COMPUTATIONAL INVESTIGATION OF THE EFFECTS OF BIMODAL SEAS ON WAVE OVERTOPPING

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Abstract

The purpose of this work was to develop a computational process to investigate the effect of bimodal wave conditions on wave overtopping. The numerical model NEWRANS has been validated for the application of bimodal wave overtopping and a procedure developed to generate the desired wave conditions in the flume. When applied to bi-modal specific wave overtopping, NEWRANS works well and replicates overtopping discharge achieving good agreement with experimental data. A set of bi-modal conditions are derived and used to force the model. Swell percentage is found to have significant influence on the overtopping discharge during lower mean wave period inputs. The model was also run with a set of unimodal wave conditions to investigate the influence of increasing mean wave period on overtopping rates. For the cases investigated here it was found that the overtopping rate plateaued after initially increasing with mean wave period. These results suggest that the distribution of energy across frequencies in a random wave condition has an important influence on the overtopping rates that may be experienced. This, in turn, indicates that using a single integrated wave period parameter for predicting wave overtopping is insufficient.

Key words: Wave overtopping, swell waves, bi-modal waves, numerical modelling, coastal flooding.

1. Introduction

Wave overtopping can lead to localised flooding and cause significant damage to defences along the coastline. Wave overtopping occurs when the wave passes over the crest of the structure. It is by estimating overtopping under specific conditions that allows the design of appropriate flood defences. However, due to the complex processes associated with wave overtopping, estimating overtopping discharges and volumes can be difficult. Overtopping discharges are determined by transforming offshore wave conditions to the toe of the coastal defence. When these wave conditions are random the prediction of overtopping discharges is made more complicated. It is important tested processes are in place to quantify wave overtopping and reduce the uncertainties involved.

We consider a random sea state composed by the sum of many linear waves. When a significant number of linear waves with similar frequencies contribute to the overall sea state, the sea state can be considered unimodal. If the wave energy is clustered around two separate frequencies, as can happen with wind sea and swell waves, the sea state is considered bimodal. Bimodal sea states usually occur when both high-frequency waves (or wind-waves) are observed at the same time as low-frequency waves (or swell waves). A wind wave is a wave which is still affected by the local wind conditions and is generated locally, they are usually defined to have wave periods up to 8 s. A swell wave is a wave that has been generated far from the immediate area and is no longer significantly affected by the local wind conditions. Swell waves are commonly defined to have wave periods greater than 8 s. Figure 1 presents an example bimodal spectra where the swell-wave component and wind-wave component are highlighted. Due to the long periods associated with swell waves, they are more to likely run-up and overtop structures, (Hawkes, 1999). Long period waves are therefore an important consideration when estimating wave overtopping.

Bradbury et al., (2007) provided evidence of bimodal wave conditions within the English Channel, stating they are present for 25% of the time during winter months at sites exposed to swell conditions from the Atlantic. Bradbury et al. (2007) also discuss the observed significant effect of bimodal conditions of beaches, impacting run-up, the reduction of crest-width and overtopping of seawalls. Long-period swell waves have been observed to cause significant impacts along UK coastlines as well as many other countries, as discussed by Palmer (2014). During the winter storms of 2013 – 2014 that hit the UK, long period swell is considered to have contributed to the extensive coastal flooding and damage that was observed, Sibley 2014 and Sibley 2015**.**

This work aims to develop a computational procedure for investigating the effects of bi-modal waves on wave overtopping. In earlier studies, bi-modal conditions have been applied in experimental conditions. Coates et al. (1998) undertook physical tests to investigate the impact of bimodal wave conditions on shingle beaches and coastal structures, as well as the wave breaking behaviour. Hawkes (1999) extended the experimental work of Coates et al. (1998) to demonstrate a desk study application of the swell atlas, Hawkes (1997), in order to calculate overtopping specifically for swell and bimodal seas. The work by Hawkes (1999) showed that swell and bimodal sea conditions, even with lower wave heights than the overall extreme conditions, may be a worse case for design based on overtopping rate. Further research on the experimental work of Coates et al., (1998) was done by Lorenzo et al., (2000) where overtopping formulae used to estimate overtopping discharges were compared to observations. More recently, experimental work by Kashima (2010) investigated the effects of long period swell waves on overtopping. Kashima (2010) found that the wave overtopping rate increased under the effects of the swell specific wave grouping.

