**Proceedings of the 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab16)**

Ottawa, Canada, May 10-13, 2016



# WAVE OVERTOPPING ASSESSMENT IN VERY SHALLOW WATER CONDITIONS: THE EQUIVALENT SLOPE CONCEPT

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## ABSTRACT

An extensive study on wave overtopping of sea dikes in very shallow water conditions has been carried out at Flanders Hydraulics Research. Empirical formulas are generally used for wave overtopping assessment and give reliable predictions for typical dike configuration cases based on a large number of physical model tests. The application of existing wave overtopping formulas has been proved to be inaccurate for the estimation of the overtopping for the cases tested at Flanders Hydraulics Research, that are characterized by very shallow water conditions, with remarkable differences in wave transformation and wave breaking with respect to deeper waters. Therefore, in this study, we explored suitable expression for wave overtopping in very shallow water conditions.

**KEWORDS:** wave overtopping, shallow waters, foreshore, breaker parameter, equivalent slope.

## 1 INTRODUCTION

Wave overtopping is a phenomenon that occurs when sea waves are running up the seaward face of the coastal defence, reaching the crest of the structure and passing over it. The wave overtopping is a nonlinear and stochastic phenomenon, variable in time and space. Therefore the overtopping is generally quantified by means of the mean overtopping discharge. The mean wave overtopping discharge is defined as the average discharge per linear meter of width, $q$, expressed in $m^3$/s/m or in l/s/m. The mean overtopping discharge, together with wave run-up, is normally used for the coastal structures design.

Different methods can be employed to determine the mean overtopping discharge of sea defences due to random waves. Among them, empirical formulas are usually used worldwide (EurOtop, 2007; Goda, 2009; van der Meer and Bruce, 2013; Mase *et al.*, 2013).

An empirical formula is a model that consists in a simplified and functional representation of the phenomenon that is the object of the study. For wave overtopping, this model depends on wave conditions, water level, layout of the coastal structure and its structural properties. The most important parameter in wave overtopping is the dimensionless freeboard, defined as the ratio between the structural freeboard and the incident wave height measured at the toe of the dike. Distinctions in wave overtopping formulas are usually made among non-breaking, breaking and broken waves. Generally speaking, the first two categories are usually characterized by quite deep water conditions at the toe of the dike, meanwhile the last one presents normally shallow or very shallow water conditions and a relatively gentle foreshores before the toe of the dike. The foreshore is defined as the section in front of the dike that is horizontal or up to a maximum slope of 1:10 (EurOtop, 2007). Differently from Mediterranean countries, Northern European Countries often have wide foreshores. The Belgian coastline is a typical example of it, where the sea dikes are located at the end of a very long and shallow foreshore.

A specification is here required on the use of the expression “very shallow foreshore”. A criteria for distinguishing between shallow foreshore and very shallow foreshore has not been defined yet. In a shallow foreshore the waves break with consequent reduction of the wave height, but still the wave spectrum is similar to the offshore or deepwater one. At a very shallow foreshore a single peak spectrum is difficult to recognize, the spectrum is mostly characterized by very low frequencies, the wave itself does not appear anymore as an oscillatory phenomenon but it is mostly like a bore that is running over the foreshore before reaching the coastal defence. As consequence of intensive wave breaking and drastic modifications of wave height and wave period, the wave overtopping results inevitably affected. For shallow water conditions, the formula proposed by Van Gent (1999) is generally considered as the most appropriate one. Van Gent's formula is also reported in EurOtop (2007).

Flanders Hydraulics Research laboratory (FHR), in Antwerp, has carried out physical model tests in the past few years to investigate the wave overtopping with very shallow foreshores. Van Gent's equation was expected to be used for the estimation of the overtopping for the cases tested at FHR, however the formula was proved to be inaccurate for very shallow waters. Indeed the formula was calibrated on scale model tests in shallow water conditions, but still deeper than the cases in the present study (with differences in wave transformation, breaking and wave-structure interaction).

In this study, a new fitting of mean wave overtopping results with shallow and very shallow foreshores is proposed by introducing the concept of equivalent slope in shallow water conditions.

