crest

An insight into overtopping discharges and intensities

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1 Introduction

The purpose of this report is to investigate the differences in overtopping characteristics over the
crest of a rubble mound breakwater when the crest is made either impermeable or permeable. Among
numerous characteristics that are effected by a modification in the permeability of the
crest, this report looks specifically into three separate aspects: the design level changes that are
caused by modifications in the permeability of the crest, a comparison of the total and sector-wise
overtopping discharges and finally the differences in spatial overtopping intensities between the
two.

By looking into two well-known overtopping design guidelines for overtopping, namely, Owen
and Eurotop, this report aims to look at the differences it would make in designing a breakwater
with either an impermeable or a permeable crest. This is done by building a breakwater model in
a wave flume and comparing it with the existing guidelines and assessing the changes that best
represent the modified model.

It is also important to observe how this physical modification of the crest affects the overtopping
discharges and spatial overtopping intensities behind the crest of the breakwater. This will be
relevant for designers or contractors tasked to make changes to an existing breakwater that results
in its crest becoming impermeable. An insight into the overtopping discharges and intensities will
be extremely useful to be able to predict the overall changes and cater for them.

In order to make such observations this report uses the methodology and breakwater model
designed and set up for the M.Sc work on ‘Experimental research on spatial distribution of wave
overtopping’ by Anestis Lioutas (Lioutas, 2011). It makes use of the same experimental tests with
similar wave characteristics with the only change being that the crest is made impermeable by
adding a wooden plank at the start of the crest which does not allow any water to go through it.

While a methodology and set up for the experiments conducted for this report have been briefly
described in the following sections, the exact details of the software and instruments used to
gather the data have been left out. This information would be irrelevant since this report aims to
look only at the differences in the various overtopping characteristics between that obtained by
the permeable crest, which is the original set up, and the modified impermeable one. In doing so
it aims to achieve the objective of providing a basic ground work for a detailed look into any one
of the major aspects of overtopping behavior. It offers a catalogue of the major differences in
overtopping behavior and leaves it to the reader to conclude if it would be worth an interest to
pursue a detailed thesis into any one of the characteristic behavioral changes in overtopping
discharges.
The experiments are conducted in the ‘Lange Speurwerk Goot’ wave flume installed in the Fluid Mechanics Laboratory of the Delft University of Technology. The flume has a length of approximately 40m, with both the width and the height at 0.80m. The wave flume comes equipped with a wave generator controlled by a computer program defining various parameters such as the water depth in the flume, the required wave height and the required wave length. The wave generator uses Active Reflection Compensation (ARC) with a second order wave generation technique which allows the second-order effects of the first higher and first lower harmonics of the wave field to be accounted for in the wave generator motion. The wave generator produces irregular waves with a JONSWAP spectrum. This spectrum is assumed to be especially suitable to imitate conditions of the North Sea and hence an appropriate test for the overtopping behaviour of the breakwater.

The breakwater built inside the wave-flume is a simply designed slope with two layers of stones. The armor layer consists of stones with a stone size of $D_{50} = 60$mm while the layer below it consists of much smaller stones. The armor layer simply rests on the under-layer and there is no geo-textile present between the two. Figure 1 shows that the core of the breakwater consists of a wooden structure which extends behind the slope and makes up the storage spaces for the water which flows over the top or through the crest. The existence of the impermeable wooden structure also gives the breakwater an ‘impermeable core’.

Figure 2 shows the storage spaces which have been designated the term ‘sectors’ henceforth for the entire report. There are seven sectors in total with the first one lying directly under the crest.
While all of the sectors have the same width across the flume and the same depth, they vary in their lengths along the flume. Figure 3 shows a simplified plan view of the sectors with the varying lengths along the length of the wave flume. As can be observed from the figure the first few sectors immediately after the end of the crest have a smaller length of 5cm each while the 4th and 5th sectors have a length of 10cm each and the 6th and 7th have lengths of 20cm. The various sectors have been designed as thus since the intensity of the amount of water that overtops behind the crest is expected to decrease exponentially. While the breakwater has been designed only with the intention of studying overtopping processes it can be said to represent scales roughly between 1:15 or 1:25. Thus, on average, a distance on the breakwater model from the end of the crest to the end of sector 7 is roughly a distance of 14m in real life. The width of the crest corresponds to the length of the first sector along the wave flume making it roughly 5.6m in real life. Since overtopping measurements are recorded from the end of the crest the first sector is there solely to provide a better insight into the effects of having overtopping through a permeable crest compared to an impermeable crest.

As can be seen from Figure 2 all of the sectors were filled with the same stones used in the first under-layer of the armored breakwater. These stones are meant to replicate the real-life situation where the crest and the adjoining details behind it will be constructed on a particular surface. This surface may be grass, concrete or anything else but there will most certainly not be a hollow empty storage area for water to simply flow in to. These sectors collect the overtopped discharge and then transport them to the measuring tanks shown in Figure 4 with pumps. The measuring tanks are later weighed by a crane to obtain the volumes of water collected by each sector.
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Figure 3. A simplified plan-view of the dimensions of the water collection sectors S1 to S7. (All dimensions in centimeters)

Figure 4. The measuring tanks where water from the seven sectors is pumped into.
2.1 **The Crest**

This section clearly explains the difference between the permeable and the impermeable crest.

![Image of crest and sector boxes](image)

**Figure 5.** Red box indicates the crest and the blue box indicates the location of the first sector which is directly below the crest.

**Figure 5** shows the exact demarcation of the crest for the purpose of this report. It shows the exact point where the occurrence of overtopping is measured from. In this report overtopping is defined as that discharge which is recorded immediately after the end of the crest. This is the discharge which makes it to storage sectors S2 and beyond. In a real-life construction the location of sectors S2 and S3 will most likely be where a road or pedestrian path or any other structure meant for public use will be constructed.