Very little work on numerical modelling of wave overtopping structures addresses incident waves consisting of bimodal random waves. Several works by McCabe (2011), Tsung et al., (2012), Hsiao and Lin (2010), Tuan and Oumeraci (2010) among others focus on modelling wave overtopping, while Reeve et al. (2008) and Jones et al. (2013) applied RANS models to estimate overtopping. These studies demonstrated the capability of numerical models to estimate overtopping. Numerical models that use the Navier-stokes equations and the VOF method have been applied and validated to a wide number of cases for the analysis of wave interaction with coastal structures. The benefits of these models are that they are able to describe the complex processes involved in breaking wave conditions and overtopping as the velocity is calculated for the whole computational domain and few assumptions are involved. For example, Lara et al., (2006) applied a RANS model to investigate the effects of random waves on submerged permeable structures. However, none of the mentioned studies have considered bimodal or long period wave sea states.

The next section introduces the RANS model and some validation against experimental data. Included is a description on the process of generating desired wave trains. The setup of the investigation of bimodal and long-period unimodal waves and wave conditions is then described followed by results and concluding remarks in the following sections.

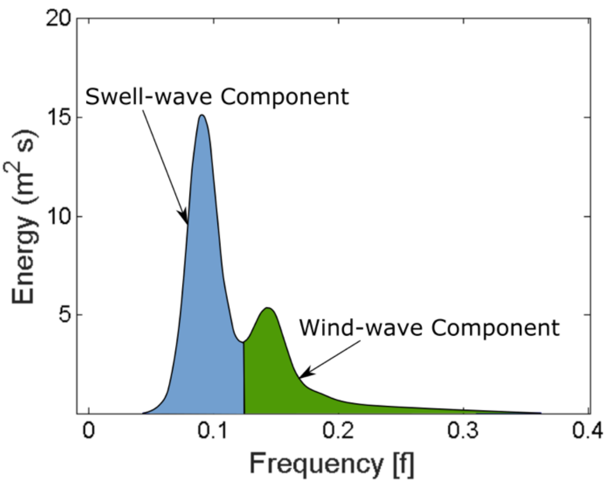

Figure 1. Example of Bi-modal spectra highlighting the swell and wind-wave components

2. Numerical model

The original core of the NEWRANS model was developed by Lin and Liu (1998) and solves the 2D Reynolds-averaged Navier-Stokes equations by decomposing the instantaneous velocity and pressure fields into the mean and turbulent components. Reynolds stresses are described by an algebraic nonlinear $k - \varepsilon$ turbulence model. To capture large deformations in the water surface caused by wave breaking and wave overtopping the front tracking volume-of-fluid capturing scheme functions are applied, originally developed by Hirt and Nichols (1981). A detailed description of the model can be found in Lin and Liu (1998).

The generation and absorption of bimodal seas in a numerical wave tank provides unique challenges during long simulations. Increased simulation times are required to ensure the development of the desired sea state and overtopping volumes. Generating a sea state with desired swell and wind wave components requires a method that can accurately produce high and low frequency waves simultaneously. Additionally, low frequency waves can cause significant reflections. The reflected waves can affect the accuracy of wave generation due to secondary wave reflection at the generating boundary and the long simulations can cause mass stability issues which in turn affect the water level and thus the accuracy of results and wave generation. Thompson et al, (2016) summarise an investigation of these phenomena and describe how the wave paddle method, where velocity and free surface value are specified at the wave boundary, produces the target spectra and conserves mass.

2.1 *Model Validation*

To assess NEWRAN's capabilities in describing the hydrodynamic process involved with bimodal wave generation and overtopping, the model was compared to a set of experimental test conditions related to bimodal wave overtopping. The report, produced by HR Wallingford, was commissioned by the Ministry of Agriculture, Fisheries and Food. The three principles of the project involved: investigating the effects of combined swell/storm waves on wave overtopping on simple seawall structures; investigating the cross-shore response of shingle beaches to bimodal and wind sea waves; and to study the important of approach slopes on the form of breaking waves and the subsequent effects on wave pressures on simple seawall structures. As an outcome of the report, a further report was produced investigating solely the impact of bimodal seas on beaches and control structures, Hawkes (1998) and Hawkes (1999), looking at the mean overtopping rate in swell and bimodal seas.

