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UNCERTAINTIES RELATED TO WAVE OVERTOPPING OVER COASTAL STRUCTURES

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Abstract: The European Manual for the Assessment of Wave Overtopping ("EurOtop") gives guidance on analysis and prediction of wave overtopping for flood defences. The prediction models for overtopping are empirically based on physical model data and therefore comprise inherent uncertainties. This paper deals with new insights in uncertainties of the prediction models of the EurOtop [2007] manual and discusses the influence of new data collected at Ghent University. Furthermore, the revised formulae by Van der Meer and Bruce [2014] are also investigated regarding uncertainties using the same data sets.

INTRODUCTION

Coastal structures are generally designed to protect coastal regions against wave attack, storm surges, flooding and erosion. Due to climate changes, the sea level is rising and more severe storms might occur [see e.g. Woth et al., 2005]. This emphasizes the importance of the design of these structures where the amount of sea water transported over the crest of a coastal structure, referred to as 'wave overtopping', is a critical design factor in this context [Verhaeghe, 2005].

The European Manual for the Assessment of Wave Overtopping ("EurOtop") gives guidance on the analysis and/or prediction of wave overtopping for flood defences attacked by wave action [EurOtop, 2007]. The prediction methods in the manual are empirical equations mostly derived from physical model data. Hence inherent scatter has to be taken into account, the EurOtop manual distinguishes between so-called probabilistic and deterministic approaches where the former follows a mean approach (trend line through all data) and the latter increases the mean by one standard deviation , respectively [EurOtop, 2007]. This standard deviation can be considered an indicator of the uncertainty of the considered formula.

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Generally, the empirical formulae in the EurOtop manual describe a relation between a relative overtopping discharge q^* and a relative freeboard R^* as shown in Fig. 1.

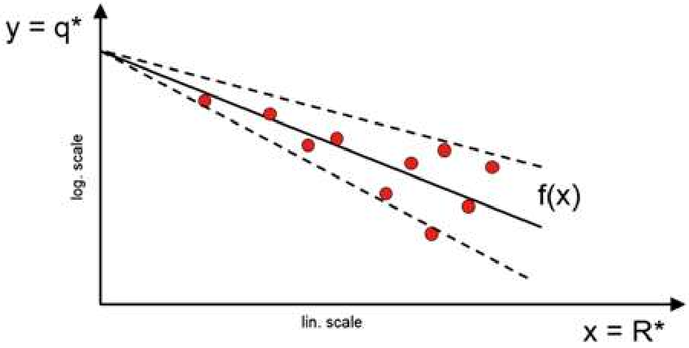

Fig. 1: Relative wave overtopping q^* plotted against a relative freeboard R^*

Fig. 1 shows some artificial data points (red points) which are usually scattered around a trend line which represents the empirical formula f(x). The latter function is the probabilistic approach in EurOtop [2007]. Fig. 1 also shows two dashed lines which represent the confidence bands (90% confidence bands were usually selected where 90% of all data points fall within the dashed lines) resulting from the statistical analysis of the scattered data around f(x). EurOtop [2007] defines the deterministic approach as a function which is one standard deviation higher than the trend line. In this paper, all considered prediction formulae follow the probabilistic approach where the provided formula is represents the mean trend line through the data.

The background data for deriving the EurOtop [2007] formulae and their respective uncertainties were included in the CLASH database [Van der Meer et al., 2004]. This database exists out of more than 10,000 test data of wave overtopping tests with a vast range of geometries and wave characteristics. In the meantime, more data for wave overtopping are available, especially for areas where little information was available from the CLASH database. The new data sets considered here are named UG10, UG13, and UG14, respectively and are briefly described here as follows:

- **UG10:** this dataset comprises wave overtopping data over smooth and steep slopes with small relative freeboards and deep foreshores. The data were obtained from a Phd thesis [Victor, 2012] in the wave flume of the Civil Engineering Department at Ghent University. More descriptions can be found in [Victor & Troch, 2012a, 2012b].
- **UG13:** This research, again undertaken at Ghent University, extended the UG10 dataset to steeper slopes and vertical walls, again with low relative freeboards and deep foreshores. More description can be found in [Troch et al., 2014].
- **UG14:** The UG14 dataset also used mild to steep slopes and vertical walls for small relative freeboards, but has used shallow foreshore conditions. Again, model tests were performed at Ghent University and more information can be found in [Gallach-Sánchez et al., 2014].

