Wave overtopping pressures and spatial distribution behind rubble mound breakwaters

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Abstract

Currently, there is no widely accepted method to determine the pressure profiles induced by wave overtopping behind the crest of a breakwater other than physical modelling. In this experimental study, the spatial distribution of overtopping pressures on a vertical structure is investigated at various distances behind a rubble mound breakwater with a crown wall. A 2D physical modelling study in presented in an attempt to derive a practical method for estimating these overtopping pressures. The variability of overtopping wave pressures behind the crest of a breakwater is also discussed. Rule of thumb guidelines are proposed which will contribute to better concept and schematic structural designs in advance of physical model testing.

1 Introduction

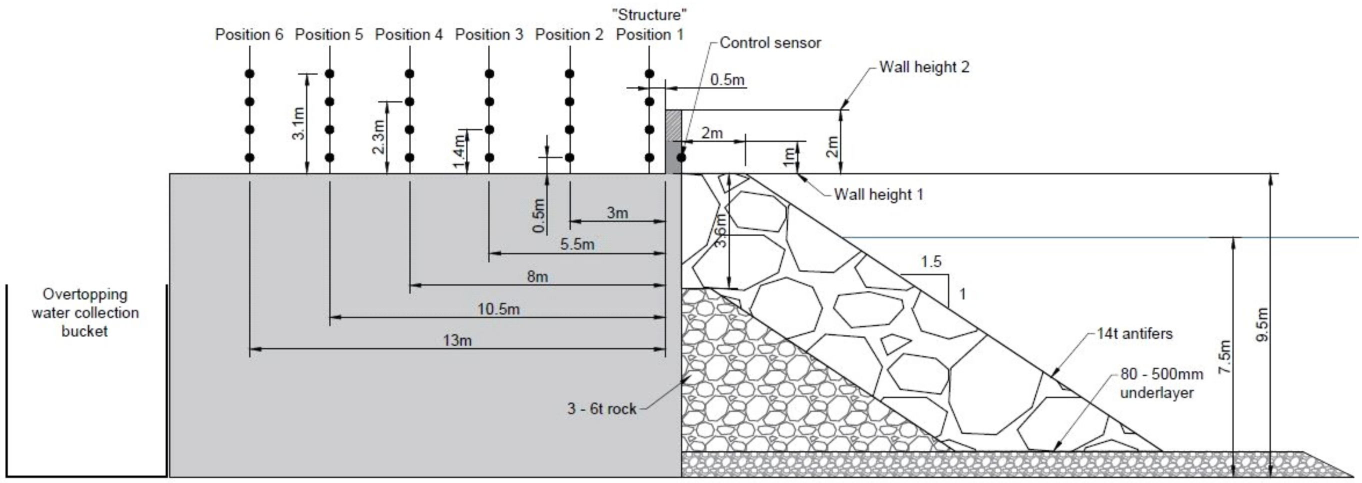
Urban developments in coastal areas subject to wave attack and coastal flooding are often protected by coastal defence structures (e.g. breakwaters, dikes, revetments). Usually these developments are located outside of the zone of impact of overtopping waves and are so protected from wave forces. However, occasionally there is a requirement for buildings to be located close to the crest of these defence structures for practical or architectural purposes, for example a coastguard station. For structures within the range of wave overtopping of a sea defence, wave impact must be considered in the design. In addition to this, these loads are expected to increase both in magnitude and frequency due to climate change and sea level rise.

Wave overtopping occurs when the highest run-up levels exceed the crest of the coastal defence structure. In extreme cases, it can cause structural failure, damage to harbour infrastructure, properties, and loss of life. Overtopping volumes are influenced by the design of coastal structures, including geometrical and structural parameters, as well as the wave conditions to which the structure is subject. (Bakker et al, 2017).

Considerable research has been carried out for the overtopping volumes and flows, as summarised in the EurOtop manual (pre-release, 2016) and associated neural network (Formentin et al., 2017) which provides estimations of overtopping rates mainly at the crest of a variety of structures. For the spatial distribution of wave overtopping of conventional rock breakwaters EurOtop provides the methodology by Lykke Andersen and Burcharth (2006), which involves the exceedance probability of the travel distance behind a rough breakwater crest.

Regarding the wave impact loading, various methodologies have been proposed to calculate the wave forces acting on different types of breakwaters. Some of these methods for wave loads on vertical breakwaters are outlined and compared by Kisacik et al. (2010). Studies have also been carried out to define the wave forces on the crown walls of rubble mound breakwaters. A selection of these methods are outlined and compare by Valdecantos et al, (2013). Very recently, Molines et al. (2018) focused on the explicit relationship between wave forces on crown walls and wave overtopping rates.