Sector S1, immediately below the crest will be useful in understanding the difference in overtopping when the crest is allowed to remain permeable and when it is made impermeable. In the wave flume model of the armored breakwater the crest is made impermeable by adding a solid piece of rectangular shaped plank at the location where the slope ends. **Figure 6** shows the plank resting at the start of the crest forcing any discharge with enough energy to pass over it. The plank has rubber borders and fits perfectly with the sides of the wave flume and the start of the storage sectors to make it absolutely water-proof. The only way to go beyond the plank is by going over it. Hence, this modification in the crest is expected to provide an insight into overtopping behavior.
3 Movement of water at the crest

This section provides an insight on the physical behavior observed in the motion of water that meets the crest. When the crest is permeable, the overtopped water can be seen to make its way to sectors S2 and beyond through the crest and especially through the interface between the bottom of the crest and the layer upon which it rests. The larger waves would see a significantly larger proportion of the discharge go over the top of the crest while the medium and smaller sized waves would prefer the route venturing through the crest.

On the other hand, when the crest is impermeable the option of going through the crest is no longer available. Any overtopping that would occur would need to travel over the top of the crest. For this to take place, only waves with a high enough energy would be able to generate overtopping. Figure 7 show one such high energy wave meeting the impermeable crest. These high energy waves contribute significantly to overtopping in sectors S2 and S3. The trajectory and the quantities in which they overtop is so intense sometimes that a lot of the discharge bounces off the surfaces of S2 and S3 to be collected by S4 or S5 and beyond. Sometimes the discharge would bounce out of the range of the collecting sectors. It was also observed that the discharge over the top of the impermeable crest would fall on the sectors with much greater force displacing the little stones on the surface of the sectors. This was not witnessed during overtopping over the permeable crest where the passage through and under the crest did not allow for massive build-ups in the intensities of the overtopped water. These movements will again be discussed in the following sections in the context of the different results obtained.
4 Measurements

Data was already available for the overtopping discharges of the exact same model measured with exactly the same procedure as that followed to measure overtopping discharges with the impermeable slope. Since the objective of this report is solely to provide a comparison of the overtopping behavior between a slope with an impermeable and permeable crest it is not relevant to provide the details of the tools and instruments and the methodology of finding out wave details such as the significant wave height $H_s$ and average time period $T_p$, although these can be found in the M.Sc work of Anestis Lioutas titled ‘Experimental research on spatial distribution of wave overtopping’ (Lioutas, 2011).

In brief, the procedure for the laboratory measurements was as follows: For a given run a certain electrical input signal was sent to the wave generator which generated waves simulating a ‘storm’. These waves, approximately 3000 for each run, produced a record of different wave heights and time periods. By adjusting the electrical signal the waves were however controlled to ensure that the significant wave heights, $H_s$, and the average time period, $T_{p,avg}$ for the entire ‘storm’ would be different for each trial run. This was necessary to ensure that the overtopping discharges could be observed for ‘storms’ with different significant wave heights and wave periods. Three wave gauges recorded the wave heights and the time periods of the waves near the toe of the slope. The data from the gauges would be run through a pre-set program which would then give a final value of the $H_s$ and $T_{p,avg}$ for the entire length of the ‘storm’.

At the end of the ‘storm’ the volume of water in the measuring tanks from the various sectors is measured and the values recorded. The exact same procedure was repeated for slopes of 1:1.5, 1:2 and 1:3 and in turn the exact same procedure was repeated all over for the impermeable crest. Since the data for the
permeable slope was already available as part of the M.Sc work of Lioutas (Lioutas, 2011), for the purpose of this report the author repeated all of the tests for the 1:2 slope while only some specifically chosen tests were repeated for the 1:1.5 and 1:3 slopes. This was so because there were some ‘storms’ with such low \( H_s \) which contributed such small discharges for the permeable crested slope that it was obvious that they would hardly provide any meaningful data for overtopping discharge when the crest is made impermeable. The results for the 1: 2 slopes are the main data set used for comparison and analysis in this report.

Here, it is again worth mentioning that the sole aim of this report is to state the different characteristics observed between overtopping with a permeable crest and an impermeable crest. More than the absolute values of the results, this report focuses on the differences in the results. Hence, by adopting the exact same procedure for acquiring data on overtopping for the impermeable slope as for the permeable slope, any major errors are taken care of. While there might be errors in the absolute measurements or details of things, it will be the same for both the impermeable and permeable crests having little bearing on the results on the differences between the two separate sets of experiments.

5 Weaknesses

Before embarking upon the results it is imperative to mention some weaknesses and errors in the procedure followed to give some idea to the reader about the different sources of error. This should help the reader avoid similar mistakes when conducting similar tests with similar methodologies and give insight into the problems faced in the experimentation phase for this report.

The errors as such are not so grave that the final results of the analysis would be adversely affected. They contribute more to weaknesses in values obtained from individual test runs. For example if, with a slope of 1: 2, the overtopping discharge was measured for fifteen different ‘storms’, each with a different significant wave height and average time period, then in one of them the desired free board might not have been achieved. This may have been due to the fact that the water level in the wave flume had not settled over the entire length of the wave flume after it was refilled to begin the tests with a new slope.

While very insignificant and hardly worth warranting a mention, another problem that occurred involved the process of measuring and weighing. While measuring, water would sometimes spill out of the measuring tanks when they were full to the brim. This was caused either by maneuvering the crane abruptly or by overlooking the fact that the measuring tank was full and switching the pipes from the full measuring tank to another empty measuring tank.

A significant error was caused at one stage of the experimentation due to a malfunction of the equipment. Water from each sector is pumped to an adjoining measuring tank with the use of several pumps. Since the sectors are filled to the brim with the smaller stones it is not possible to tell sometimes if water is being pumped out or not. During one stage of the tests the pipes in sector 6 and sector 7 developed holes which meant that the water from these tanks was not being pumped to the measuring tank. During this time the volume of overtopped discharge in these sectors was recorded as zero. This problem was however, realized after two runs and the pipes were fixed. The erroneous tests were however not repeated since the volume of discharge recorded in the last two sectors was judged to be insignificant to ensure that they be very accurate. The accuracy at that stage did not make any difference since all of the other tests were performed without any malfunction in the equipment.

Another similar problem would occur when the power of the pumps in sectors 5, 6 and 7 would not be sufficient to pump out water at the same rate as it was overtopping into the sectors. This would then cause
the water to flow over the full sectors and fall into the next empty one. Again this happened in only one or two experimental runs and therefore did not adversely affect the overall results.