In addition to new data sets, new prediction formulae have also been found, e.g. in [Van der Meer & Bruce, 2014]. The authors underline that the key changes as compared to EurOtop [2007] are mainly within areas of low relative freeboards but mainly suggest a Weibull type approach no longer leading to a straight line in a linear-log plot of the relative wave overtopping against the relative crest freeboard. However, for the uncertainties involved it still has to be checked whether more data and a new approach lead to significant changes in uncertainty estimates.

The main goal of this paper is therefore to revisit the CLASH database, re-analyse the uncertainties, and add more data to obtain better knowledge on wave overtopping over coastal structures with respect to the related uncertainties. The following research questions are of key importance:

1) Is the EurOtop [2007] approach for uncertainties still valid today given that there are more data available and that there are new prediction formulae?
2) Is the assumption of normally distributed parameters still valid?

It is therefore not the purpose to propose new prediction formulae since this has been done already [Van der Meer & Bruce, 2014] or is still under progress within the upcoming update of the EurOtop manual. Also, this paper addresses the existing or upcoming formulae in the EurOtop manual and is not comparing any other semi-empirical approaches. However, it should be noted that the methodology used here can principally be used for other

The paper is structured as follows: first, the methodology is explained in which way the data were re-analysed and how the uncertainties were derived. Secondly, the prediction formulae for sloping and vertical structures are briefly revisited before the key results are presented and discussed. Finally, some conclusions are drawn and a final recommendation regarding the uncertainty analysis is provided.

METHODOLOGY

The focus with respect to structures under wave overtopping are sloping structures and vertical structures. For sloping structures, the datasets were filtered to obtain three principally different datasets, details of the filers can be found in [Corne, 2015]:

- S1) Simple and smooth sloping structures;
- S2) Smooth, sloping structures (incl. berms), and
- S3) Sloping structures (incl. rough surfaces and berms).

For vertical structures, two different filters for the datasets were considered:

- V1) Plain vertical walls, and
- V2) Composite vertical walls.

For each dataset, the uncertainties of the EurOtop [2007] formulae were first derived considering data only from the CLASH database. In this way, a reference case was created for each of the aforementioned structures.

The CLASH database was then extended by the three UG datasets and again the uncertainties were determined. The UG data did not comprise any mounds or roughness elements and were thus simply added to the CLASH dataset for both sloping structures and vertical structures, i.e. simple, smooth sloping structures (S1) and plain vertical walls (V1). The influence of including the UG data on the uncertainties was then examined.

Finally, the prediction formulae were changed to the more recent formulae by Van der Meer and Bruce [2014]. Again, the uncertainties were derived using the same datasets considered before from CLASH together with the UG data. Differences in these prediction formulae were analysed and discussed. Overall, this resulted in the analysis summarized in Table 1.

Table 1. Overview of analysis of uncertainties for wave overtopping

No.	Structure	Dataset	Br/Nbr	Filter	Data	Equations
A1	Sloping	CLASH	Br	S1	492	EurOtop [2007]
A2				S2	724	
A3				S3	955	
A4			Nbr	S1	511	
A5				S2	520	
A6				S3	2655	
A7		CLASH + UG	Br	S1	501	EurOtop [2007]
A8			Nbr		782	
A9			Br	S1	547	Van der Meer & Bruce [2014]
A10				S2	781	
A11				S3	1020	
A12			Nbr	S1	640	
A13				S2	645	
A14				S3	2783	
A15	Vertical	CLASH	NImp.	V1	80	EurOtop [2007]
A16				V2	284	
A17			Imp	V1	148	
A18				V2	185	
A19		CLASH + UG	NImp.	V1	80	EurOtop [2007]
A20				V2	282	
A21			Imp.	V1	148	
A22				V2	175	
A23				V1	808	Van der Meer & Bruce [2014]
A24				V2		

Br = breaking waves; Nbr = non breaking waves; Imp = impulsive region; NImp = non impulsive

It can be seen from Table 1 that the amount of data differ significantly for the various empirical equations for which the uncertainties were determined. Generally, the data for vertical structures are a lot less than for sloping structures where most data for the latter are rough structures with berms. The uncertainties for these type of structures have not yet been analysed specifically, e.g. in the range of sloping structures, uncertainty approaches within EurOtop [2007] have so far only considered smooth sloping structures without berms.