The bimodal sea conditions consist of two superimposed JONSWAP spectra, with each spectra defined by its significant wave height, H_s, and peak wave period, T_p, Coates et al., (1998) divided the bimodal wave conditions into six sequences of five tests and one sequence of eight tests. Sequences 1 - 3 have wave conditions with equal energy, with a wind sea peak period at 7 s coupled with swell at 11 s, 14 s and 19 s. For the validation, sequences 1 - 3 are used to compare wave conditions and overtopping results. The same procedure of creating a bimodal sea by superimposing two JONSWAP spectra will be used for creating the wave train in the model.

The report provided the wave input conditions, observed mean wave conditions, and overtopping discharge. A procedure was therefore developed where a set of input wave conditions would create a wave train with ‘target’ derived wave conditions. The procedure allowed the definition of a number of derived wave conditions (i.e. swell percentage, $T_{m-1,0}$, T_p, T_{m02}, H_{m0}). The initial spectrum is defined by the significant wave height, H_{m0}, and peak period, T_p. To produce wave trains with more than one peak in the spectra, each spectrum was defined by a $H_{m0,i}$ and $T_{p,i}$, where *i* represents the spectrum number. The defined spectra are then superimposed, from which the random wave train was derived. An automated iterative procedure is then applied where the created wave train’s characteristics are checked against the desired conditions. If the measured wave characteristics fall outside a specified error limit, the input $H_{m0,i}$ and $T_{p,I}$ are adjusted according to the measured error and the processes is repeated until the desired wave conditions are met. Figure 2 provides an example of how a desired resultant wave condition is defined, and a wave train of 1000 waves is generated from the procedure to be fed into the NEWRANS model as

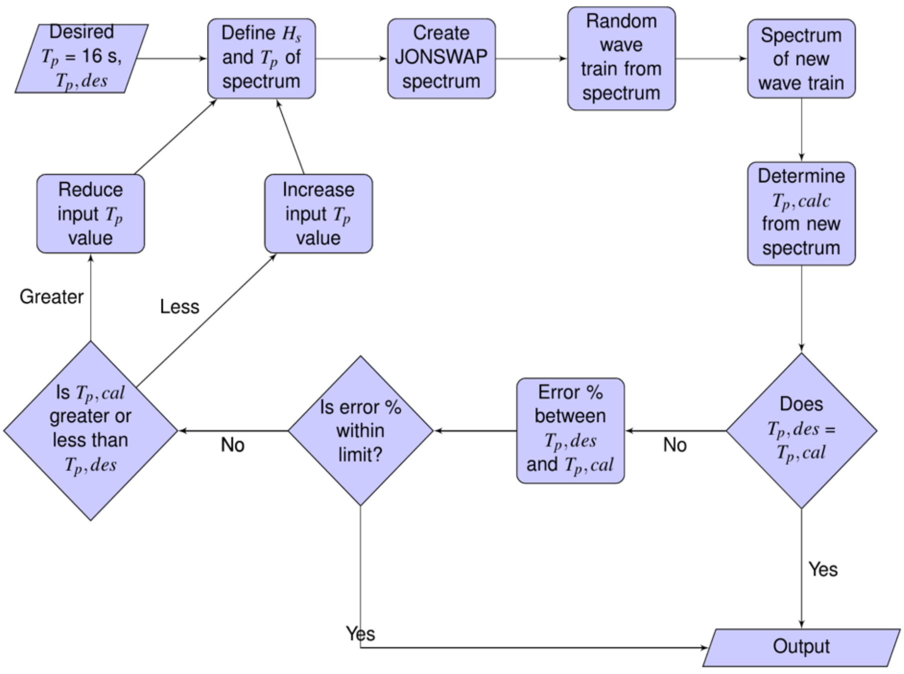

Figure 2. Process developed to derive wave train with desired wave parameters.

described by Thompson et al. (2016).

2.1.1 Model setup

The model was setup up with a 1:2 structure slope at the end of a 1:50 foreshore slope placed at a depth of 8m, and structure slope levelled off at 18m. This setup replicates an embankment structure at the edge of a gentle beach slope. The computational domain was setup at prototype scale. Figure 3 presents the setup of the model. A fixed grid was used, keeping it uniform in both x- and y- directions. The domain was 740m long, and with a height of 24m. The grid sizes are 0.6m and 0.32m in the x- and y- direction respectively, giving a total of 1233 cells in the x- direction and 75 in the y- direction. The same model setup was used for both the bimodal and unimodal investigations.