## 2 EXISTING FORMULA FOR WAVE OVERTOPPING WITH SHALLO WATERS

For overtopping calculations, it is common practice to use empirical formulas. The formulas reported in EurOtop (2007) are widely used for wave overtopping assessment. Not only for deep water conditions, EurOtop (2007) also includes a formula for shallow foreshore cases (Van Gent, 1999). So far, the studies conducted by Van Gent represents the most comprehensive analysis on wave overtopping in shallow water conditions. Van Gent (1999) in fact carried out small scale model tests on a 1:100 and 1:250 foreshore with smooth structure slopes of 1:4 and 1:2.5. Due to the heavy breaking the spectral wave period, $T_{m-1,0}$, is drastically changed (towards very long periods) and the wave height is reduced. Therefore the breaker parameter can become very large. The breaker parameter $\xi_{m-1,0}$ is defined as follows:

$$\xi_{m-1,0} = \frac{\tan(\alpha)}{\sqrt{{2\pi H_{m0}}/{gT_{m-1,0}^2}}} \tag{1}$$

where $H_{m0}$ is the significant incident wave height at the toe of the structure, $T_{m-1,0}$ is the spectral wave period and $\alpha$ is the dike angle. The formula proposed by Van Gent (1999) as reported in van der Meer (2002) and EurOtop (2007) is expressed by the following equation:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 10^c exp\left(-\frac{R_c}{H_{m0}\gamma_f\gamma_\beta(0.33+0.022\xi_{m-1,0})}\right) \tag{2}$$

where $q$ is the overtopping discharge per meter width of the structure, $R_c$ is the crest freeboard, $\gamma_f$ is the reduction coefficient that considers the effects of the slope roughness and $\gamma_\beta$ is the reduction coefficient that considers the effects of the obliqueness.

The $c$ parameter in Eq.2 is assumed as normally distributed parameter with mean value equal to -0.92 and a standard deviation $\sigma$ equal to 0.24. The 5% upper and under exceedance limits can be calculated as $(-0.92)\pm 1.64\sigma$. All the data from Van Gent (1999) are included in database from CLASH (Verhaeghe *et al.*, 2004). A sketch of the geometrical set-up as used in Van Gent (1999) is depicted in Figure 1 and also described in van der Meer (2002).

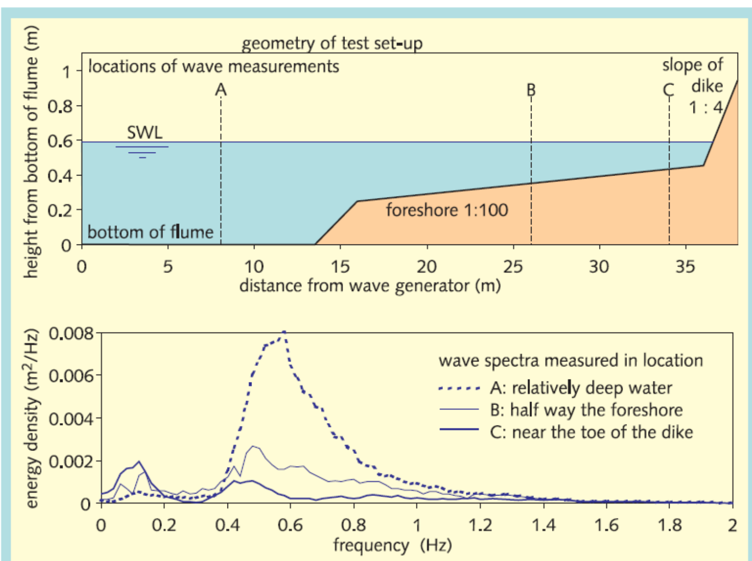


**Figure 1. sketch of the geometrical set-up as in Van Gent's tests (Source: van der Meer, 2002)**

## 3 EXPERIMENTAL CAMPAIGNS

Four different experimental campaigns were conducted at Flanders Hydraulics Research (dataset id.: 13-116, 00-142, 00-025, 13-168). The model scale of the tests conducted at FHR was 1:25. The wave flume at FHR is 70 m long, 4 m wide and 1.5 m high. The maximum water depth at the wave generator is 1.2 m. The results from FHR have been gathered together those seven selected datasets from CLASH database (dataset id.: DS-042, DS-109, DS-221, DS-226, DS-227 and DS-956). The CLASH DS-226 dataset corresponds to the data of the experimental campaigns conducted by Van Gent (1999). Data with zero overtopping rate or oblique wave attack were not used in the present analysis. This results in 348 data in total, all the them characterized by smooth, impermeable slopes, simple geometries without any berm or storm walls. The foreshore slope, $cot\theta$, varies between 29.3 and 250 meanwhile the dike slope, $cot\alpha$, between 2 and 6; the range of $h_{toe}/H_{m0}$ between (-0.88) and 2.85, where $h_{toe}$ is the water depth at the toe of the sea dike.

