EFFECTS OF DIFFERENT ARMOUR UNITS AND PLACEMENT METHODS ON WAVE LOADS ACTING ON CROWN WALLS

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INTRODUCTION

Numerous previous experiments aimed to clarify and predict the detailed mechanism of wave forces on crown walls of mound breakwaters. However, a comprehensive study has not yet been conducted for cases involving different placement methods and packing densities of armour units. This study examines how various placement methods and packing densities of tetrapod and Antifer units, in combination with natural rocks in the armour layer design, influence the distribution of wave forces on the crown walls. Physical model tests were carried out using 1:1.5 and 1:2 face slopes, allowing for modifications to model units in the armour layer and a comparison of changes in wave-induced forces experienced by the crown wall. As a result of the study, the empirical coefficients of Pedersen (1996) formulae adjusted by Norgaard et al. (2013) for shallow water condition were modified for Antifer and tetrapod units.

METHODOLOGY

Experimental studies were conducted at Middle East Technical University, Civil Engineering Department, Coastal and Ocean Engineering Laboratory in a wave flume having 26.9 m length, 6.0 m width and 1.0 m depth. In this study, two closed pyramid (CP), four double pyramid (DP) and two irregular (IR) placement methods for Antifer units were tested for a rubble mound breakwater trunk section with a face slope of 1:1.5 and 1:2.0. Moreover, three different tetrapod (TP) placement methods were investigated in the following stages of the experiments. Rock armour (NR) slope with a 1:1.5 face slope was also examined to have an accurate comparison of the model section with Norgaard et al. (2013) experimental study results. Within the scope of the experiments, a total of six different irregular wave series were generated. The minimum number of 1000 waves criteria condition was fulfilled for all six irregular wave sets throughout the duration of the experimental investigation. In the wave generation process, JONSWAP spectrum with γ = 3.3 was employed. The random wave series had wave steepnesses ($H_{m0}/L_{m-1,0}$) ranging between 0.02 and 0.04, and relative crest heights (R_c/H_{m0}) ranging from 0.85 to 1.80. Water surface elevations were measured at ten different locations along the wave flume. The experimental programme encompassed a total of 234 experiments, involving three different crest heights, eight Antifer placement methods, three tetrapod placement methods, and three different randomly arranged natural rock placements, enabling a comprehensive examination of their performance on wave force development acting on crown walls. A technical schematic representation of the experimental setup, crown wall model and the positions of the pressure sensors within the wave flume are provided in Figure 1 and Figure 2, respectively.

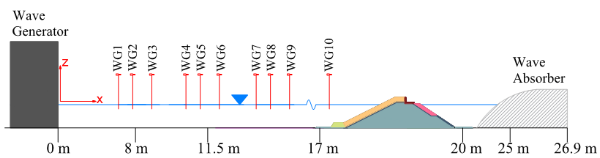

Figure 1 - Layout of the 2D model test in the wave flume.

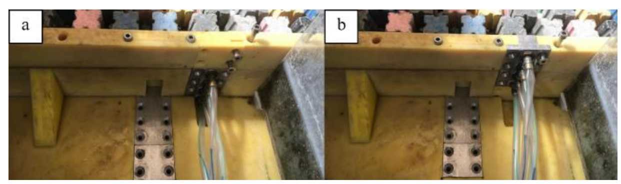

Figure 2 - Crown wall model and locations of a pressure sensors from lee-side (a) top position, (b) bottom position.

RESULTS

The findings of the current study reveal that the utilisation of different units within the armour layer results in notable changes in the resultant wave forces on crown wall structure. Furthermore, it has been observed that different placement methods for the same armour units also lead to disparities in the wave forces. Examining the overall distribution of wave forces, it is evident that the natural rock units exhibit the least force, followed by Antifer units, while the highest forces are observed with tetrapod units. Upon analysing the horizontal wave forces at the conclusion of the experiments, it was observed that the $F_{h0.1\%}$ formulations proposed by Pedersen (1996) and Norgaard et al. (2013) tend to underestimate the wave forces acting on the crown wall fronted by Antifer and tetrapod armour units. A best-fit approach was applied to the experimental measurements, followed by an assessment of their accuracy through various statistical performance evaluations. Consequently, adjustments were made to the coefficients *'a'* and *'b'* within Norgaard et al. (2013) $F_{h0.1\%}$ formula, concerning different placement methods of Antifer armour units. These modified coefficients (hereafter a_{mod} and b_{mod}) were optimally set at 0.36 and 1.31 for mound breakwater sections having 1:2 face slope, respectively. Comparative plot of the $F_{h0.1\%}$ measurements is given in Figure 3.