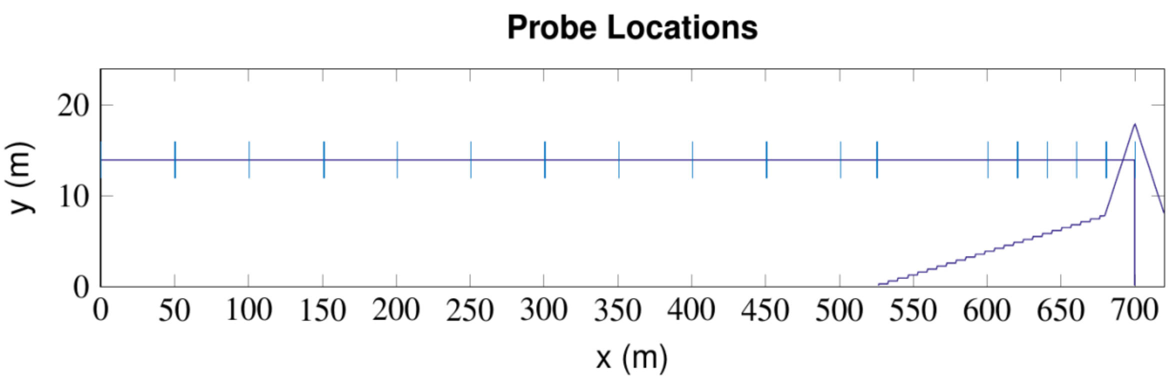

Figure 3. NEWRANS domain including probe locations.

2.1.2 Results of validation

Figures 4 and 5 plot the observed overtopping discharges in the model against those observed in the experiment. Wave overtopping is determined at the crest of the structure via the velocity flux and water layer thickness as described in Peng and Zou (2011). NEWRANS replicated the overtopping discharge with good agreement to the experiment. However, when little overtopping occurs, the overtopping discharge from the model is under-predicted. The good agreement with the experimental results also provided confirmation that the wave generation method used is suitable for the application of wave overtopping under bimodal sea states and long period waves.

3. Method

3.1 Model setup

The numerical model setup used for the validation was next applied to wave overtopping with the foreshore slope set to 1:20 instead of 1:50. The 1:20 slope is commonly used for many studies in the UK and is representative of steeper sand beaches. The tests were performed on an impermeable embankment with a 1:2 structure slope and a 1:20 beach slope at prototype scale. All geometric parameters were kept constant for each wave input (freeboard, water level, structure and beach slopes). The model setup and domain size, with probe locations, can be found in Figure 3.

3.2 Wave conditions

A set of wave inputs were derived to investigate the effects of increasing mean wave period, T_{m02}, and swell percentage, P_{sc}, on overtopping discharge. The wave conditions were defined by 3 key parameters: total energy; swell percentage; mean wave period. Total energy was the sum of the energy in the spectra

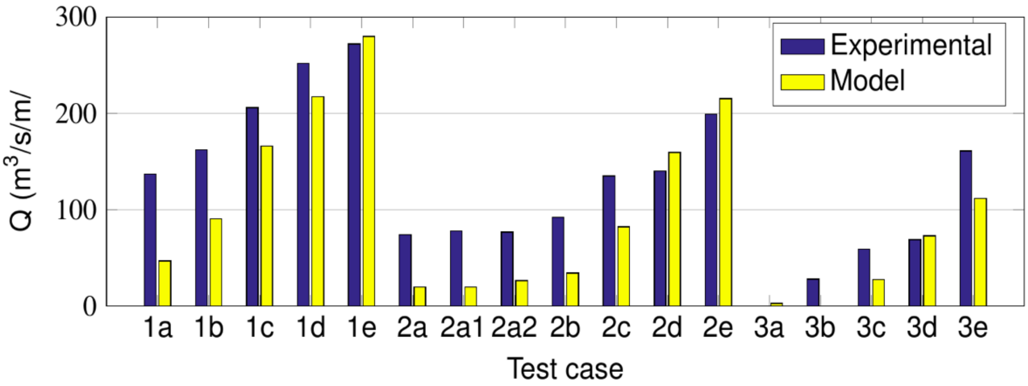

Figure 4. Modelled mean overtopping discharge and experimental overtopping discharge for sequences 1 - 3.

