Proceedings of the 9th International Conference on Physical Modelling in Coastal Engineering (Coastlab24)

Delft, Netherlands, May 13-16, 2024

Extended Abstract, DOI: 10.59490/coastlab.2024.710

HYBRID MODELLING OF WAVE OVERTOPPING AT RUBBLE MOUND BREAKWATERS

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KEYWORDS: Wave overtopping, Coastal structures, Rubble mound structures, OpenFOAM, Wave flume tests

This abstract re-uses material as published in Irías Mata and Van Gent (2023). Numerical modelling of wave overtopping discharges at rubble mound breakwaters using OpenFOAM®, Coastal Engineering, 181, Article 104274. https://doi.org/10.1016/j.coastaleng.2022.104274

1 INTRODUCTION

Wave overtopping at rubble mound structures is one of the most important phenomena affecting the hydraulic performance of these coastal structures. In addition to the design of coastal structures, also the climate adaptation of coastal structures has become more important due to sea level rise. Adding a crest wall to an existing structure, increasing the height of a crest wall, adding a berm, or increasing the width or height of a berm, can be effective measures to account for effects of sea level rise. For this purpose, the individual effects of a crest walls and a berm need to be predicted, but also the combination of both (see for instance Van Gent, 2019, and Van Gent and Teng, 2023).

Wave overtopping estimates are generally based on physical modelling in wave flumes and wave basins. Numerical modelling of wave overtopping provides additional opportunities to examine wave overtopping for a wide variety of structure geometries. The combination of physical modelling with numerical modelling is referred to as hybrid modelling. To provide design guidelines for rubble mound structures with a crest wall and for structures with a berm in the seaward slope, Van Gent *et al* (2022) provides design guidelines based on physical model tests. Numerical modelling provides opportunities to examine wave overtopping at structures with a crest wall and a berm to further extend guidelines for the design and (climate) adaptation of rubble mound structures. In Irías Mata and Van Gent (2023) guidelines based on physical modelling have been extended based on numerical modeling with OpenFOAM to examine the influence of several aspects such as the wave steepness, crest wall and recurved parapet, berm, and structure slope on wave overtopping at rubble mound breakwaters. Although the present work focusses on wave overtopping, also forces on crest walls have been examined using the applied numerical model, see for instance Jacobsen *et al*, 2018, and Irías Mata *et al*, 2023.

2 CONCLUSIONS

The numerical model was first validated against the physical model tests from Van Gent *et al* (2022). The validation showed that the numerical model is able to reproduce accurately the wave conditions while reasonable estimates of wave overtopping discharges were obtained. The validation revealed that the numerical model can capture the trends in the dependency of wave overtopping discharges on structural parameters such as wave steepness, berm and a crest wall on top of a rubble mound breakwater (see Irías Mata and Van Gent, 2023). Since the numerical model offered significant understanding regarding how wave overtopping discharges correlate with different structural parameters, additional geometries and wave conditions were simulated in the numerical model yielding the following insights:

- Wave steepness: The numerical model results confirm that wave overtopping at rubble mound breakwaters depends on the wave steepness, thus also for wave loading that can be characterised as non-breaking waves. The results indicate that the lower the wave steepness, the larger the overtopping volumes (see for instance Figure 1c).
- Crest wall: The numerical model results indicate that the earlier developed influence factor for crest walls by Van Gent *et al* (2022) is also valid for larger crest walls with protruding parts that cover half of the total crest height (Figure 1a).

• Recurved parapet: The numerical model results indicate that having a recurved parapet on a crest wall of a rubble mound breakwater is only effective for rather low overtopping discharges (Figure 1b).

• Berm: The numerical model results confirm that wave overtopping at rubble mound structures with a berm depends on the level of the berm, the berm width and the wave steepness. The results reveal that the higher the berm level, the smaller the overtopping discharge, but the effect becomes negligible for berms located below still water level. Regarding the berm width, the results indicate that the wider the berm, the smaller the overtopping discharge. Deviations between numerical model results and the empirical expression by Van Gent *et al* (2022) increase significantly for wide berms in combination with steep waves indicating that the range of validity of the empirical expression cannot be extended to these conditions outside the range of validity of the empirical expressions. Finally, additional tests unveil that the size of the core material; *i.e.* the permeability inside the berm, appears not to affect the overtopping discharge within the range of evaluated geometries.

• Slope angle: The numerical model results show that wave overtopping at rubble mound breakwaters depends strongly on the slope angle (*i.e.* one or two orders of magnitude difference between structures with a slope of 1:1.5 and 1:4), thus also for wave loading that can be characterised as non-breaking waves. The outcome of the numerical model indicates that the overtopping discharge increases for steeper slopes. In Irías Mata and Van Gent (2023) the effect of the slope angle has been incorporated in an existing guideline for estimates of wave overtopping discharges at rubble mound structures and in a guideline developed based on physical reasoning. In their research, it is advised to verify the dependency between wave overtopping and slope angle based on physical model tests.

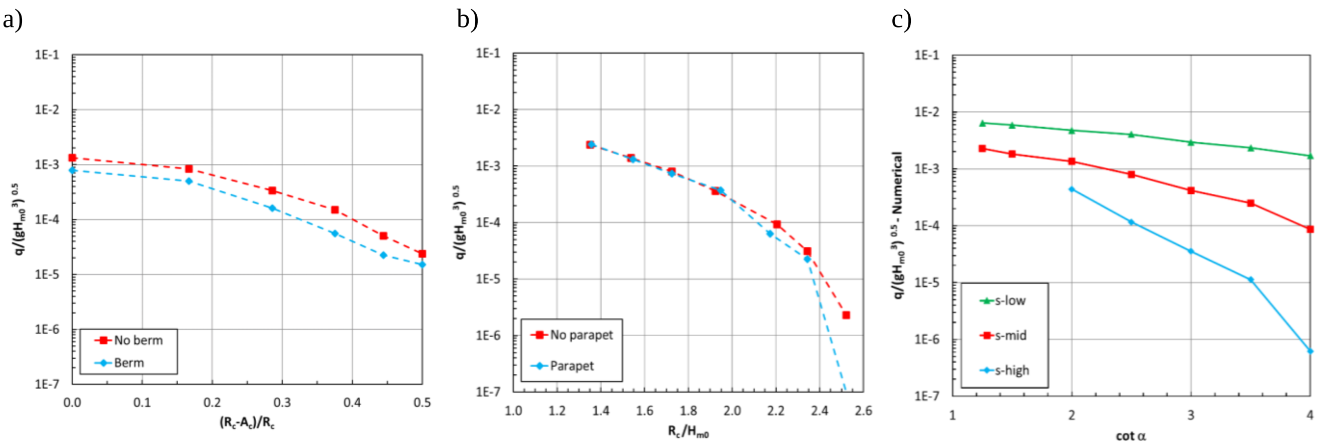

Figure 1. Numerical non-dimensional overtopping discharges as function of a) the protruding part of the crest wall (R_c - A_c)/R_c , b) the addition of a recurved parapet, and c) the slope angle *cot α*

As showcase in this study, hybrid modelling is a powerful tool that can be applied nowadays in coastal engineering given the increase capabilities of the computers. Nonetheless, there is still room for improvement and it is recommended to further improve the accuracy of the OpenFOAM model in estimating overtopping discharges as well as to enable studying 3D effects on wave overtopping numerically with a fast and accurate model.

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