6 Results

Appendix 1 displays all of the measurements taken from all of the tests. While the data for the permeable crest was already available from (Lioutas, 2011), the experiments were repeated for the Impermeable crest. Using this data various analyses have been performed in the following sections to document the difference in different overtopping characteristics between an impermeable and permeable crest.
6.1 Comparison with Owens method and EUROTOP

This section of the report investigates the significance of a modification in the permeability of the crest to the changes in the overall design guidelines that it represents. It does so by plotting the experimental overtopping discharges obtained using both Owen’s method and the Eurotop method and comparing them with the theoretical results in an effort to ascertain which, either an impermeable or permeable crest better suits the theoretical results obtained from both the methods.

This test also serves as a check to see if the manner in which the crest is made impermeable i.e. by adding a wooden plank at the start of the crest, provides a good model. This will be important in establishing that the differences in overtopping intensity between impermeable and permeable slopes are accurate and the results representative of real results.

6.1.1 Owen’s Method

While there are a number of studies on the overtopping performance of sea walls, one of the most widely applied results are those described by Owen (Owen, 1980). Hence, Owen’s method is one of the two, the other being the EUROTOP method, which has been chosen to serve as a brief study in this report on the comparison between impermeable and permeable crests.

Owen uses a dimensionless freeboard, $R^*$ and a dimensionless discharge $Q^*$ which are plotted using the mean wave period, $T_p$ and significant wave height, $H_s$ at the toe of the structure. It ought to be mentioned here that for all of the tests performed for this report the crest freeboard $R_c$ was taken to be the height from still water level (SWL) to the top of the crest. Using the following equations, a plot was obtained for the experimental dimensionless discharge. This will then be compared with Owen’s empirical method to ascertain the nature of the breakwater designed in the wave flume when it is left permeable or made impermeable.

\[
R^* = \frac{R_c}{T_p \sqrt{gH_s}} = \frac{R_c}{H_s \sqrt{s_{0m}/2\pi}}
\]

\[Q^* = \frac{Q}{(T_p, g, H_s)}\]

Owen’s method was developed to predict the overtopping performance of smooth impermeable simply sloping structures. It is based on model test measurements of ‘overtopping discharges for a range of simple and bermed embankments with seaward slope angles 1:1, 1:2 and 1:4’. ‘Owen (1980) extended his work on simply sloping and bermed sea walls to cover rough impermeable and armored (rough permeable) structures’ (Herbich, 2000). He did this by adding a roughness coefficient for the surface of the wall, $r$, to the empirical coefficients A and B in the following equation:

\[Q^* = A\exp\left(-\frac{BR^*}{r}\right)\]
Table 1. Parameters used in Owen’s empirical method.

<table>
<thead>
<tr>
<th>Slope</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1.5</td>
<td>8.84E-03</td>
<td>19.9</td>
</tr>
<tr>
<td>1:2</td>
<td>9.39E-03</td>
<td>21.6</td>
</tr>
<tr>
<td>1:3</td>
<td>1.09E-02</td>
<td>28.7</td>
</tr>
</tbody>
</table>

Table 1 shows the parameters used for the different slopes. A roughness coefficient representative of the permeable rock armor slope model in the wave flume according to Owen is $r = 0.55$ who categorizes its use for a ‘Armorstone – two layers on impermeable base’.

Figure 8 shows an interesting comparison between the experimental and the theoretical overtopping dimensionless discharges using Owen’s method for a permeable crest head on a 1:1.5 slope. While the theoretical values show that the $Q^*$ values are expected to decrease with an increase in $R^*$ the experimental results show that $Q^*_{\text{exp}}$ does not depend on $R^*$ for the breakwater model constructed in the flume. However, the magnitude of results for $Q^*_{\text{exp}}$ are closely related to $Q^*_{\text{theo}}$ and lie in the same order of magnitude. It may therefore be concluded about Owen’s method that it may be providing too sensitive a prediction which relies on the parameters making up $R^*$ i.e. $H_s$, $T_{p,\text{avg}}$, and the freeboard, $R_c$. But using the appropriate roughness coefficient factor along with the appropriate slope factors does provide a design value for a slope with an armor layer and a permeable crest like that modeled in the wave flume.

![Figure 8. Comparison of experimental and theoretical dimensionless overtopping discharge over a Permeable Crest using Owes Method with a 1:1.5 slope.](image)

It is worth remind the reader here that checking the accuracy or reliability of Owen’s method is not the objective of this report; it is simply to compare the difference in the characteristics of overtopping between an impermeable and permeable crest. If the same roughness coefficient, $r = 0.55$, is used along with the same slope parameters A and B for an impermeable crest then it can be observed from
Figure 9 that Owen’s method would provide an overestimate of the overtopping discharge. This is as expected since the method of calculation in terms of the selection of the various parameters has been kept the same while the slope model has been changed. The change - making the crest impermeable - leads to an overall decrease in the total volume of water passing through the crest.

In order to get more accurate results appropriate parameters and coefficients have to be chosen. A roughness coefficient of $r = 0.4$ would have provided a better fit of the theoretical data with the experimental results but Owen does not provide for a coefficient less than 0.55.

The results from Owen’s method show that it is a good design method to use for designing armored slopes. It is especially worth noting that the roughness coefficient provided by Owen accurately represents the case when water is able to flow through the crest of the slope. Since one of the primary aims of this report is to check the results against some well-known design guidelines, this conclusion is a further approval of Owen’s method.

It also allows the conclusion that, if, only the crest is made impermeable then in terms of getting a design for such an instance, in Owen’s case, a greater roughness coefficient should be used. This makes sense since by making the crest impermeable, there is effectively a limit placed on the amount of water that goes over the top. Whereas, previously waves with lower energy could pass through the crest and ‘overtop’, now only waves with sufficient energy to be able to pass over the top of the plank at the start of the crest contribute to overtopping. In terms of whether or not an impermeable or permeable crest makes a difference to the amount of overtopping, the answer is clear that it makes a significant difference. There is enough of a difference to ensure that completely different design guidelines are followed to account for a crest becoming impermeable.
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Figure 9. Comparison of experimental and theoretical overtopping discharge over an Impermeable Crest using Owens Method in a 1:1.5 slope

The same trend can be seen when the slope of the model was changed to gradients of 1: 2 and 1: 3. The only observation worth noting is that for a 1: 3 slope Figure 12 and Figure 13 show that Owen’s method provides an overestimated result for the overtopping discharge \( Q^*_{\text{theo}} \) over the impermeable crest. This is true even in the case of the permeable crest where previously, for the 1: 1.5 and 1: 2 slopes, the theoretical results have conformed well to the experimental results.
Figure 10. Comparison of experimental and theoretical overtopping discharge over an Impermeable Crest using Owens Method in a 1: 2 slope.