Figure 1. Breakwater cross-section and position of sensors (full scale)



Other studies have focused on the overtopping flow loads on vertical structures behind without a crown wall. Van Doorslaer et al (2017), De Rouck et al. (2012) and Ramachandran et al. (2012) related the wave impact forces to the overtopping flow parameters for a vertical wall behind a smooth dike. In relation to overtopping loads on building, Chen et al. (2012) assessed the loads due to wave overtopping acting on buildings behind a dike. This study considered two different locations for the building and showed considerable reduction in pressures for the building set 15m back from the crest of the dike. In a further study Chen et al. (2017) examined the effect of wave overtopping forces on a building behind a dike with specific consideration given to masonry buildings. These studies suggest formulae for the calculation of forces and pressures due to wave overtopping on a building or vertical wall behind a dike.

Research has also been carried on the spatial distribution of wave overtopping behind a breakwater, which demonstrated that the effect of wind on the wave overtopping volumes decreased as the wave overtopping volumes increased (Bruce et al, 2005). Further studies have been carried out to examine horizontal wave impacts on the crown of a breakwater, particularly for vertical breakwaters, which have suggested that the downfall pressure on the crown deck of a breakwater are smaller but of the same order of magnitude as pressures on the face of a crown wall (Wolters et al, 2005). However, little research has been carried out to examine overtopping pressures on a vertical face of a building behind a crown wall, particularly in relation to rubble mound breakwaters, which is the focus of this study.

2 Experimental Methodology

This experimental study was carried out using a 2D physical model in the LIR-National Ocean Test Facility of University College Cork. The model was a 1/25 scale of a rubble mound breakwater with a crown wall. It is presented in Figure 1. The breakwater armour had a 1V/1.5H slope and consisted of 14t antifers blocks (in prototype dimensions). Pressures due to wave overtopping were measured at four equidistant levels on the front-face of a rigid structure at four equidistant levels 0.5m, 1.4m, 2.3m, and 3.1m from the base of the wall. For the remainder of this paper, all references to the "structure" shall refer to this rigid structure behind the crown wall to which the 4 sensors were attached. One pressure sensor was also placed on the face of the crown wall as a control.

Figure 2. Physical model testing

The spatial distribution of overtopping pressures was investigated by changing the position of this structure behind the crown wall for each set of tests. Six locations behind the crown wall were tested, 0.5m; 3m; 5.5m; 8m; 10.5m; and 13m. Two crown wall heights were tested, a 1m high wall, and a 2m high wall to examine the effect of the crown wall height and the reduced overtopping on the pressures imposed on the structure behind. The positions, and the locations of the sensors, are shown in Figure 1.

Wave overtopping pressures were measured with ATM.1ST pressure transmitters with a 10mm diameter face, recording at a frequency of 160Hz. The duration of each tests was 30min, prototype scale dimensions. The volume of water from overtopping was measured in a collection bucket using a wave probe to record water levels. Due to large overtopping volumes, this water was pumped out and the volume of overtopping calculated based on the speed of the pump and the recorded water levels. Figure 2 shows two photographs of the testing set-up. A total of 12 different wave spectrums generated, as outlined in Table 1, with normal wave propagation directly to the rubble mound breakwater.

Table 1. Model Tests

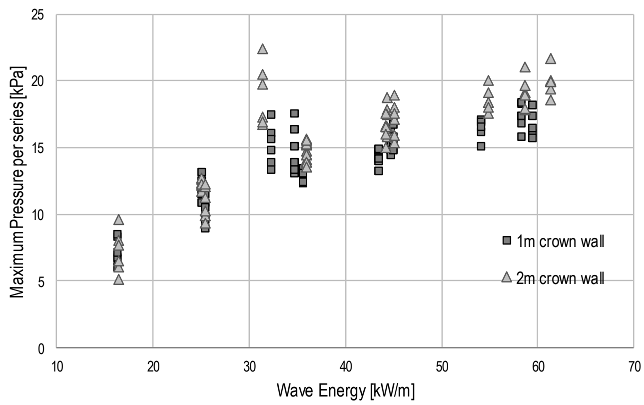
Crown wall [height in m]	Test Number	Measured Waves	
		H_s *[m]*	T_p *[s]*
1	1	2.3	6.0
	2	2.7	7.1
	3	2.8	8.4
	4	3.1	9.2
	5	3.3	9.9
	6	2.6	10.9
	7	2.8	6.6
	8	3.2	6.9
	9	3.3	8.4
	10	3.5	9.3
	11	3.5	9.9
	12	2.8	10.9
2	1	2.3	6.0
	2	2.7	7.1
	3	2.7	8.4
	4	3.1	9.1
	5	3.3	9.9
	6	2.6	10.9
	7	2.8	6.6
	8	3.2	7.2
	9	3.3	8.4
	10	3.6	9.3
	11	3.5	9.9
	12	2.9	10.9