The uncertainties are described by a standard deviation resulting from the statistical analysis of a stochastic parameter. Generally, the parameter describing the slope of the function in Fig. 1 is used for this purpose. This required the following steps:

- The mean value approach was followed by finding a trend line for the respective dataset.
- The results of the trend line were stored and compared to the existing prediction formulae. However, as explained before, the trend line analysis was not used to replace the existing formulae.
- The intersection of the trend line with the abscissa (parameter a) was assumed constant for the further analysis. This approach was used in EurOtop [2007] and was therefore also used for this analysis.
- The values for the stochastic parameter (parameter b) were then calculated for each data point based on the value for parameter a from the trend line.
- The standard deviation of the stochastic parameter b were calculated and considered the indicator for uncertainties.

Furthermore, histograms were used to check the assumption of a normal distribution around the trend line. In addition, measured against predicted wave overtopping rates were plotted to visually analyse the reliability of the considered formula.

PREDICTION MODELS

The key prediction models are repeated in this section and their use is briefly discussed. A distinction is made between sloping structures and vertical structures, similar to the distinction in the EurOtop manual.

Sloping Structures

The EurOtop [2007] formulae are of the exponential type for sloping structures:

$$Q^* = a \cdot \exp[-(b \cdot R_c^*)] \tag{1}$$

where Q^* is the relative overtopping discharge; R_c^* is the relative crest freeboard made nondimensional according to EurOtop [2007] and depending on breaking or non-breaking conditions; the parameters a and b are fitted coefficients. These exponential equations result in a straight line in a log-linear graph (Fig. 1).

The more recent formulae by Van der Meer and Bruce [2014] are of the Weibull type which results in a curved line in a log-linear graph:

$$Q^* = a \cdot \exp(-(b \cdot R_c^*)^c) \tag{2}$$

where the coefficient c is a constant ($c = 1.3$). The relative overtopping discharge Q^* and the relative freeboard R_c^* are non-dimensionalised in the same way as in EurOtop [2007]. Note that the parameters a and b are different from the same parameters in Eq. (1) since the function is of a different type.

It is to be expected that the formulae by Van der Meer and Bruce [2014] fits better for small freeboards (the authors also used the UG10 data set in their analysis) whereas the EurOtop [2007] formulae is expected to overpredict the overtopping discharge in this area.

Vertical structures

The EurOtop [2007] formula in the non-impulsive regime for vertical structures is again of an exponential type. The formulae in the impulsive regime, however, is of a power law type (Eq. (3)):

$$Q^* = a \cdot R_c^{*\,(-b)} \tag{3}$$

The relative overtopping discharge Q^* and the relative crest freeboard R_c^* are non-dimensionalised differently here [EurOtop, 2007].

Due to the power law the scatter in the logarithm of the data is described by a standard deviation on the parameter a whereas for sloping structures the parameter b has been used. Power law equations give a curved line in a log-linear graph.

A different approach needs to be followed for composite vertical walls than for plain vertical walls. A vertical wall is treated as composite only if the mound is significant.

The more recent formulae by Van der Meer and Bruce [2014] are again either of the exponential type or of the power law type. In addition however, the parameters a and b also depend on the slope of the structure. For the new formulae an additional distinction is made between structures with or without a foreshore. Also, a different formulae is suggested each time for small relative freeboards compared to larger relative freeboards.

KEY RESULTS

This section describes and discusses the key results obtained for sloping structures and vertical walls. Results are presented and briefly discussed. For more details the reader is referred to [Corne, 2015].