The incident wave height and period at the toe of the dike have been measured by means of resistive wave gauges. Classical reflection analysis methods (e.g. Mansard and Funke, 1980) are not suitable in shallow water conditions because non-linear effects are dominating in the very shallow foreshore cases. Therefore the wave height and wave period have been measured using wave gauges at the location of the dike toe but, removing the dike itself and installing an horizontal platform just after the foreshore. The wave reflection has been minimized in this way and the time series analysis provides only the incident wave characteristics. The wave overtopping has been collected in tanks located just after the dike. Measuring the variation in time of water level inside the overtopping tank has given indirectly a measure of the overtopping discharge.

The wave flume at FHR is depicted in Figure 2 as setup for the experimental campaign related to dataset 13-168. It can be observed that the flume is divided in four parts: one part (without dike) is used for measuring incident wave boundary conditions; the other three parts are used for overtopping measurements. Further details on the wave flume setup for the experiments conducted at FHR can be found in Altomare *et al.* (2014) and Chen *et al.* (2015).

A)

B)

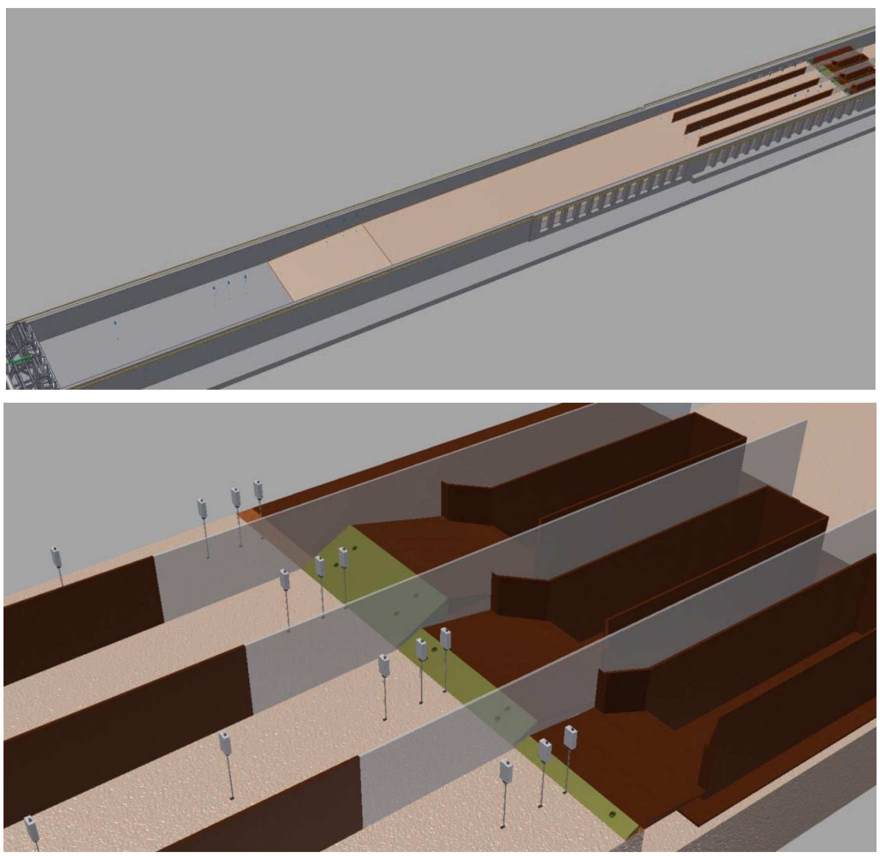

**Figure 2. Detailed view of the wave flume at Flanders Hydraulics Research for the experimental campaign corresponding to dataset 13-168.**

## 4 APPLICATION OF VAN GENT FORMULA TO PHYSICAL MODEL RESULTS

The results of the application of Eq.2 to the physical model test from FHR and CLASH are shown in Figure 3. The x-axis represents the dimensionless quantity $R_c/H_{m0}(0.33+0.022\xi_{m-1,0})$. The black solid line represents the prediction using Eq.2, meanwhile the dot lines indicate the 5% under and upper exceedance limits.