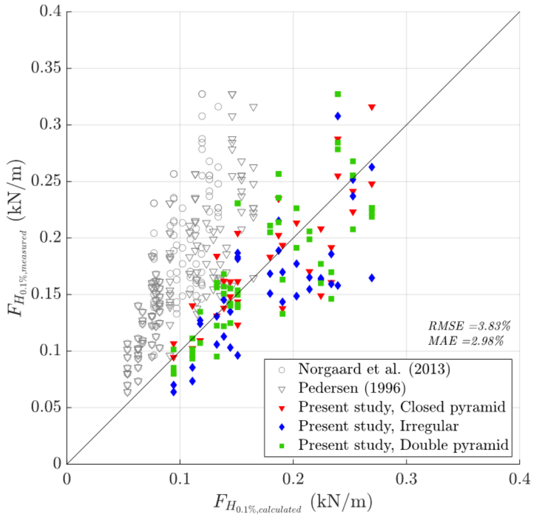

Figure 3 - Comparison plot for $F_{h0.1\%}$ measurements.

When evaluating the performance of the Antifer armor units across the CP, IR, and DP placement methods, a clear pattern emerged. Notably, the IR consistently yielded the most moderate wave forces acting on the crown wall. On average, it was observed that the IR method tended to reduce wave forces by approximately 15% in comparison to DP. It is also showing a more substantial average reduction of 30% when compared to CP. The results of the statistical performance assessment indicate that, following the modification of empirical coefficients, the RMSE and MAE values exhibited a notable reduction. Specifically, there was a 49.9% decrease in RMSE compared to computations with Pedersen (1996) and a more substantial decrease of 57.7% compared to the computations with Norgaard et al. (2013). Regarding MAE values, the current study demonstrated a 54.6% reduction in comparison to Pedersen (1996) and an even more pronounced decrease of 62.4% when compared to Norgaard et al. (2013). When evaluating the performance disparities between packing density (for CP, IR, and DP) and staggered arrangement (for DP) within the same placement method, an average of 10-15% variance was observed. However, no clear pattern emerged in terms of the relationship between the change in packing density and the corresponding change in wave forces.

The same methodology was applied in this study to the modified moment equation for shallow water, as introduced by Norgaard et al. (2013). However, it's worth noting that, in this case, the coefficients e_1 and e_2 within this formula remained unaltered. This decision was based on the observation that employing the $F_{h0.1\%}$ value derived from a_{mod} and b_{mod} in this formula already yielded highly satisfactory results for the performance of Antifer units. Comparative plot of the $M_{h0.1\%}$ measurements is shown in Figure 4.

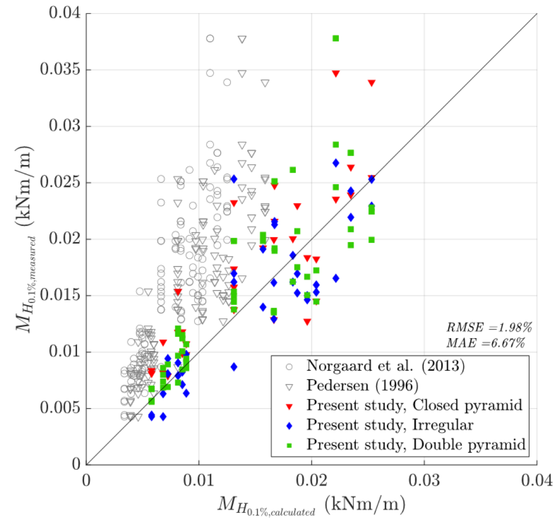

Figure 4 - Comparison plot for $M_{h0.1\%}$ measurements.

During the final stage of the analysis, the magnitudes of the base pressures were evaluated using the same methodology. It became apparent that there was a weak correlation between $P_{b0.1\%}$ and the other two force components, $F_{h0.1\%}$ and $M_{h0.1\%}$ as also stated by Pedersen (1996). Consequently, it is evident that a new formulation is required to effectively represent the base pressure.

CONCLUSION

The present study's findings indicate that the design formulations by Pedersen (1996) and Norgaard et al. (2013) tend to provide underestimation of the wave forces acting on crown wall fronted by Antifer and tetrapod armour units. As a result of wave force measurements, adjustments were made to the *'a'* and *'b'* coefficients in the $F_{h0.1\%}$ formula, without the need for modifications in the corresponding coefficients in the $M_{h0.1\%}$ formula. The experiments suggested the necessity of devising a new formulation for $P_{b0.1\%}$. It was observed that IR outperformed DP and CP.

For the breakwater section featuring a 1:1.5 face slope, physical experiments involving Antifer, tetrapod and natural rock armour units has been successfully conducted, and the subsequent data analysis is currently underway. Empirical coefficients, a_{mod} and b_{mod}, will be subjected to a thorough reanalysis to ensure their accuracy and relevance to the observed results.

ACKNOWLEDGEMENTS

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