For each of the rows in Table 1 analysis of the uncertainties has been performed by plotting the data with the 90% confidence bands, checking the assumption of a normally distributed data around the trend line, and cross-check the results by plotting prediction against measurements. In this paper, only key selected results of this analysis can be presented. Reference is provided to the analysis numbers of Table 1, first column.

Sloping structures

The filtered CLASH data for sloping structures with smooth slopes and no berms are plotted in Fig. 2 for breaking waves and in Fig. 3 for non-breaking waves (for reference of the dataset number see Table 1).

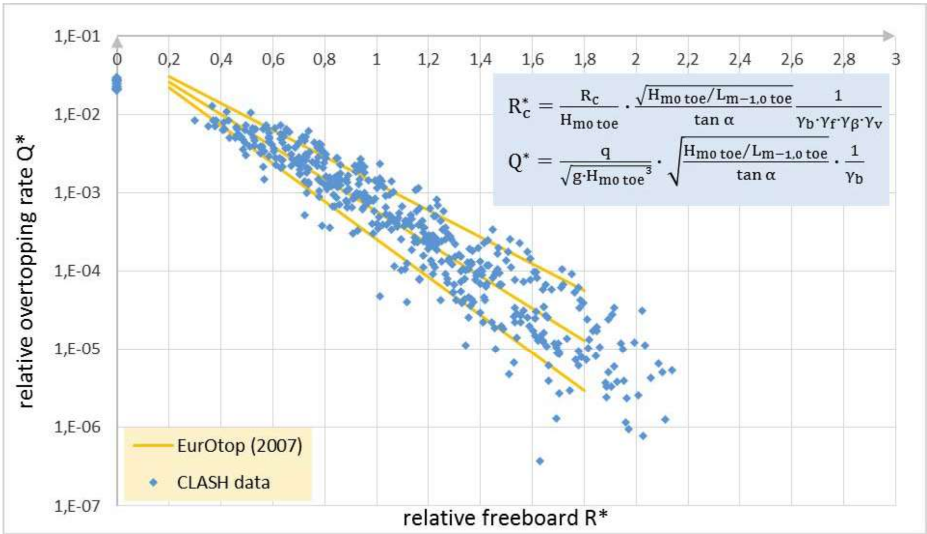

Fig. 2. Relative wave overtopping against relative freeboard for dataset A1 (breaking waves)

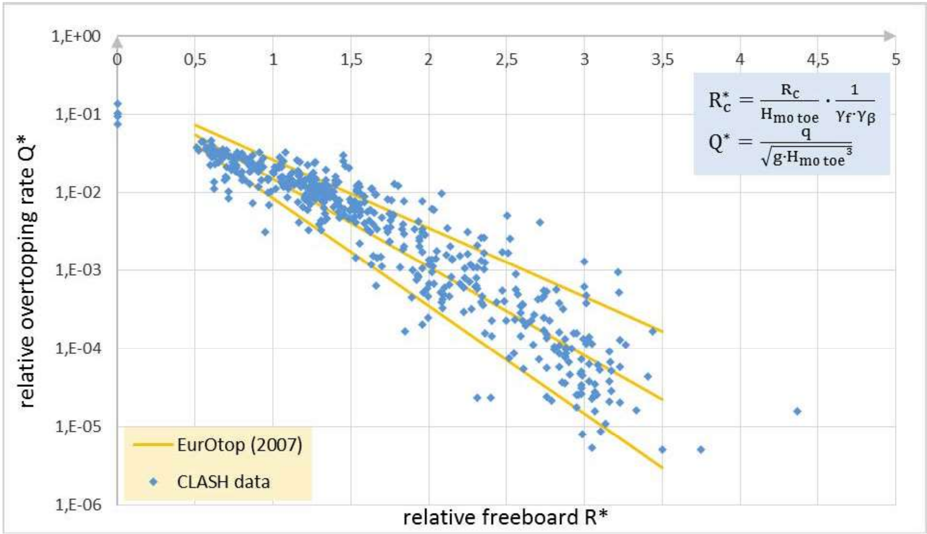

Fig. 3. Relative wave overtopping against relative freeboard for dataset A1 (non-breaking waves)

The relative standard deviations obtained for each dataset are on average 5% larger than the relative standard deviations given in the EurOtop (2007) manual (14% as compared to 10.5% for breaking waves and 19% as compared to 13.5% for non-breaking waves). This difference is not considered relevant since most of the data points fall within the confidence bands provided and therefore below the 'deterministic' line as proposed by EurOtop [2007]. Furthermore, the relative standard deviations are larger for non-breaking waves. The latter is also observed in the EurOtop [2007] manual.