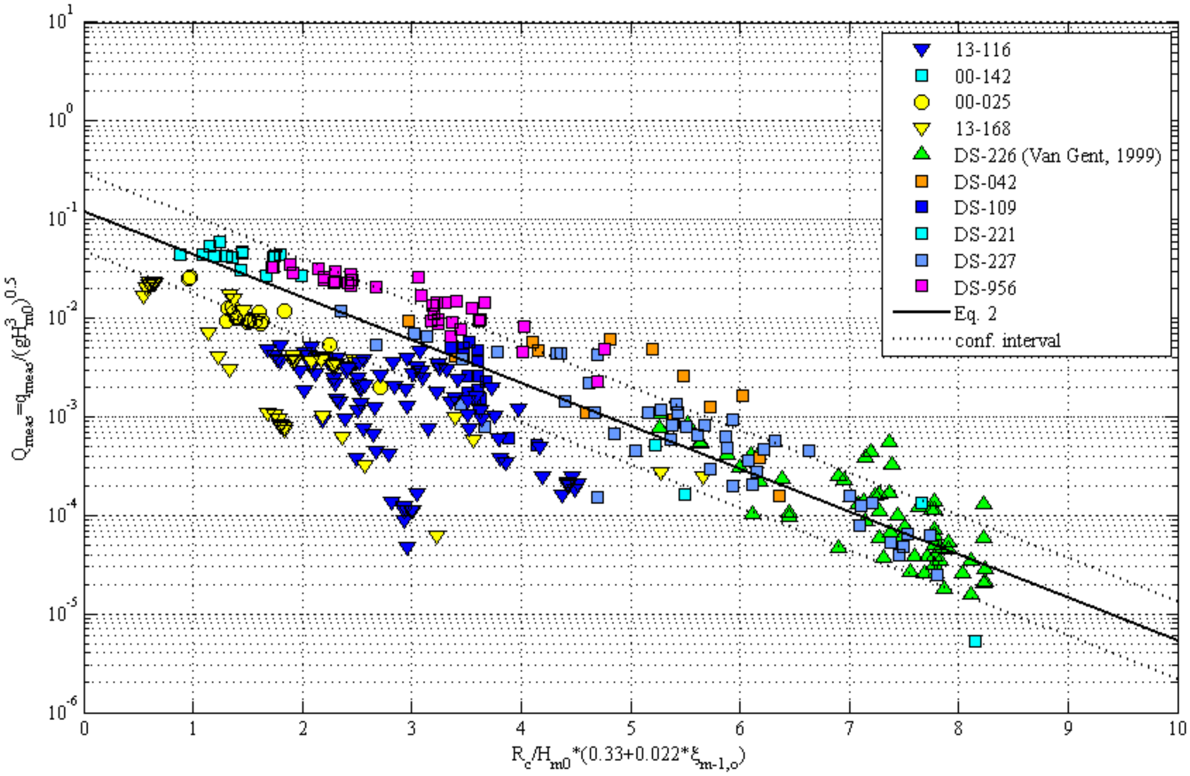


**Figure 3. Wave overtopping data and prediction using Eq.2 as in Van Gent (1999) with 5% under and upper exceedance limits**

The results in general show a tendency of overestimation especially for those cases characterized by very shallow waters. This tendency is noticeable in Figure 4 where the ratio between the dimensionless predicted and the measured overtopping, $Q_{pred}/Q_{meas}$, is plotted versus the ratio between the water depth at the toe of the dike and the wave height in deep water conditions, $H_{m0\text{-}DEEP}$. The water depth at the toe and the wave height in deep water conditions were firstly selected by Van Gent (1999) to determine a criteria that establishes whether the foreshore is shallow or very shallow. Van Gent (1999) performed tests from relatively deep waters to shallow waters ($h_{toe}/H_{m0\text{-}DEEP} \geq 0.67$). Very shallow conditions, based on Van Gent's criteria, correspond to $h_{toe}/H_{m0\text{-}DEEP} \leq 0.33$: this is the case of most of the physical model tests carried out at FHR; the results with $h_{toe}/H_{m0\text{-}DEEP} \leq 0.33$ are actually those results that show the biggest error when Eq. 2 is used for the prediction.

