

ON THE UNCERTAINTIES IN ROCK-ARMOURED BREAKWATERS STABILITY

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INTRODUCTION

Design of the armour of rubble mound breakwaters has historically been based on empirical equations relating armour stone movement resistance to wave-induced forces. These empirical equations are developed primarily from small-scale laboratory studies and show considerable uncertainty. While new relations have been introduced to expand ranges of application, little progress has been made in several decades to decrease equation uncertainty. There is still no consensus on the best design equation and its field of application. The design manuals, such as the Coastal Engineering Manual (USACE (2002)) and the Rock Manual (CIRIA, CUR, CETMEF (2007)), show overlap between formulas and new formulas have been introduced since these manuals were published, creating design uncertainty.

Stability uncertainty is primarily due to intrinsic aleatory uncertainty related to the stochastic nature of waves, stone geometry, and inter-stone contacts/interlocking, as well as epistemic uncertainty related to knowledge limitations, laboratory measurements, errors, etc. Here, we refer to aleatory uncertainty as irreducible while epistemic is reducible. Effects of aleatory uncertainty in hydraulic stability have often been assumed dominant over epistemic uncertainty. Nevertheless, the magnitude of both contributions has yet to be explicitly quantified to assess the validity of this assumption. Modern probabilistic design and simulation provide strong motivation for an improved understanding of uncertainty. A clear understanding of the relative magnitudes of epistemic and aleatory uncertainty could better focus studies to improve physics research. As a first step, the present study investigates the influence of hydrodynamic uncertainty from laboratory wave and water level measurements on the predictive models using a validated 1-D Boussinesq numerical model.

MAIN SOURCES OF UNCERTAINTY

Wave height is the dominant parameter in armour stability and damage formulas, but wave period and duration are influential. Related uncertainties are critically important. These uncertainties enter from observations and mostly empirical parametric characterizations. Uncertainty inherent in wave observations can be attributed to wave generation, measurements, reflection quantification methods, how and where the incident waves are observed, wave analysis procedures, and other phenomena. Wave uncertainty is typically more pronounced in shallow water conditions with wide surf zones (Hughes (1993)), partly because of the linear wave theory methods to resolve incident and reflected waves, which are not accurate in such conditions. Laboratory methods are relatively more influential under these conditions. Mansard and Funke (1987) conducted the same experiment at 9 laboratories with the scope to evaluate the difference in test results caused by the different experimental conditions. They found high variability in the bulk wave parameters, significantly affecting the wave-structure parameter relationships in the stability design formulas.

METHODOLOGY

A new comprehensive database was created (more than 700 data), collecting armour stability data from various international laboratory studies. Taking advantage of this new dataset, the most popular rock armour stability equations have been critically compared. Such comparison has concluded that no stability equation is significantly better than the others due to high uncertainty in the laboratory data. However, it is difficult (if not impossible) to quantify epistemic uncertainty when comparing nonhomogeneous data where laboratory, measurement and analysis techniques vary between studies.

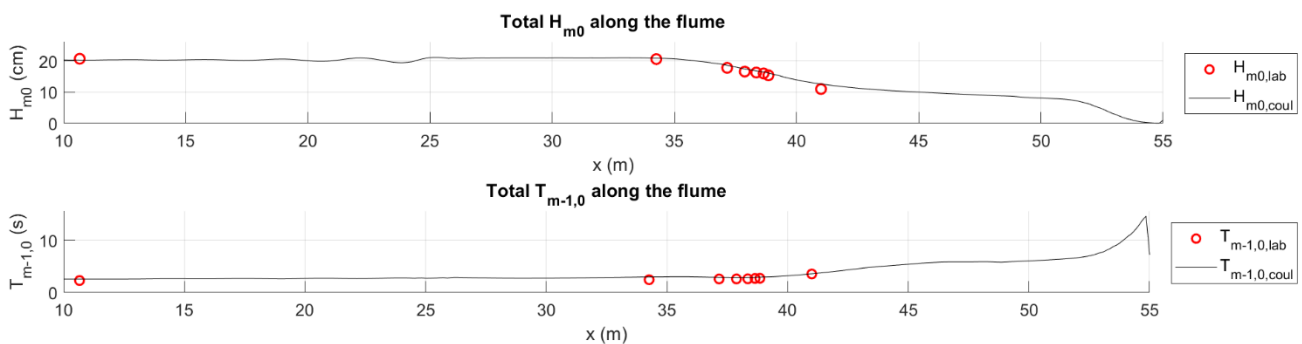


Figure 1 - Lab measured and numerical computed cross-shore variations of H_{m0} and $T_{m-1,0}$ along the wave flume.