The wave spectrum used for these tests was the irregular JONSWAP spectrum. The same wave input wave conditions were used for the two different crown wall heights. The significant wave heights calculated from these measurements ranged between 2.3 - 3.6m, with wave periods from 6.0 - 10.9s, measured at the toe of the structure. Reflections were measured, and are included in the measured wave heights. A reflection coefficient between 0.33 and 0.63 was calculated.

3 Data Analysis

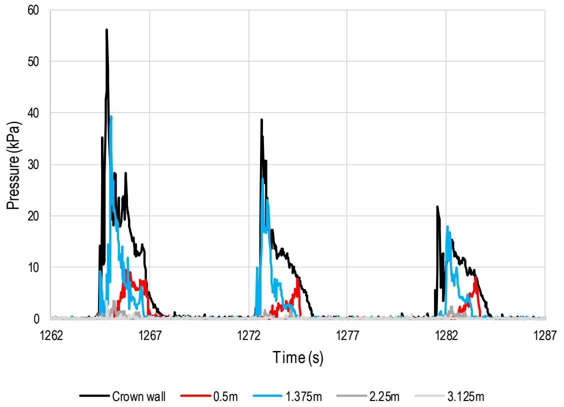
The repeatability of the tests was assessed first by analysing the wave probe signals. A difference of 3% between the measurement for two test runs of the same wave conditions was measured, thus arguing for the repeatability of the tests. However, the analysis of the recorded pressures time series from the sensors showed that the wave pressure signal varied despite the repeatability of the wave conditions. Figure 3 shows the range of maximum pressure readings recorded on the crown wall, giving a deviation from the average of between ±0.5 and ±2.8kPa.

Figure 3. Variability of wave pressure on crown wall



This variation is due to the natural variability of wave attack. The overall variation in the pressures recorded on the crown wall was between 5% and 30%, with an average variation of 10%. The highest percentage variations were observed at low recorded pressure values. In order to understand the overall pressure acting on the structure during each overtopping event, rather than instantaneous peaks, the quasi-static pressure on the structure was calculated by taking total area under each peak and dividing by the duration of the event. Figure 4 shows a sample of the pressure time series recorded. All pressure values referenced in this paper are the quasi-static pressure values calculated using this approach, similar to that presented by Cuomo et al (2010) for examining quasi-static pressures on vertical seawalls. It was observed that the maximum pressure value recorded on the structure was in a few cases higher than the pressure recorded on the crown wall at that event. However, the quasi-static pressure applied during the event, as calculated above, was consistently larger on the crown wall. This method also gave less variability in the results than the instantaneous maximum pressures recorded.