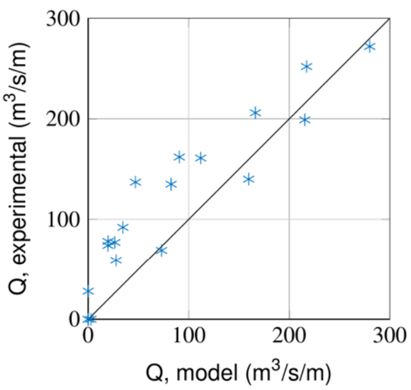

Figure 5. Modelled mean overtopping discharge against experimental mean overtopping discharge.

and was defined so that all wave conditions had equal energy. The sequences were defined with a high-

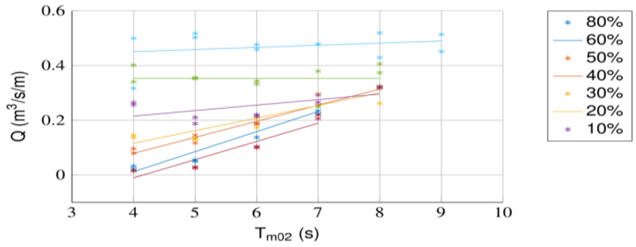

Figure 6. Mean overtopping discharge plotted as a function of the mean wave period input.

energy content. Swell percentage is the total amount of contribution to the overall spectra that is defined by the swell component. Figure 1 presents a spectra where swell percentage, P_{sc} , is 80%. The wave conditions derived for both bimodal and unimodal investigation used the process of Figure 2 to generate a wave train of at least 500 waves which were then fed into the NEWRANS model. The unimodal investigation consisted of sequences of waves defined by equal total energy, with an increasing mean wave period (T_{m02} = 6s to 16s). Table 1 provides a breakdown of the bimodal wave conditions simulated.

Table 1. Breakdown of the input wave conditions for the bi-modal tests.

Bi-modal	P_{sc} = 10%	P_{sc} = 20%	P_{sc} = 30%	P_{sc} = 40%	P_{sc} = 50%	P_{sc} = 60%	P_{sc} = 80%
T_{m02} = 4s	Simulated	Simulated	Simulated	Simulated	Simulated	Simulated	Simulated
T_{m02} = 5s	Simulated	Simulated	Simulated	Simulated	Simulated	Simulated	Simulated
T_{m02} = 6s	Simulated	Simulated	Simulated	Simulated	Simulated	Simulated	Simulated
T_{m02} = 7s	Simulated	Simulated	Simulated	Simulated	Simulated	Simulated	Simulated
T_{m02} = 8s			Simulated	Simulated	Simulated	Simulated	Simulated
T_{m02} = 9s							Simulated

4. Results

4.1 Bi-modal Results

Results are presented in terms of the input mean wave period, T_{m02}, and input swell percentage, P_{sc}, in Figures 6 and 7. Figure 6 plots mean overtopping discharge as a function of mean wave period input. This plot represents all observed overtopping discharges, with the line of best fit showing the averages observed for the given swell percentage. A positive correlation between increasing mean wave period and overtopping discharge is observable. The spread in overtopping discharge reduces as you increase in the mean wave period input, suggesting swell percentage has a greater effect on resultant mean overtopping discharge on the lower mean wave periods.

Figure 7 highlights the greater difference observed in mean overtopping discharge between different swell percentages for the same mean wave period input. The rate of increase of mean overtopping discharge for the lower mean wave periods (4s - 5 s) as swell percentage is increased is much larger than for the slightly longer mean wave periods (7 s - 8 s). A clear positive correlation is observed between swell percentage and mean overtopping discharge (correlation value = 0.87). It is therefore clear that swell percentage has a greater effect on resultant mean overtopping discharge for lower mean wave periods, but influence of swell percentage is still observed for the higher mean wave periods. Potentially the most important swell percentage is 20\% - 40\% due to the increased rate in overtopping discharge associated with these swell percentages (Figure 6).