## 5 THE EQUIVALENT SLOPE

The results of the application of Van Gent (1999) to wave overtopping of sea dikes with (very) shallow foreshore have been discussed in the previous section, underlining the inaccuracy of the prediction for cases with very shallow water conditions. It can be argued that the foreshore slope might have an influence on wave transformation and wave breaking especially for very low water depths and therefore an influence on wave overtopping. Due to the foreshore slope and very shallow water conditions, the wave spectra at the toe of the structure is characterized by very low frequencies and the wave height is usually significantly smaller than one in deep water conditions (less than 50%).

Conceptually, if the waves break already on the foreshore before even reaching the structure, the assumption to use the dike slope to calculate the breaker parameter is wrong. However, two dikes with same freeboard, incident wave height and period and foreshore, but having different dike slopes, are expected to lead also to different overtopping discharges. In order to calculate the breaker parameter, it might be more accurate to calculate an average slope starting from the foreshore and dike slope.

A new concept of equivalent slope is here introduced. The equivalent slope is defined as the average slope, $tan\delta$, in the zone between $SWL\text{-}1.5H_{m0}$ and $SWL+R_{u2\%}$, where $SWL$ is the still water level, $H_{m0}$ is the significant wave height at the toe of the structure and $R_{u2\%}$ is the wave run-up exceeded by 2% of the incident waves. The average slope is calculated as follows:

$$tan\delta = \frac{(1.5H_{m0}+Ru_{2\%})}{L_{slope}} \tag{3}$$

where the quantity $L_{slope}$ is the horizontal length of the zone between $SWL\text{-}1.5H_{m0}$ and $SWL+R_{u2\%}$. The equivalent slope here defined is very similar to the average slope as reported in EurOtop (2007) to evaluate the effect of composite slopes and berms on wave overtopping. The main difference with EurOtop (2007) is that the use of an average slope is extended to very gentle, long and shallow foreshores. The wave heights and wave periods are still calculated at the toe of the dike and not at the toe of the foreshore or at the breaking point.