Figure 10 and Figure 11 reiterate the point made earlier. The same is true in the case of a slope of 1: 2; the permeable crest results conform well to the experimental values but the impermeable crest is again overestimated. This once again emphasizes that there lies a stark difference in overtopping discharges by simply changing the permeability of the crest.
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Figure 11. Comparison of experimental and theoretical overtopping discharge over Permeable Crest using Owens Method in a 1:2 slope

Figure 12. Comparison of experimental and theoretical overtopping discharge over an Impermeable Crest using Owens Method in a 1:3 slope
While Figure 12 and Figure 13 emphasize the same point with a slope of 1:3 it is worth pointing out in this case that Owen’s method does not provide as good a match between its theoretical and experimental results as it did with slopes of 1:1.5 and 1:2.

Overall it can be concluded that Owen’s method provides good overtopping results for impermeable crests provided the effect of roughness is increased by using a reduction factor of \( r = 0.4 \) – 0.5. For the permeable slopes Owen’s method overestimates the dependency of \( Q^* \) on \( R^* \) while experimental data shows that this dependence is only marginal.

![Figure 13. Comparison of experimental and theoretical overtopping discharge over Permeable Crest using Owens Method in a 1:3 slope](image)

### 6.1.2 Eurotop

In this section we will compare the experimental results with another popular design guideline referred to as Eurotop. The process is repeated here again as that done for Owen’s method to check the consistency of the conclusion arrived at in the previous section. Here too this report wishes to investigate the sensitivity of changing the crest from a permeable one to impermeable.

For the model like the one set up in the wave flume the Eurotop manual describes it as ‘armored rubble slopes and mounds... characterized by a mound with some porosity or permeability, covered by a sloping porous armor layer consisting of large rock or concrete units. In contrast to dikes and embankment seawalls the porosity of the structure and armor layer plays a role in wave run-up and overtopping.’ (T. Pullen, 2007)
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It is not within the scope of this report to describe the details of the Eurotop method applied in this section since stating this will not even be useful for the reader since it is not the aim of this report to find conformity between the test results and the design guides. The aim of this report is simply to compare what happens to the results when the crest is made impermeable. These results are compared and the conclusions noted. While some details such as the parameters chosen to obtain plots of both experimental and theoretical measurement have been stated, other details of the design guidelines followed can be found in the Eurotop manual¹.

The rock armor of the rubble mound modeled in the wave flume is 2-layered with an impermeable core and hence the Eurotop recommendation of a roughness factor \( y_i \) of 0.55 for a 1:1.5 slope was chosen to obtain a deterministic design value of the overtopping discharge for the permeable crest. In order to obtain the theoretical \( Q^*_{\text{theo}} \), the following equation was used with \( C = 0.20 \) and \( D = 2.3 \) (values for safety margin for deterministic calculations):

\[
\frac{Q}{\sqrt{g \cdot H_{m0}^3}} = C \cdot \exp \left( -D \frac{R_c}{H_{m0} \gamma} \right)
\]

These values were then used in the following equations to obtain \( Q^* \) and \( R^* \) respectively:

\[
Q^* = \frac{Q}{\sqrt{g \cdot H_{m0}^3}}
\]

\[
R^* = \frac{R_c}{H_{m0} \gamma}
\]

The experimental results were plotted by simply using the measured values of \( Q \) from the measuring tanks and using them in the two equations above to obtain a plot for \( Q^*_{\exp} \).

¹ (T. Pullen, 2007)
The results in Figure 14 show that this recommendation is not suited to our model. This highlights another point about utilizing exact recommendations. They can be completely different depending on differences between the real structure and the basic definitions of its features. It can be observed that $\gamma_f$ of 0.55 has led too much of an underestimation of the real overtopping discharges. $Q^*_{\text{exp}}$ are much higher than $Q^*_{\text{theo}}$ values predicted by the Eurotop deterministic design. It would be interesting to check which roughness factor would be a more accurate representation of our model.
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Figure 15. Comparison of experimental and theoretical overtopping discharge over Permeable Crest using EUROTOP for a 1:1.5 slope with $\gamma_f = 0.77$

Figure 15 shows that a roughness factor $\gamma_f$ of 0.77 gives a better match between $Q_{\text{exp}}^*$ and $Q_{\text{theo}}^*$. According to Eurotop, this places our model in the wave flume closer to an armor layer made up of a single layer with an impermeable core. While again this is not in the main aim of this report but it is again vital to point out here that the design guidelines did not provide a result which conformed well to the experimental values. The point made here is that the parameters that the author of this report thought were representative for the breakwater constructed in the wave-flume did not conform well at all. While this report does not delve into a detailed account of the very simplistic assumptions which may be adversely affecting the utilization of the Eurotop guidelines, anyone using these guidelines must take particular attention of how exactly Eurotop or any other guideline is meant to be implemented.

After making the crest impermeable with the same 1:1.5 slope and repeating the same coefficient fitting exercise we obtain the following figure. Figure 16 shows that a roughness factor of $\gamma_f = 0.57$ gives an accurate fit of the $Q_{\text{theo}}^*$ with $Q_{\text{exp}}^*$. This roughness coefficient places the impermeable crested armored rubble slope model in the 2-layered rock armor with an impermeable core. Hence, according to the Eurotop design guideline, the difference in having a permeable crest and an impermeable one is that of an addition of another layer of rock in the case of a rock armored slope like that modeled in the wave flume.
Figure 16. Comparison of experimental and theoretical overtopping discharge over Impermeable Crest using Eurotop for a 1:1.5 slope with $\gamma_f=0.57$

Figure 17. Comparison of experimental and theoretical overtopping discharge over Permeable Crest using Eurotop for a 1:2 slope with $\gamma_f=0.68$
Figure 17 and Figure 18 show the same armored rubble slope model with slope gradients of 1:2 and 1:3 respectively. It can be seen that for the permeable crest with the 1:2 slope a roughness factor of $\gamma_f = 0.68$ while for the 1:3 slope $\gamma_f = 0.58$ provides a suitable design criteria. The former places the slope under the Eurotop category of the single-layered rock armor with an impermeable core. The latter falls between a single–layered and double-layered rock armor with an impermeable core.