4.2 Unimodal Results

Figure 8 plots observed mean overtopping discharge in the model as a function of input mean wave period, T_{m02} . Very small overtopping amounts occur for the cases of the low energy content in the spectrum. For the cases with a high-energy content, the mean overtopping discharge increases rapidly during the mean wave period inputs of T_{m02}= 5 s to T_{m02}= 9 s, before levelling and falling slightly to a relatively constant overtopping discharge as the mean wave period input increases. This result was also observed by Hawkes (1999) and has since not been visited. As the structure and foreshore is like that of Hawkes (1999), it was decided to test a further range of structure slopes, to see if the structure slope had any influence on the rapid increase followed by a levelling of the overtopping discharge.

The same wave input of Med/High in the initial unimodal tests were used for several different structure tests: 1:1.6; 1:2; 1:3; 1:4; a foreshore slope of 1:50; a straight wall (no structure slope). It is clear from Figure 9 that the structure, and also foreshore slope, has no influence on the results observed in Figure 8

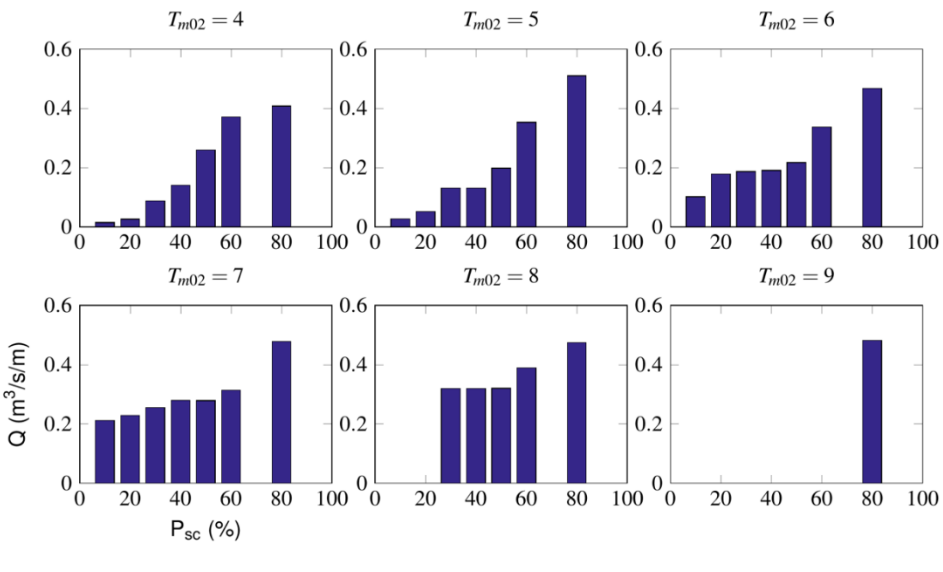

Figure 7. Mean overtopping discharge plotted as a function of swell percentage for each mean wave period input.

where the overtopping discharge is limited beyond a wave period of T_{m02}= 8 s or 9 s.

5. Conclusion

We have described a computational procedure to investigate the effects of bimodal wave conditions on wave overtopping discharge. The results obtained have shown that the wave generation procedure developed to produce a set of specific wave conditions and swell percentages works well, and allows flexibility and control of the desired wave conditions. The results were compared to experimental overtopping discharge results where the NEWRANS model was able to adequately replicate the experimentally observed overtopping discharges.

Numerical tests were conducted to investigate bimodal and unimodal wave conditions. For the case of bimodal conditions, the effects of an increasing mean wave period and increasing swell percentage were investigated, where mean wave period input ranged from T_{m02} = 4 to 9 s, and P_{sc} = 10 % to 80 %. Overtopping was observed to increase as swell percentage and mean wave period increased. For a given mean wave period input, especially for T_{m02} = 4 s to 6 s, the effect of increasing swell percentage was considerable. At a swell percentage of 80 %, the mean wave period input had little effect on the resultant