Figure 4. Sample Pressure Time Series

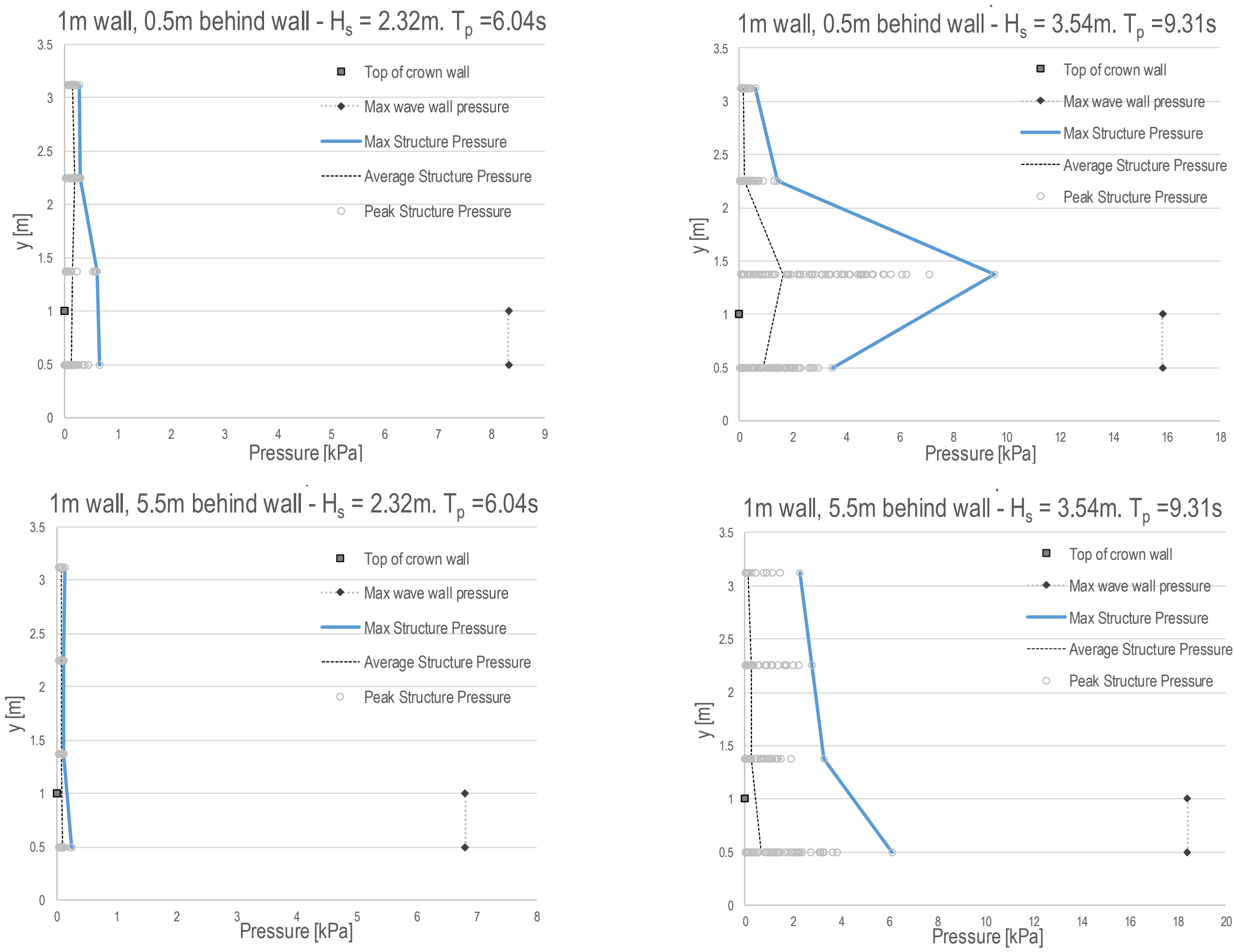


4 Results

In order to examine the maximum pressure envelope, the peak pressure readings on the structure were compared to the highest pressure on the crown wall, for which well-established calculation methods exist. Measured crown wall pressures were found to be smaller but of the same order of magnitude as those calculated by the empirical formula proposed by Martin et al. (1999).

The envelope of pressures applied on the structure were plotted, with the elevation y on the vertical axis and the prototype scale pressures on the horizontal axis. This method is similar to that used by Kisacik et al. (2010) to show the distribution of pressures over a vertical crown wall. Figure 5 presents the pressure envelope for two different tests, the minimum and maximum wave heights tested, for two distances behind the wall, 0.5m and 5.5m. The pressure recorded on the crown wall is also presented, together with the maximum and average pressure values. The maximum pressure on the structure was considerably less than the pressure on the crown wall for the lower wave heights tested. This was correlated to the lower overtopping flows.

Figure 5. Distribution of maximum pressures on structure – 1m high crown wall



It was confirmed that the maximum pressure on the structure increased as the wave height and period increased. In particular, two areas of higher pressure were identified. Near the crown wall, the highest pressures were recorded on the sensor directly above the top of the crown wall. At a distance from the crown wall, a reduction in pressures was observed for the lower wave heights. However, as the volume of overtopping increased, the vertical distribution of pressures showed an increase in the pressures recorded closest to the ground level. This applied for all distances behind the crown wall measured and is believed to be due to the overtopping surface flow behind the structure.

This effect was further explored by examining the pressure envelope for the case of the 2m high wall, which is shown in Figure 6. As for the 1m high crown wall, low pressures were recorded for the lower wave heights. With increased wave energy and wave overtopping, the pressure envelope showed that the highest pressures were recorded in the sensor nearest the top of the wall. However, the pressures recorded on the structure for the 2m high crown wall were less than those measured on the 1m high wall, due to the reduced wave overtopping.