![Graph](image)

Figure 18. Comparison of experimental and theoretical overtopping discharge over Permeable Crest using Eurotop for a 1:3 slope with $\gamma_f = 0.58$.

When both the crests for the 1:2 and 1:3 slopes are made impermeable the roughness factors of $\gamma_f = 0.53$ and $\gamma_f = 0.45$ provide a better fit. These roughness factors place the impermeable crested slopes in the category of ‘rocks – 2 layers, impermeable core’ and ‘rocks – 1 layer permeable core’ respectively. This shift in roughness factors is very significant and shows how much of a difference the permeability or impermeability of the crest makes on the overtopping discharges. Table 2 shows a summary of the Eurotop classification for the various crests with different slopes.
Table 2. Summary of the Eurotop slope classifications for the different roughness factors, $\gamma_f$ for different crest types on different slopes.

<table>
<thead>
<tr>
<th>Slope</th>
<th>Crest</th>
<th>$\gamma_f$</th>
<th>Eurotop Slope Classification</th>
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</thead>
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<tr>
<td>1:1.5</td>
<td>Permeable</td>
<td>0.77</td>
<td>Rocks (1 layer, impermeable core)</td>
</tr>
<tr>
<td></td>
<td>Impermeable</td>
<td>0.57</td>
<td>Rocks (2 layers, impermeable core)</td>
</tr>
<tr>
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<td>Permeable</td>
<td>0.68</td>
<td>Rocks (1 layer, impermeable core)</td>
</tr>
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<td></td>
<td>Impermeable</td>
<td>0.53</td>
<td>Rocks (2 layers, impermeable core)</td>
</tr>
<tr>
<td>1:3</td>
<td>Permeable</td>
<td>0.58</td>
<td>Rocks (2 layers, impermeable core)</td>
</tr>
<tr>
<td></td>
<td>Impermeable</td>
<td>0.45</td>
<td>Rocks (1 layer, permeable core)</td>
</tr>
</tbody>
</table>

Figure 19. Comparison of experimental and theoretical overtopping discharge over an Impermeable Crest using Eurotop for a 1:2 slope with $\gamma_f = 0.53$. 

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A comparison of overtopping behaviour over a permeable and impermeable crest

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6.2 Discharges

6.2.1 Total Discharge

This section of the report will look into the differences in the total discharge of overtopped water in the cases of the permeable and impermeable crests. This is done by using the equations provided by the Eurotop manual for overtopping over armored rubble mound structures. The equations used are follows with the same roughness factors used as stated in Table 2:

\[ Q^* = \frac{Q}{\sqrt{g \cdot H_{m0}^3}} \]

\[ R^* = \frac{R_c}{H_{m0}} \cdot \frac{1}{\gamma} \]

Q is the total discharge in m³/s/m while \( Q^* \) is the dimensionless discharge which is plotted against \( R^* \), the dimensionless freeboard.

In the following figures the total dimensionless discharges will be compared between the values obtained with a permeable crest and that obtained after making it impermeable. This will give us an assessment of the physical difference in terms of the movement of water around a modified crest. Through this analysis
a better insight can be provided into how much water goes over and through the crest in the case of the permeable crest while how much goes only over in the case of the impermeable crest.

It is stated to remind the reader that in this report overtopping has been defined to occur at the end of the crest. But since sector 1 (S1) lies immediately below the crest it is also possible to focus more on the water that is stored in this sector. This sector is actually really important for two different scenarios: in the first scenario there is water travelling towards the crest with very high energy. This water will have enough energy to literally be able to go over the top of the crest and skip S1 and fall into S2 and S3 and beyond. But not all of the water in this high energy wave that reaches the crest goes over the top. A lot of this water goes through the permeable crest and manages to reach S2 and S3 or simply losses its energy in the crest and is collected by S1. In the case of the breakwater model built in the wave flume the wave crest is resting on an impermeable layer i.e the small stones which fill up S1. It is important to keep this in mind during the design phase since the permeability of the layer below the crest directly affects the intensity of overtopping behind the crest. In case this layer was completely impermeable but the crest permeable then a lot overtopping can be expected to occur right through the crest especially at the interface between the crest and the impermeable layer on which it rests.

The analysis looks first into a comparison of the overall total overtopping measured in both the cases of the impermeable and permeable crest. **Figure 21** has been plotted with the discharge \( Q \) in \( m^3/s/m \) against a dimensionless wave characteristic, \( H^*T^* \), which takes into account all of the various wave characteristics recorded in a ‘storm’: \( H^*T^* = \frac{Hs}{Rc} \times Tp \times \sqrt{g/Rc} \).

\[
H^*T^* = \frac{Hs}{Rc} \times Tp \times \sqrt{g/Rc}.
\]

This wave characteristic allows a comparison to be made of all the different storm characteristics in the different tests. The linear trendlines shows that with the 1:2 slope and the crest being permeable the
discharges, $Q$, are considerably higher than those for the impermeable crest. This result is as expected since the wave has to have enough energy to travel over the crest of the impermeable crested rubble breakwater. While both the trend lines show that $Q$ increases as the wave characteristics such as $H_s$ and $T_p$ increase, the rate of increase of $Q$ for the permeable crest is larger. An increase in $H_s$ and $T_p$ for waves in an impermeable crest does not lead to a greater rise in $Q$. On the other hand, Figure 22 shows that for the steeper 1:1.5 slope the rates of increase with wave characteristics are almost similar between an impermeable and permeable crest and that the range of the discharge data in both the cases are more than that for both the 1: 2 and 1: 3 slope. The former can be explained by the fact that due to the steeper slope a larger part of the crest is exposed to a ‘direct hit’ by the wave. In this case, for both the permeable and impermeable crests, an increase in $H_s$ would more likely contribute to similar increases in overtopping by contributing more to the water going over the top than through the crest. The higher rate of increase of $Q$ with increasing $H_s$ for the permeable crest could be explained by a proportionate increase in the amount of water going through the crest, an option not available in the case of the impermeable crest.