Including the rough slopes, especially for non-breaking waves, leads to a significant increase of the amount of data and a lot of scatter in the plots (Fig. 4). Correspondingly the relative standard deviation has increased considerably (up to 28.7%).

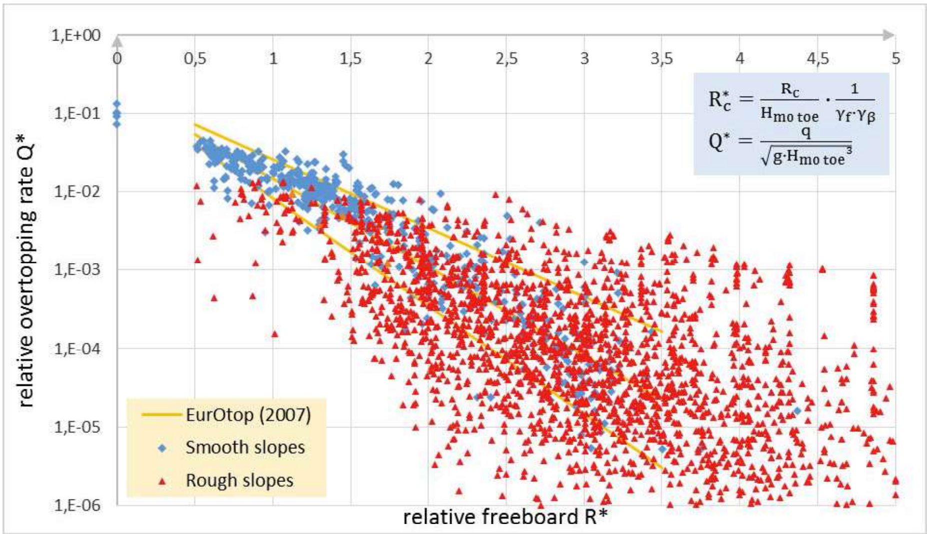

Fig. 4. Relative wave overtopping against relative freeboard for dataset A6 (scatter due to rough slopes, non-breaking waves)

The UG data increase the relative standard deviation for both regimes (breaking (17.8%) and non-breaking waves (29.7%)). The effect is the largest for non-breaking waves since the UG data generally have steeper slopes and therefore fall into this region (Fig. 5). It should also be noted that the UG data points are located below the EurOtop [2007] curve, indicating an over prediction.

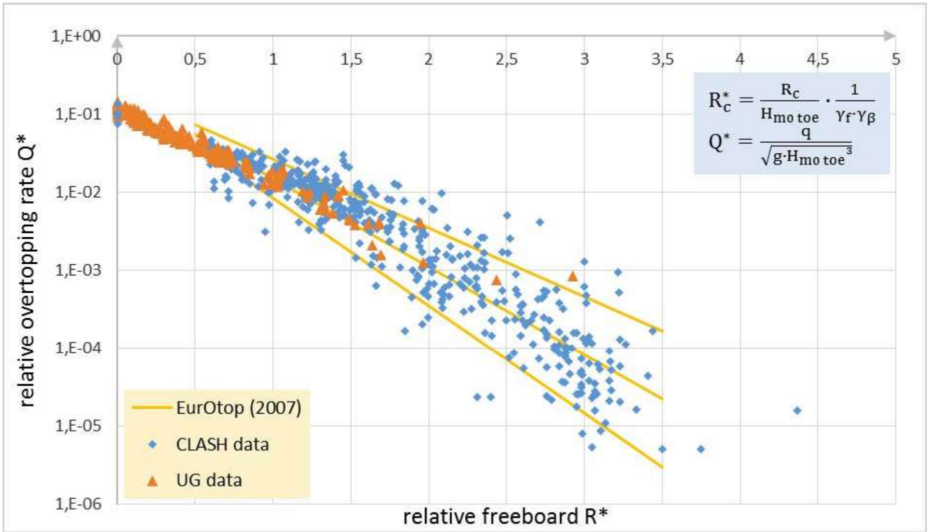

Fig. 5. Relative wave overtopping against relative freeboard for dataset A8 (CLASH and UG data, non-breaking waves)