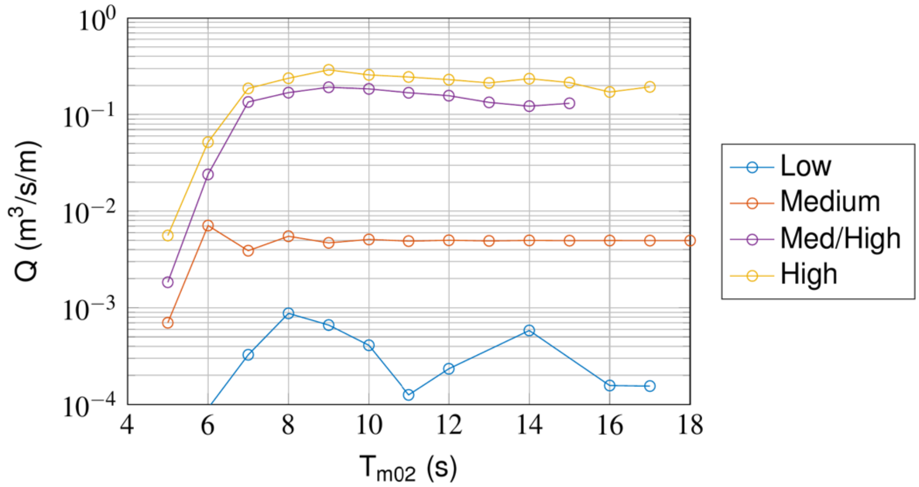

Figure 8. Mean overtopping discharge plotted as function of the mean wave input for unimodal conditions

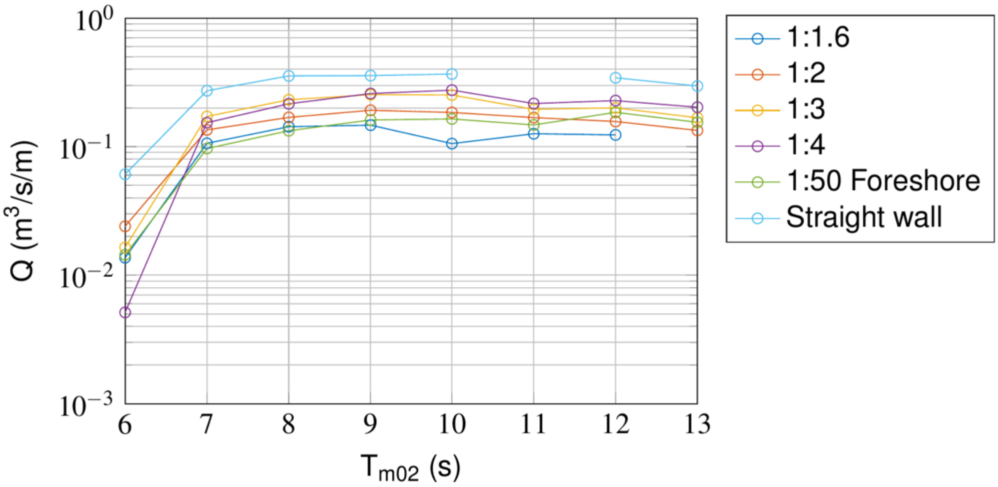

Figure 9. Mean overtopping discharge plotted as a function of the mean wave input for med/high unimodal input and a range of structural parameters.

overtopping discharge. The results highlight the importance of considering a bimodal sea and potentially the swell percentage of the spectrum, as high swell percentages can still occur even if a low mean wave period is observed, and the resultant effect of increased overtopping discharge associated with the increased swell percentage is an important consideration.

Further numerical tests were conducted for unimodal conditions with mean wave period, T_{m02} , varied between 6s to 15s. The purpose was to examine the effects of long period swell on overtopping and the sensitivity of the overtopping discharge as waves transitioned from wind-waves to swell waves. The results showed a rapid increase in overtopping discharge as T_{m02} varied from 6 s to around 8 s or 9 s. Beyond this overtopping did not increase but either reduced slightly or maintained a similar mean overtopping rate. The wave inputs were then tested on a number of different structure slopes where similar results were observed.

Estimating overtopping rates is a continuously evolving science. Pullen et al. (2016) and Van der Meer (2013) suggests more overtopping data is required for different structural parameters. The preliminary results presented here also demonstrate the importance of further research into the description of the wave loading. In particular, the distribution of energy across frequencies in a random wave condition has an important influence on the overtopping rates that may be experienced. This, in turn, indicates that using a single integrated wave period parameter for predicting wave overtopping is insufficient.

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