The reason for an increasing amount of discharge, $Q$, recorded with a steeper slope can also be explained by the same reason that the steeper slopes take a more direct impact of the wave in a region closer to the crest. As the slope becomes less and less steep, the waves break in a region further away from the crest and hence contribute less to the overall overtopping discharge.

Figure 22. Comparison of the total overtopping discharge, $Q$, over a permeable and impermeable crest in a 1: 1.5 slope.
A comparison of overtopping behaviour over a permeable and impermeable crest

Figure 23. Comparison of the total overtopping discharge, $Q$, over a permeable and impermeable crest in a 1:3 slope.

It is important to note in Figure 23 that while the rate of increase of the overtopping discharge over a permeable crest is slightly larger than that for the impermeable crest, which has almost no effect whatsoever with increasing wave characteristics, the difference in the amounts of discharges can be attributed solely to water going through the crest in the case of the permeable crest.

At this stage it can be confidently concluded that there is considerably more overtopping taking place over the permeable crest as compared to the impermeable crest. There is also greater variation in the overtopping discharges with the wave characteristics over the permeable crest while the impermeable crest gives a less varied more consistent measurement. It will be interesting at this juncture to take a look into how much water goes through the crest when it was made impermeable or when it is left permeable. To do this the report will focus on the data gathered from doing these tests on the 1:2 slope since the largest amount of tests were carried on this slope. First we will take a look only at the discharges in S1 for the different slopes and between impermeable and permeable crests.
A comparison of overtopping behaviour over a permeable and impermeable crest

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Figure 24. A comparison of the dimensionless overtopping discharge, $Q^*$, in sector S1 only on a slope of 1 : 2.

It can be seen in Figure 24 that there is clearly a larger dimensionless overtopping discharge in the case of the permeable crest. It is also interesting to note the large concentration of values between $Q^*$ = 0.0015 and $Q^*$ = 0.002. This shows that there is a consistency in the values of various overtopping discharges for the various waves. On the other hand, the values of dimensionless overtopping over the impermeable crest shows that the permeability of the crest clearly plays a major role in overtopping values. This makes it possible to conclude that there is a significant portion of overtopping that happens through and under the crest. The difference in the $Q^*$ values are illustrating that volume of water that would have normally gone through the crest to either S2 and beyond or settled in S1 below the crest.

Since the discharge that travels through the crest could also have enough energy to arrive at S2 and beyond, it will be interesting to compare the overall differences in discharge beyond S1. This would give a clear idea of the amount of water that would have overtopped in case of a permeable crest but was not allowed to do so by the impermeable crest. This is to show that it is most certainly a process whereby water ‘overtops’ through the crest all the way beyond the end of the crest.
Figure 25 provides very interesting results. There are two distinct regions in the figure above: close to the x-axis there is a conglomerate of data points from both the impermeable and permeable crest tests. While all of the impermeable data sets are in that group, a large proportion of the permeable crest data set is also present in the same region. This clearly means that the permeable crest has two significant modes of contribution to overtopping behind the crest: 1. The discharge going over the top of the crest and falling over the various sectors; 2. The discharge going through the crest and between the interface of the bottom of the crest and the under layer and contributing to the various sectors. In the case of the former, it can be seen that the explanation is entirely plausible since it correlates completely with the data sets of the impermeable crest where the water had to travel over the crest in order to be collected beyond sector 1. Where the permeable crest data is way higher than the impermeable crest data it is obvious that the discharge has travelled through means which were not available to the impermeable slope i.e. through the crest.

It would be interesting to compare the sector-wise discharge of the two crests to see if a similar trend is visible in the individual sectors.
A comparison of overtopping behaviour over a permeable and impermeable crest

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S2

\( \sigma \)

0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012

\( R^* \)

0
1
2
3
4

Imper. S2
Perm. S2

S3

\( \sigma \)

0
0.0007
0.0006
0.0005
0.0004
0.0003

\( R^* \)

0
1
2
3
4

Imper. S3
Perm. S3

S4

\( \sigma \)

0
0.00005
0.0001
0.00015
0.0002
0.00025
0.0003
0.00035
0.0004
0.00045
0.0005
0.00055

\( R^* \)

0
1
2
3
4

Imper. S4
Perm. S4

S5

\( \sigma \)

0
0.00001
0.00002
0.00003
0.00004
0.00005
0.00006
0.00007
0.00008
0.00009
0.0001
0.00011
0.00012
0.00013
0.00014
0.00015

\( R^* \)

0
1
2
3
4

Imper. S5
Perm. S5
Figure 26 shows the overtopping discharges measured sector-wise from S2 to S7. While the discharge over the permeable crest is spread over a significantly larger range of values as compared to the values over the impermeable crest in S2, the trend seems to be that of a decrease the larger values to more similarity between the impermeable and permeable discharges. The larger $Q^*$ values seem to grow less in number and grow closer to the impermeable crest discharge values from S2 to S7. In S6 and S7 it is clear that both sets of discharge data are consistent with one another. This increasing conformity in data between the two types of crests show that the affects of having a permeable crest lasts roughly only up till the 3rd sector, S3 which is a length 33cm away from the start of the crest. Since the prototype is built to a scale of 1 : 20, it means that the water through a permeable crest can result in a discharge of almost 7m behind the start of the crest or 1m behind the end of the crest. This means it is able to cover a distance of 6m through the crest. This shows that water travelling through the crest needs to be accounted for in the design values.