The reason for the increased relative standard deviation when UG data are included, is the increased amount of data with small relative freeboards. The reason is that the parameter a in the exponential equation (Eq. (1)) is determined by a trend line and is further assumed constant. This parameter represents the intersection point with the relative discharge axis. The required slopes or the values of parameter b to go through each measured data point are then calculated using this fixed parameter a. As a consequence, the deviations for the parameter b are the largest for small relative freeboards. This effect is illustrated in Fig. 6.

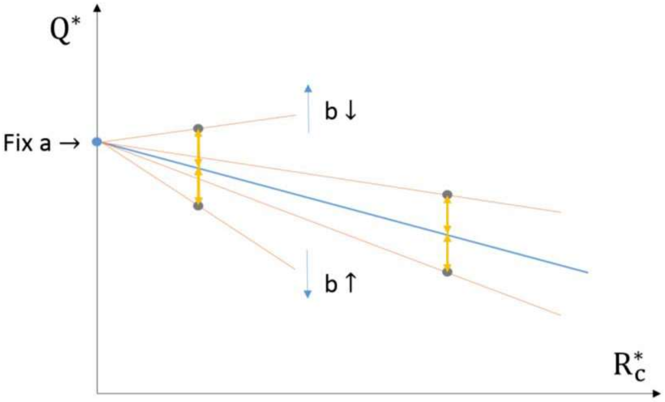

Fig. 6. Effect of fixing parameter a on parameter b

As expected, the formulae by Van der Meer and Bruce [2014] fit better for small relative freeboards. The derived relative standard deviations are the same order of magnitude (about 15%) as the ones obtained for the different datasets from CLASH but with the UG data now included in the analysis.

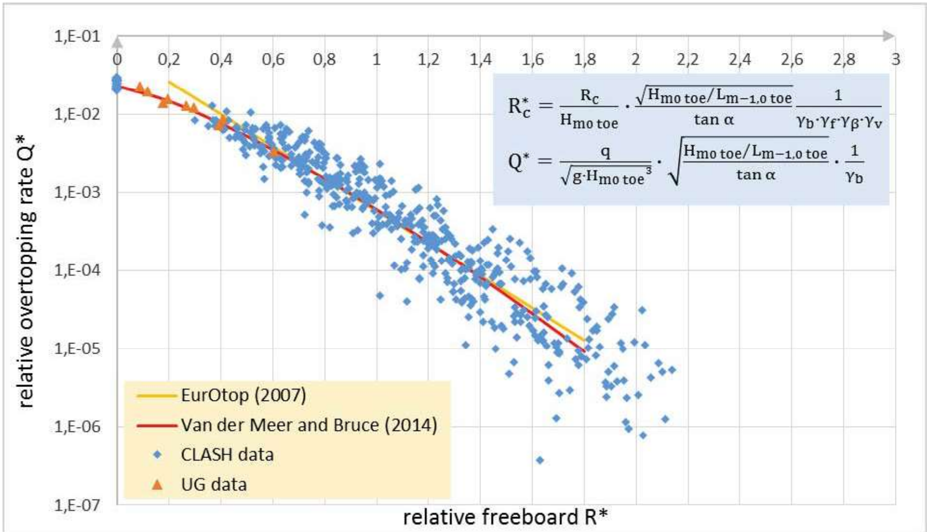

Fig. 7. Relative wave overtopping against relative freeboard for dataset A14 (CLASH and UG data, breaking waves, new formulae)

Vertical structures

For vertical structures, there is less data available in the CLASH database resulting in smaller datasets (see Table 1).