The spatial distribution of pressures was also investigated by examining the percentage reduction in pressures, calculated by dividing the maximum pressure measured in each sensor by the maximum pressure on the crown wall in that test run. The results for the lowest and highest wave heights tested are presented in Tables 2 to 5. These tables show that, for the lowest wave height tested, the pressures recorded on the structure were under 10% of that recorded on the crown wall. However, with increased wave height and period, two areas of higher pressure were identified, as discussed previously

Figure 6. Distribution of maximum pressures on structure – 2m high crown wall

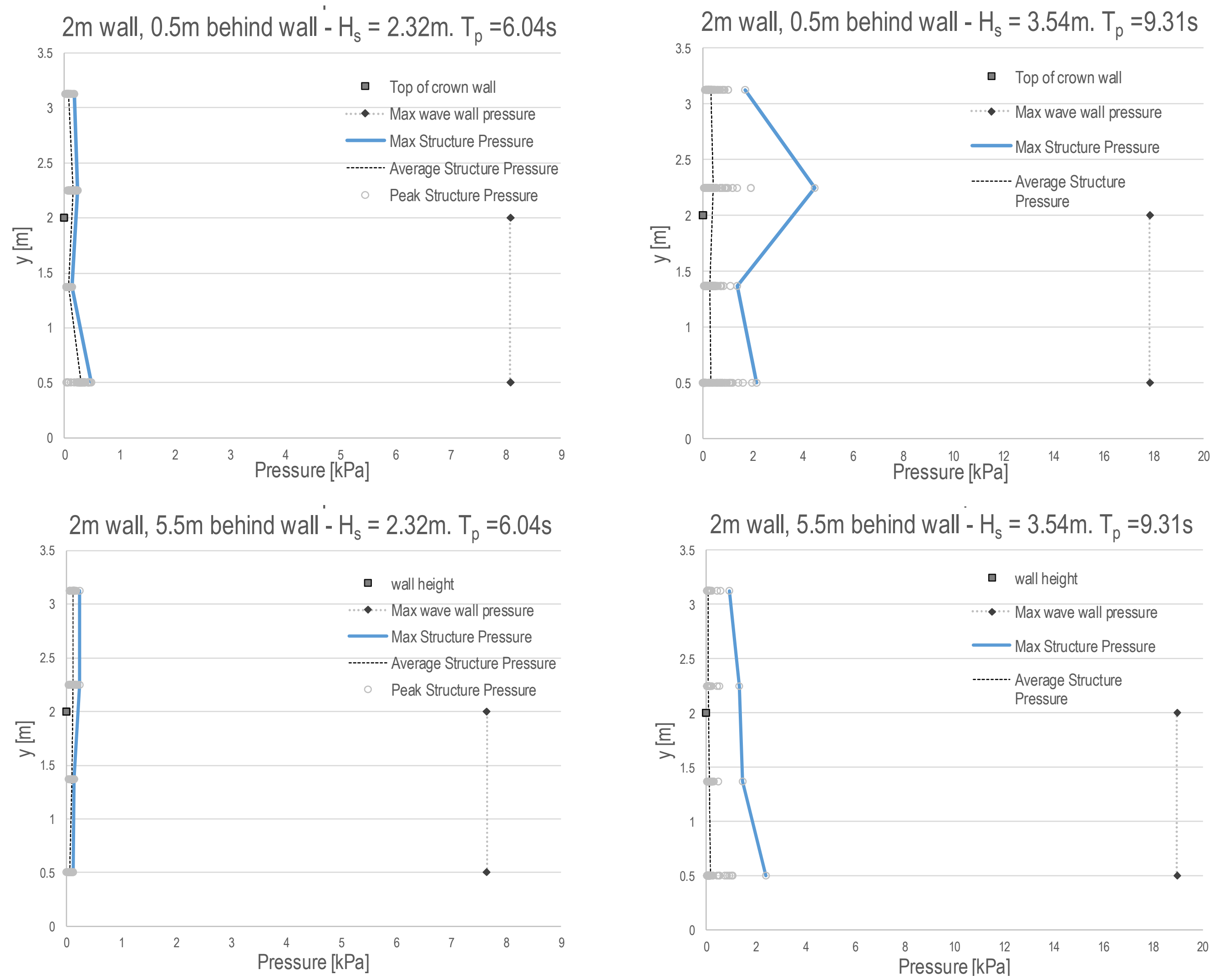


Table 2. Pressures on structure,% of maximum pressure on 1m crown wall, lowest wave height tested (Test.No.1)