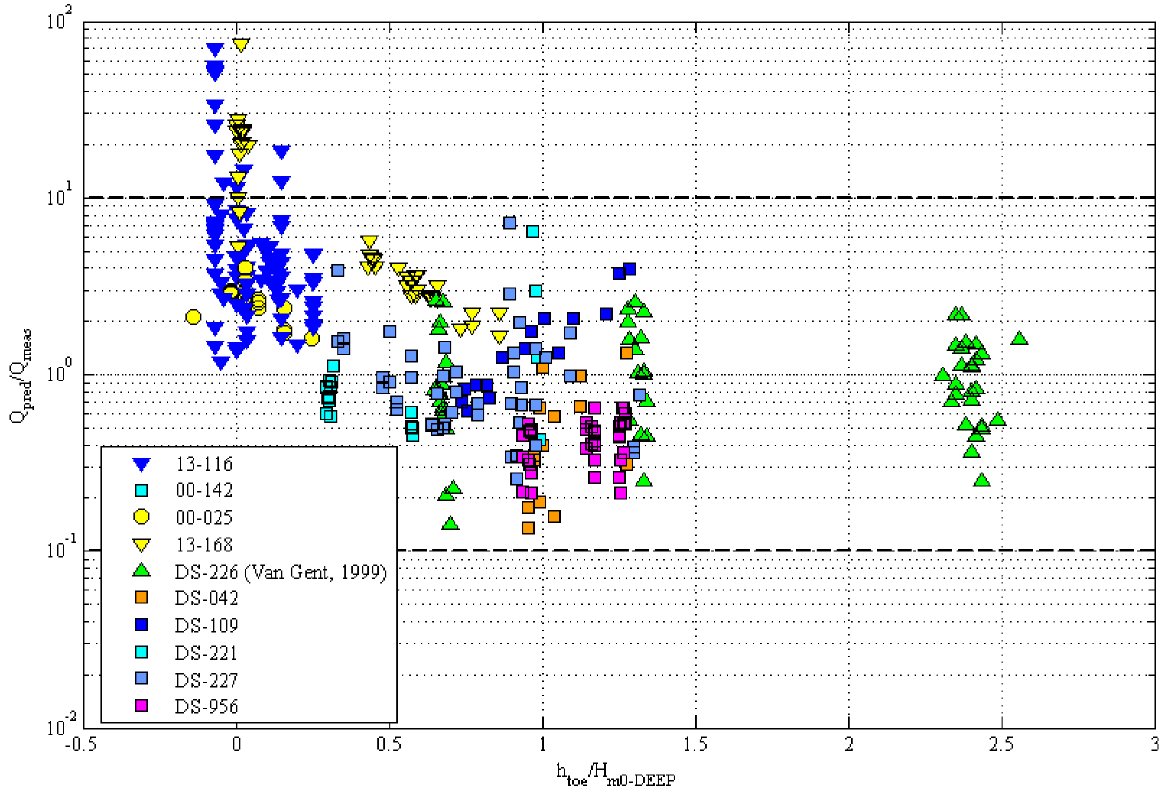


**Figure 4. Ratio of the dimensionless predicted to the measured overtopping versus ratio between the toe depth and the wave height in deep water conditions.**

To calculate the wave run-up the following formula is used (eq. 5.3, EurOtop, 2007):

$$Ru_{2\%} = 1.65\gamma_b H_{m0}\xi_{m-1,0} \quad \text{with maximum of}$$

$$Ru_{2\%} = \left(4.0 - \frac{1.5}{\sqrt{\xi_{m-1,0}}}\right)\gamma_b H_{m0} \tag{4}$$

The wave run-up is not known a priori because its calculation depends on the slope used to calculate the breaker parameter. Therefore the application of Eq.4 needs an iterative process that stops when the results for wave run-up start to converge. If the water depth at the toe of the dike is larger than 1.5*$H_{m0}$, then the equivalent slope is not calculated and only the dike slope is used to determine the breaker parameter.

The results of using the equivalent slope to calculate the breaker parameter and then the mean overtopping discharge are depicted in Figure 5 and Figure 6. The accuracy of the prediction improves significantly. All the cases are now in between 0.1 and 10 times the average predicted value (Figure 6) and the accuracy does not depend anymore on the relative water depth at the toe. Thus the model (Eq.2 with the implementation of the equivalent slope) can be considered valid. The effect of the foreshore slope on the wave transformation process and then on the wave overtopping is well caught.