The relative standard deviation in the non-impulsive regime considering only plain vertical walls (no berm or toe) is only two third of the relative standard deviation indicated in the EurOtop [2007] manual. When, however, the composite vertical walls are added to the analysis, the resulting standard deviation is the same order of magnitude as the one of EurOtop [2007].

The UG data increase the relative standard deviation in the non-impulsive regime for the same reason as for sloping structures: the UG data increase the amount of data with small relative freeboards (Fig. 8). In this case, however, the data points are higher than the prediction curves, hence leading to a potential underprediction of the prediction formulae.

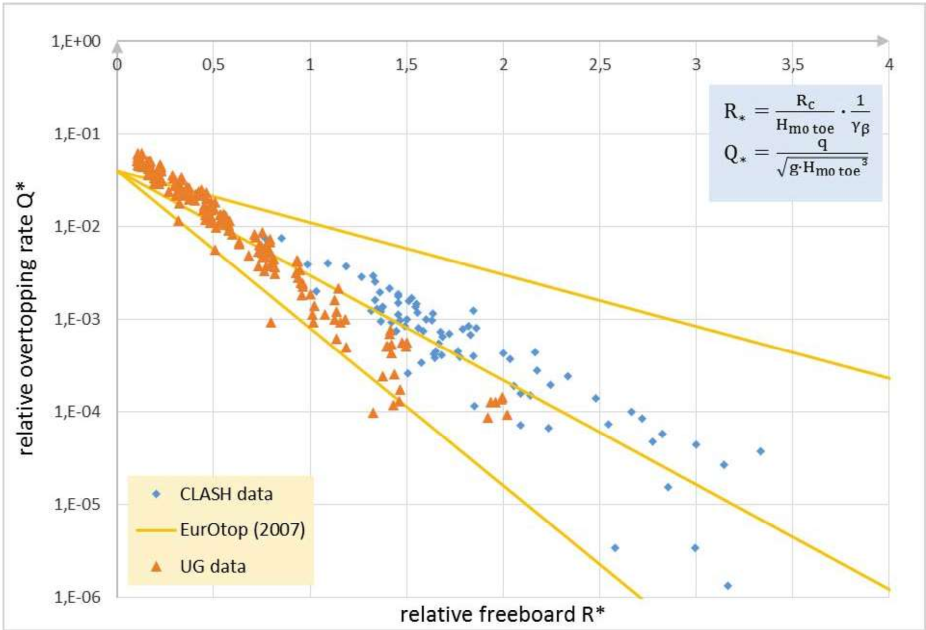

Fig. 8. Relative wave overtopping against relative freeboard for dataset A20 (plain vertical walls, CLASH and UG data, non-impulsive regime)

SUMMARY AND CONCLUDING REMARKS

This paper addresses uncertainties related to wave overtopping over coastal structures based on existing datasets (CLASH database) and more recent data obtained from research performed at the Civil Engineering department at Ghent University (UG10, UG13, and UG14).

The key objectives of this research were to obtain new insights of uncertainties for a wider data basis and an updated set of empirical formulae for the upcoming update of the EurOtop manual. Following the structure of the EurOtop manual the work has been split according to sloping and vertical structures. The key findings for *sloping structures* may be summarized as follows:

- the uncertainties for simple smooth sloping structures are only slightly larger than the uncertainties in the EurOtop [2007] formulae. Therefore, a revision of these uncertainties is not regarded necessary for these formulae.
- adding rough slopes (and berms) to the dataset, leads to significant scatter for non-breaking waves. However, this is mainly due to the roughness factor γ_f in the equations which may have been assessed incorrectly in the CLASH database.
- the EurOtop [2007] formulae fit less good for small relative freeboards (in the range of the new datasets). The formulae by Van der Meer and Bruce [2014] take these areas into account and generally fit better over a larger range of relative freeboards resulting in similar uncertainties for sloping structures than using the EurOtop [2007] prediction formulae.

For *vertical structures*, less data were available and the results are therefore based on much smaller quantities of data. However, the following results were achieved:

- the proposed power law formulae and the resulting uncertainties for the stochastic parameter a should be reconsidered since the resulting relative standard deviations proved to be very large for the existing approach. These uncertainties should be re-considered.
- the formulae proposed by Van der Meer and Bruce [2014] are more consistent with the formulae provided for sloping structures but do not result in smaller uncertainties.