Hs = 2.32m Tp = 6.04m		Distance behind the crown wall [m]					
		0.5	3.0	5.5	8.0	10.5	13.0
Height above ground [m]	3.1	4%	2%	2%	2%	1%	2%
	2.3	4%	2%	2%	1%	3%	1%
	1.4	9%	2%	2%	2%	6%	3%
	0.5	9%	3%	3%	2%	2%	3%

Table 3. Pressures on structure, % of maximum pressure on 1m crown wall, highest wave height tested (Test.No.10)

Hs = 3.54m Tp = 9.31m		Distance behind the crown wall [m]					
		0.5	3.0	5.5	8.0	10.5	13.0
Height above ground [m]	3.1	4%	9%	13%	4%	2%	1%
	2.3	8%	22%	16%	8%	8%	1%
	1.4	55%	27%	19%	14%	6%	20%
	0.5	20%	31%	35%	41%	40%	30%

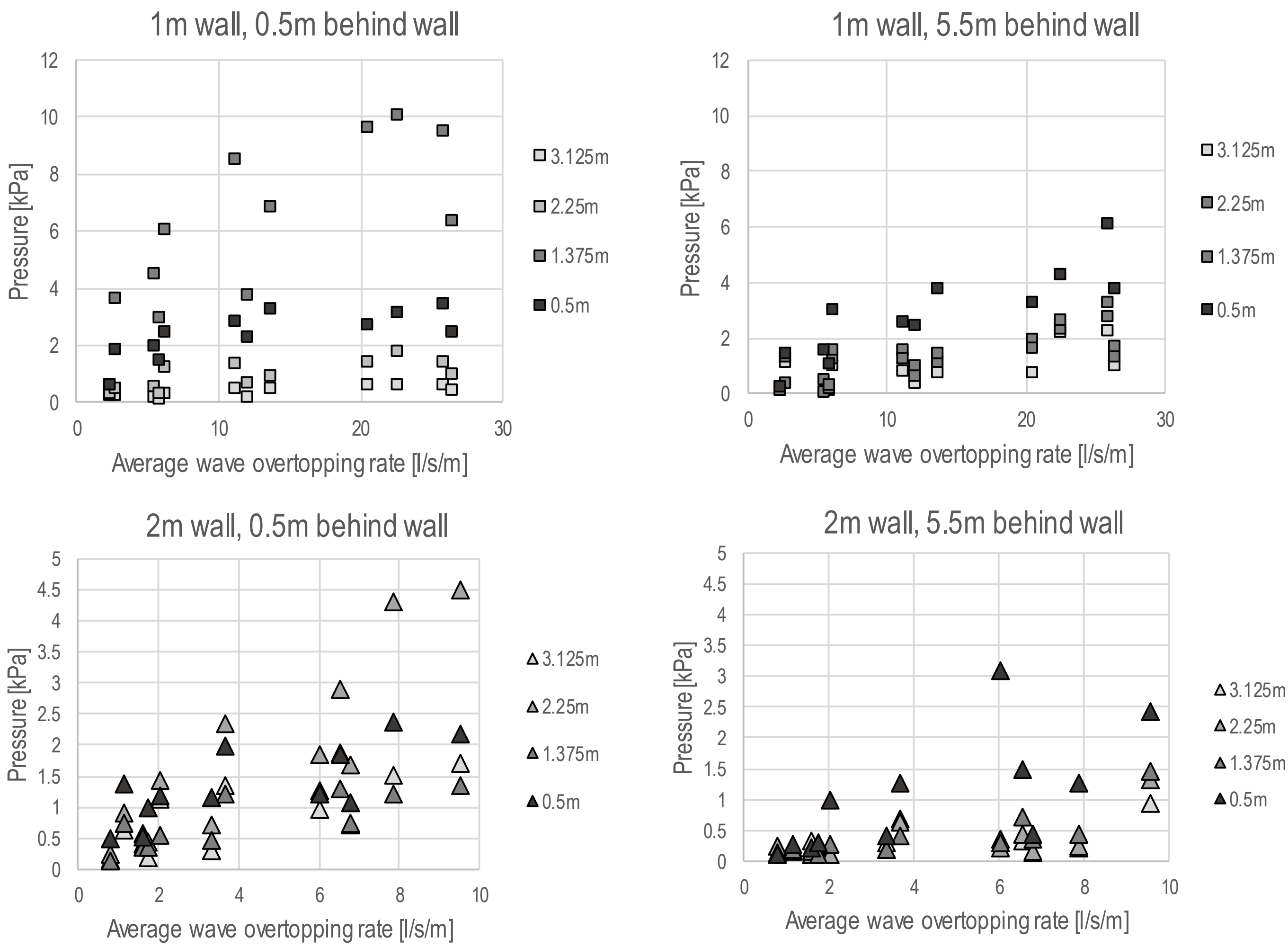
Table 4. Pressures on structure, % of maximum pressure on 2m crown wall, lowest wave height tested (Test.No.1)