Another trend visible is in the decreasing $Q^*$ values for both the impermeable and permeable data sets starting from S2 down to S7. This is as expected as the intensity of overtopping discharges is expected to decrease exponentially along the distance away from the crest. The overtopping intensities will be further discussed in the next section.
6.3 Intensities

This part of the report will look into the intensities of overtopping and compare them between that measured with the impermeable crest and the permeable crest. For this comparison the spatial distribution of wave overtopping discharge behind the crest as defined by Juul Jensen (Jensen, 1987) has been used. According to Jensen on average the intensity of overtopping, \( q(x) \) in \( \text{m}^3/\text{s/m/m}^2 \), should decrease exponentially with the distance, \( x \), from the crest of the breakwater:

\[
q(x) = q_0 \cdot 10^{-\left(x/\beta\right)}
\]

Since the tests were repeated for different \( H_s \) and \( T_p \) for both the impermeable and permeable crest they are compared together by utilizing a dimensionless intensity \( q^* \) along with a dimensionless distance parameter \( x/H_s \) where

\[
q^* = \frac{\text{vol. of Sector}}{\text{duration of storm} \cdot \text{width of flume} \cdot \text{dist. of sector behind the crest}} \times \frac{1}{\sqrt{g \cdot H_s}}.
\]

![Graph showing measured dimensionless intensity, \( q^* \text{exp} \) with an Impermeable Crest with a 1 : 2 slope.](image)

Figure 27. Measured dimensionless intensity, \( q^* \text{exp} \) with an Impermeable Crest with a 1 : 2 slope.

---

2 Overtopping discharge per meter width and per meter length of the crest.
Figure 28. Measured dimensionless intensity, $q_{\text{exp}}$ with a Permeable Crest with a 1 : 2 slope.

Both Figure 27 and Figure 28 show the discharge intensities recorded for an impermeable and permeable crest respectively. While both figures display a similar exponential decline in the intensity it can be observed that there are two significant differences in the intensities between the two. The first is that the S2 and S3 data points of all of the various tests conducted on the permeable crest are in general a magnitude higher than those recorded for the impermeable crest. Secondly, while there is a clear drop in the intensity from the onset for the permeable crest, the intensities for the impermeable crest seem to be a little constant between $x/Hs = 2$ and $x/Hs = 3$ before dropping of exponentially. This behavior can be explained by two reasons: firstly, that in the case of the permeable crest, the intensity in the beginning is of a much higher value due to overtopping contributions both through and over the crest. This makes the following intensities look smaller hence giving an overall exponentially decreasing trend. The second reason is that in the case of the impermeable crest, the water that does overtop over the crest has enough energy to fall directly on both sectors 2 and 3 which are very close to each other. Hence, this provides with both S2 and S3 an almost equal distribution of water contributing to similar intensities initially before dropping of exponentially beyond S3.
Figure 29. Measured dimensionless intensity, $q^*\exp$ with an Impermeable Crest on a logarithmic scale with a 1 : 2 slope.

Figure 30. Measured dimensionless intensity, $q^*\exp$ with a Permeable Crest on a logarithmic scale with a 1 : 2 slope.
Both Figure 29 and Figure 30 show that the intensity data when plotted on a logarithmic scale almost gives straight lines for both the impermeable and permeable crests. This provides a very strong conclusion of the fact that the intensities for both permeable and impermeable crests decrease exponentially. It is also worth pointing out that while the logarithmic plot of both the permeable and impermeable crests are almost alike, the gradient of the permeable plot in general is slightly steeper than the gradient of the impermeable crest intensity data. In fact the gradients are extremely similar with the permeable crest intensities slightly larger at the very beginning. The intensity data on a logarithmic is indeed a very interesting result.

It would be extremely useful to ascertain which factors in the wave characteristics determine where the exponential trend line would be within the range of data sets of the various test runs. This however, is beyond the scope of this report and is covered by Lioutas in his M.Sc thesis. For this report it suffices to conclude for this section that for practical purposes there is little difference that is made when a permeable crest is made impermeable in terms of overtopping intensities. While the intensities remain somewhat equal in the distance closest to the start of the overtopping i.e. S2 and S3 for the impermeable crest, these quantities are an entire order of magnitude smaller than those recorded for a permeable crest. Hence, there is little practical consequences that might affect an existing design adversely by the crest becoming impermeable.

7 Conclusion

The results from the previous section provide some interesting insights into the mechanism of overtopping over a crest and the effect the permeability of the crest has on its behavior. By using the overtopping guidelines provided by both Owen and Eurotop it was first established that a switch from a permeable to an impermeable crest can be accurately represented by modifying the design codes in terms of the different parameters and various factors used in the empirical equations or by defining the breakwater differently. This was necessary due to the significant differences measured in the overtopping discharges over an impermeable and permeable crest.

The insight into the movement of water through the crest by looking into the various sector-wise discharges was of great interest. The results showed that the ability of water to travel through an impermeable crest should not be underestimated. A look into the intensities led to the conclusion that the exponential nature of the decrease in overtopping away from the crest is quite similar in both cases but that the intensities over the impermeable crest are a lot lower.

The aim of this report was to look into the changes in the overtopping behavior over the crest of the breakwater when the permeability of the crest was modified. By looking into the major characteristics such as discharge and intensities this report wished to find some major differences which could provide an interesting avenue to conduct further research on. While the individual results and comparisons provided some very interesting insights and observations, on a whole it can be safely concluded that the movement of water through the crest along with the various wave characteristics that contribute to different intensities have the potential to warrant further investigations. But overall, by making a crest impermeable the overtopping discharges are reduced on a whole and thus a design which is safe for a permeable crest would remain safe for an impermeable crest.

While it was beyond the scope of this report, further investigations could focus into one of the characteristics discussed in this report and try to ascertain a relationship between the different wave

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3 ‘Experimental research on spatial distribution of wave overtopping’. (In progress)
characteristics such as $H_s$ and $T_p$ and the affect it has on the overtopping intensities over an impermeable crest and compare them with those over a permeable crest. This would be useful since it would not only provide a better understanding of the interaction of waves and impermeable crests but also other impermeable surfaces or structures which may be developed on breakwaters.
Bibliography