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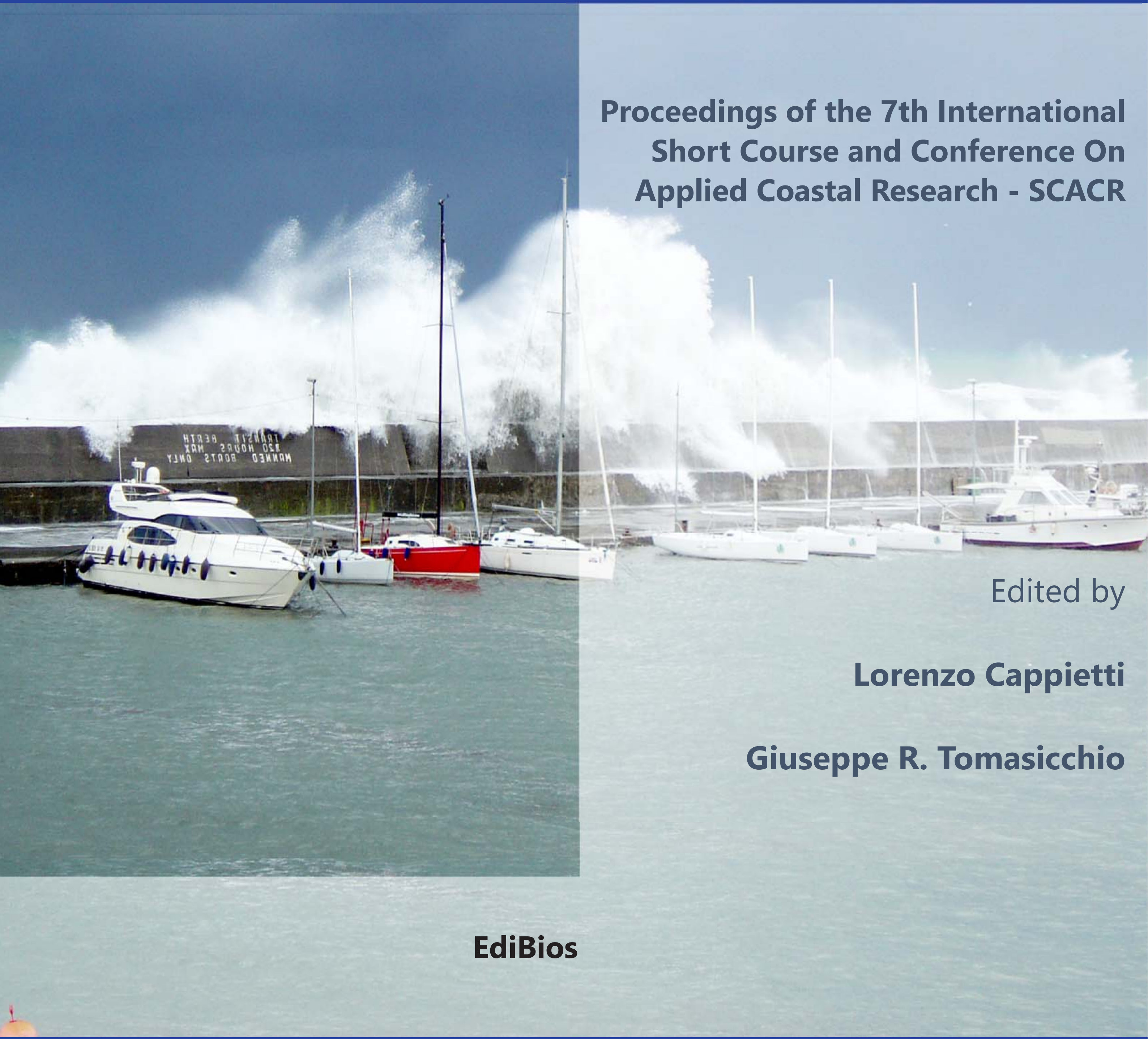

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