Hs = 2.34m Tp = 6.01m		Distance behind the crown wall [m]					
		0.5	3.0	5.5	8.0	10.5	13.0
Height above ground [m]	3.1	2%	2%	3%	4%	4%	6%
	2.3	3%	4%	3%	4%	4%	4%
	1.4	2%	3%	2%	3%	5%	6%
	0.5	7%	6%	2%	6%	4%	6%

Table 5. Pressures on structure, % of maximum pressure on 2m crown wall, highest wave height tested (Test.No.10)

Hs = 3.55m Tp = 9.31m		Distance behind the crown wall [m]					
		0.5	3.0	5.5	8.0	10.5	13.0
Height above ground [m]	3.1	9%	6%	5%	4%	3%	2%
	2.3	23%	7%	7%	5%	6%	2%
	1.4	7%	6%	8%	3%	6%	1%
	0.5	11%	9%	13%	18%	11%	3%

Figure 7. Pressure v Overtopping volume



The first area of higher pressure, at the location nearest the top of the crown wall, had a maximum pressure recorded of up to 60% of the maximum pressure recorded on the crown wall considering all wave conditions tested. Note that the highest percentage pressure was recorded at this location for test run 11 (measured wave height of 3.46m and wave period of 9.94m), which had a lower wave height but higher wave period than test run 10 shown in Table 3.

Higher pressures were also observed at the base of the structure. These pressures were not as high as the pressures on the sensor near the top of the crown wall. However, unlike the concentrated pressures near the top of the crown wall, little reduction was observed for the increased horizontal distance from the wall. To further examine this effect, the pressures on the structure behind the 2m crown wall were examined. The reduction in overtopping volume resulted in a considerable reduction in the pressures recorded on the structure. When the crown wall is increased, less overtopping occurs. These tables show both the significant reduction in pressure between that recorded on the crown wall and that on the structure. In addition to this, the higher pressure directly above the top of the crown wall and at the base of the structure are evident, though the pressure reduction is increased.

Plotting the pressure against the wave overtopping volume also demonstrates this characteristic of the pressure envelope. The graphs shown in Figure 7 present the measured pressures versus the average wave overtopping rate for the two different distances of the structure behind the crown wall. These values demonstrate the increase in pressure on the structure as the wave overtopping increases. It also shows the change between the higher pressures directly above the top of the crown wall for a structure near the wall to the maximum pressure in the envelope being at the base of the structure due to the overtopping flow path.

5 Conclusions

In this experimental study, the spatial distribution of pressures due to wave overtopping was investigated. Results show that the pressure measured at the top of the crown wall of an antifer armoured breakwater was always the highest. A considerable difference between pressures on the crown wall and the pressures recorded on the structure was observed. A number of conclusions have been extracted as rule of thumb guidelines as outlined below. These guidelines are suggested for concept and scheme design in advance of physical model testing.

- In the case of lower wave overtopping, pressures under 10% the pressure recorded on the crown wall were observed on the structure.
- For higher wave overtopping, higher pressures were observed in two locations:
    - Firstly, higher pressures were observed at the location nearest to the top of the crown wall, both in terms of horizontal and vertical distances. Pressures at this location were observed to be more than 50% of the pressure recorded on the crown wall.
    - Secondly, higher pressures were observed at the base of the structure for all distances behind the crown wall, with pressures up to 41% of the pressure recorded on the face of the crown wall.
- The results obtained can be used for further consideration of "safe distances" behind the wall

The above conclusions can have a significant impact when considering the design of structures behind the crown wall of a breakwater. Given that the predicted wave overtopping may increase the design loads applied to the structure, relocation of the structure outside the area of the higher pressures nearest the crest of the crown wall can provide significant pressure reductions. Furthermore, at a distance behind the breakwater crown wall, the pressures near the ground level are increased compared to higher elevations due to the overtopping surface flow. Such observations may be useful for the placement of windows etc.