Therefore, to homogenise the datasets, a 1-D fully nonlinear Boussinesq numerical model (COULWAVE by Lynett et al. (2004)) has been used to accurately reproduce the wave conditions for the stability dataset.

Wave parameters have been matched near the wave generator and the structure toe. Indeed, assuming the proper calibration of the numerical model, generating identical wave conditions offshore allows comparison of various laboratory data inshore with consistent and comparable waves. Figure 1 shows the cross-shore variation of the wave parameters (H_{m0} and $T_{m-1,0}$) along the flume measured in the laboratory (red circles) and computed numerically (solid line), demonstrating accurate reproduction of laboratory measurements by numerical model.

Various methodologies for wave analysis used across laboratories have been analysed, including testing with and without structure in place, frequency vs time domain, variations in reflected wave analysis, and single gauge frequency analysis. In addition, contributions spanning the entire spectrum were assessed, including infragravity frequencies.

PRELIMINARY RESULTS

Results show considerable systematic differences when comparing studies from different laboratories and time periods. Typical incident-reflected wave analysis using linear wave theory produces a significant bias in shallow water, and this bias increases with decreasing depth with a significant proportion of incident wave energy being attributed to reflection. Variations from one incident-reflected analysis method to another are relatively less influential.

Results show significant differences when comparing studies conducted in different laboratories and at different historical periods. Differences are greater for wave periods ($T_{m-1,0}$) than wave heights (H_{m0}) calculated at the toe of the structure (Figure 2, where only some of the data from the entire dataset are plotted). There can be many causes of this uncertainty. For example, it is impossible in the laboratory to completely eliminate re-reflection due to physical limitations. Again, classical reflection analyses based on linear theory introduce high uncertainty when applied in nonlinear conditions.

Studies that utilize wave measurements without the structure in the flume and using classical reflection

analysis method have shown relatively lower uncertainties than those with the structure in the flume. Such uncertainties in the wave laboratory data can hide the physics of the phenomena.

CONCLUSIONS

The present study provides improved understanding of the uncertainty in stability model data, and hence stability predictive equations, with a focus on the epistemic uncertainty in laboratory wave data. The analysis shows that it is possible to separate the error to evaluate the contribution of hydrodynamic uncertainty on the total uncertainty of predictive models. Understanding uncertainty in wave data is essential for accurate quantitative stability estimation aiming to provide a more physically based probabilistic formulation for the design of rock-armoured breakwater.

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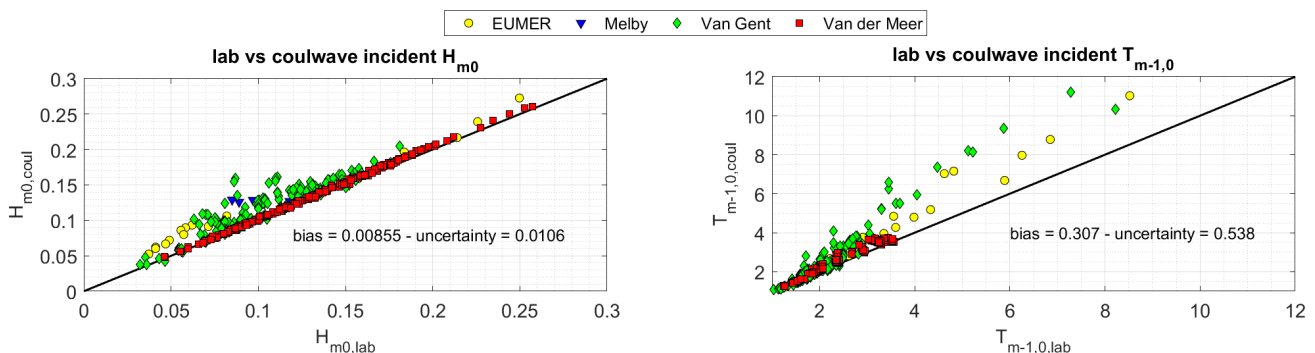


Figure 2 - Comparison between numerical and laboratory incident wave parameters (H_{m0} and $T_{m-1,0}$) computed at the toe of the structure.