## Appendix 1

Table 3. Recorded volumes of overtopping in the different sectors behind an Impermeable and Permeable crest with a slope of 1: 1.5.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Significant Wave Height, $H_s$ (cm)</th>
<th>Average Period, $T_{avg}$ (sec)</th>
<th>Water Depth in Flume, $D$ (m)</th>
<th>Duration, $S$ (sec)</th>
<th>Free Board, $R_b$ (m, meters)</th>
<th>Volume in S1 (l, litres)</th>
<th>Volume in S2 (l, litres)</th>
<th>Volume in S3 (l, litres)</th>
<th>Volume in S4 (l, litres)</th>
<th>Volume in S5 (l, litres)</th>
<th>Volume in S6 (l, litres)</th>
<th>Volume in S7 (l, litres)</th>
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<tbody>
<tr>
<td>z2037</td>
<td>14.8</td>
<td>1.5</td>
<td>0.52</td>
<td>1920</td>
<td>0.21</td>
<td>107.8</td>
<td>3.7</td>
<td>4.07</td>
<td>4.23</td>
<td>1.48</td>
<td>0.72</td>
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A comparison of overtopping behaviour over a permeable and impermeable crest

Table 4. Recorded volumes of overtopping in the different sectors behind an Impermeable and Permeable crest with a slope of 1:2.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Significant Wave Height, $H_s$ (cm)</th>
<th>Average Period, $T_{p,avg}$ (sec)</th>
<th>Average Water Depth in Flume, $D$ (m)</th>
<th>Duration, $S$ (sec)</th>
<th>Free Board, $R_c$ (meters)</th>
<th>Volume in S1 (l, liters)</th>
<th>Volume in S2 (l, liters)</th>
<th>Volume in S3 (l, liters)</th>
<th>Volume in S4 (l, liters)</th>
<th>Volume in S5 (l, liters)</th>
<th>Volume in S6 (l, liters)</th>
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</table>
A comparison of overtopping behaviour over a permeable and impermeable crest

| t011 | 15.3 | 1.64 | 0.54 | 1650 | 0.19 |
| t012 | 15.8 | 1.94 | 0.54 | 1530 | 0.19 |
| t012b | 13 | 1.94 | 0.54 | 1960 | 0.19 |
| t13 | 15.1 | 1.51 | 0.54 | 1560 | 0.19 |
| t016 | 14 | 1.37 | 0.52 | 1380 | 0.21 |
| t017 | 15 | 1.8 | 0.52 | 1770 | 0.21 |
| t018 | 15.6 | 2.06 | 0.52 | 2160 | 0.21 |
| t019 | 14.4 | 1.47 | 0.52 | 1440 | 0.21 |
| t020 | 14.7 | 1.91 | 0.52 | 1890 | 0.21 |
| t021 | 14.4 | 2.33 | 0.52 | 2270 | 0.21 |
| t004 | 14 | 1.32 | 0.52 | 1340 | 0.21 |
| t005 | 14.5 | 1.79 | 0.52 | 1780 | 0.21 |
| t006 | 13.5 | 2.15 | 0.52 | 2160 | 0.21 |
| t013b | 16.1 | 1.54 | 0.52 | 1560 | 0.21 |
| t014b | 18.1 | 1.99 | 0.52 | 1360 | 0.21 |
| t003 | 12.4 | 2 | 0.52 | 1960 | 0.21 |
| t019b | 15 | 1.39 | 0.52 | 1430 | 0.21 |
| t020b | 16.4 | 1.91 | 0.52 | 1890 | 0.21 |
| t021b | 14.6 | 2.29 | 0.52 | 2240 | 0.21 |
| t011 | 454.5 | 187.2 | 42.8 | 17.3 | 1.85 | 0.6 | 0.15 |
| t012 | 385.3 | 272.5 | 148.6 | 108.4 | 22.2 | 22 | 0.1 |
| t012b | 508.8 | 189.7 | 39 | 8.1 | 0.65 | 0.25 | 0 |
| t13 | 386 | 158 | 26.2 | 8.1 | 1.55 | 0.55 | 0.05 |
| t016 | 83.1 | 1.1 | 0.6 | 0.6 | 0.2 | 0.07 | 0.03 |
| t017 | 344.2 | 4.1 | 1.4 | 1.15 | 0.35 | 0 | 0 |
| t018 | 557.5 | 105.6 | 39.5 | 17.6 | 7.4 | 3.6 | 0.65 |
| t019 | 125.1 | 1 | 0.85 | 0.75 | 0.35 | 0.35 | 0.05 |
| t020 | 424.1 | 33.3 | 10.3 | 3.15 | 1.05 | 0.45 | 0.1 |
| t021 | 586.3 | 145.7 | 40.4 | 20.5 | 6.85 | 1.75 | 0.05 |
| t004 | 84.4 | 0.8 | 0.6 | 0.65 | 0.3 | 0.25 | 0 |
| t005 | 321.2 | 1.7 | 1.5 | 0.35 | 0.35 | 0.2 | 0 |
| t006 | 498.2 | 54.5 | 11.5 | 5.25 | 1.4 | 0.55 | 0.35 |
| t013b | 292.7 | 2.2 | 1.8 | 1.65 | 0.55 | 0.25 | 0.05 |
| t014b | 378.6 | 177.1 | 165.8 | 32 | 13.3 | 3.25 | 0.25 |
| t003 | 257.5 | 0.3 | 0.15 | 0.1 | 0.15 | 0.35 | 0.05 |
| t019b | 184.7 | 2 | 1.4 | 1.5 | 0.4 | 0.12 | 0.03 |
| t020b | 516.9 | 103.1 | 31.1 | 20.3 | 2.25 | 1.75 | 0.4 |
| t021b | 580.8 | 228.4 | 66.9 | 37.4 | 6.95 | 0.75 | 0.03 |
A comparison of overtopping behaviour over a permeable and impermeable crest  

Z.N. Afridi

Table 5. Recorded volumes of overtopping in the different sectors behind an Impermeable and Permeable crest with a slope of 1:3.

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<tr>
<th>Test #</th>
<th>Significant Wave Height, H_s (cm)</th>
<th>Average Time Period, T_{avg} (sec)</th>
<th>Water Depth in flume, D (m)</th>
<th>Duration, S (sec)</th>
<th>Free Board, R_c (m, meters)</th>
<th>Volume in Sector 1 (l, liters)</th>
<th>Volume in Sector 2 (l, liters)</th>
<th>Volume in Sector 3 (l, liters)</th>
<th>Volume in Sector 4 (l, liters)</th>
<th>Volume in Sector 5 (l, liters)</th>
<th>Volume in Sector 6 (l, liters)</th>
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Note: Values in green indicate sectors behind the impermeable crest, while values in white indicate sectors behind the permeable crest.