5.1 Further Research

Further research to investigate the pressure distributions due to wave overtopping will focus on analysing the present results in further detail with the support of additional physical model tests. The testing of different breakwater sections with different wall heights and water levels will be carried out to investigate the applicability of these results to other breakwater cross-sections. The use of a finer grid of sensors will help the better understanding and definition of the area of the observed concentrated pressures. We will also seek for the opportunity of testing at a larger scale with the aim of examining any scale affected. Also, the effect of wind on wave overtopping pressures, which was not included in the physical modelling, bears further investigation, especially for lower overtopping volumes where the influence of wind is greater (Bruce et al, 2005). The use of a load cell to examine the overall force on the structure, the results of a larger network of pressure sensors and comparisons to numerical modelling results would also be interest.

References

Bakker, P., Reedijk, B., Manaois, J., Van De Koppel, M., & Muttray, M, (2017) Causes for Increased Wave Overtopping on Rubble Breakwaters and Revetments, *In: Proc. of ICE Coasts, Marine Structures and Breakwaters 2017*

Bruce, T., Pullen, T., Allsop, W., Pearson, J., (2005) 'How far back from a seawall is safe? Spatial distributions of wave overtopping' *International Conference on Coastlines, Structures and Breakwaters 2005*

Chen, X., Hassan, W., Uijttewaal, W., Verwaest, T., Verhagen, H. J., Suzuki, T. & Jonkman, S. N. (2012). Hydrodynamic load on the building caused by overtopping waves. *Coastal Engineering Proceedings, 33(59), Dec 2012. ISSN 2156-1028*.

Chen, X., Jonkman, S.N., Pasterkamp, S., Suzuki, T., Altomare, C., Vulnerability of Buildings on Coastal Dikes due to Wave Overtopping, *Water 2017 9(6) 394*

Cuomo, G., Allsop, W., Bruce, T., Pearson, J., (2010) Breaking wave loads at vertical seawalls and breakwaters, *Coastal Engineering, 57(4)*, *April 2010*.

De Rouck, J., Van Doorslaer, K., Versluys, T., Ramachandran, K., Schimmels, S., Kudella, M. & Trouw, K. (2012). Full scale impact tests of an overtopping bore on a vertical wall in the Large Wave Flume (GWK) in Hannover *Coastal Engineering Proceedings, 33(62), Dec. 2012. ISSN 2156-1028*

Formentin, S., Zanuttigh, B., & van der Meer, Jentsje. (2017). 'The New EurOtop Neural Network Tool for an Improved Prediction of Wave Overtopping', *In: Proc. of ICE Coasts, Marine Structures and Breakwaters 2017*

Kisacik, D., Van Bogaerr, P., Troch, P., Comparative Study on Breaking Wave Forces on Vertical Walls with Cantilever Surfaces, *In: Proc. of the 20th International Offshore and Polar Engineering Conference 2010*

Negro Valdecantos, V., Lopéz Gutiérrez, J. S., and Polvorinos Flors, J.I. (2013) 'Comparative study of breakwater crown wall – calculation methods', *In Proc. of ICE Maritime Engineering* Vol. 166 March 2013 Issue MA1, pg. 25–41

Martin, F. L., Losada, M. A. & Medina, R. 1999. Wave Loads on Rubble Mound Breakwater Crown Walls. *Coastal Engineering, 37*, 149-174.

Molines, J., Herrera, M. P. & Medina, J. R. (2018). Estimations of wave forces on crown walls based on wave overtopping rates. *Coastal Engineering, 132*, (2018) *50-62*.

Streicher, M., Kortenhaus, A. & Hohls, C., (2016) 'Analysis of Post Overtopping Flow Impacts on a Vertical Wall at the Belgian coast', *In Proc. of 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science 2016*.

Ramachandran, K., Genzalez, R. R., Oumeraci, H., Schimmels, S., Kudella, M., Van Doorslaer, K., De Rouck, J., Versluys, T. & Trouw, K. (2012). Loading of vertical walls by overtopping bores using pressure and force sensors - A full scale model study. *In: Proc. of ICCE -International Conference on Coastal Engineering,* 2012

Wolters, G., Müller, G., Bruce, T. and Obhrai, C. (2005) Large-scale experiments on wave downfall pressures *Water and Maritime Engineering*, 158, (4), pp. 137-145.

Van Der Meer, J. W., Allsop, N. W. H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schuttrumpf, H., Troch, P. & Zanuttigh, B. (2016). EurOtop - Manual on wave overtopping of sea defences and related structures. Second ed. (pre-release, 2016) Last accessed 04/01/2018.