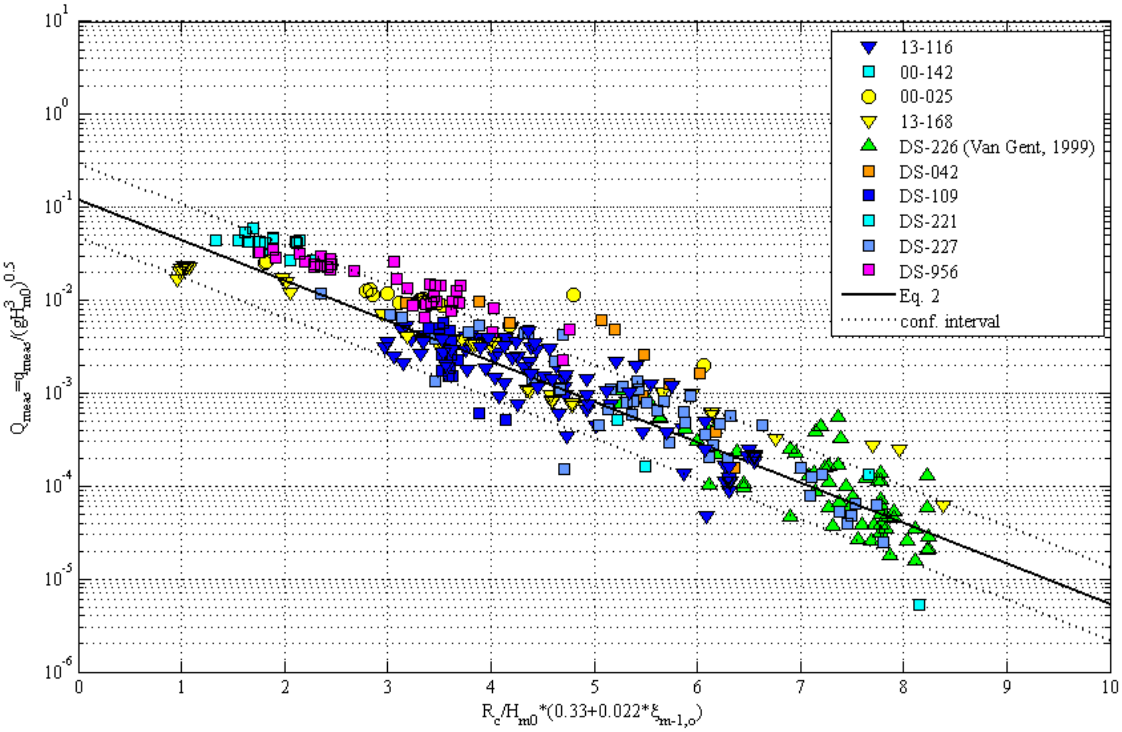


**Figure 5. Wave overtopping data and prediction using equivalent slope into Eq.2 as in Van Gent (1999) with 5% under and upper exceedance limits**

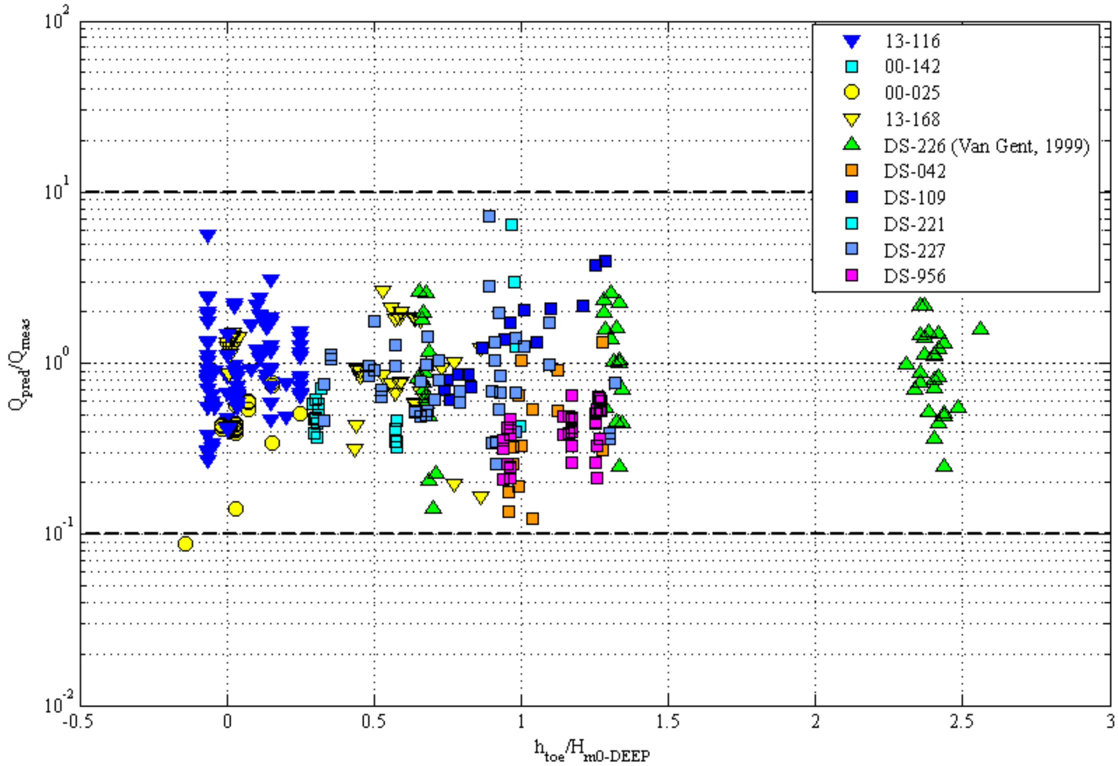


**Figure 6. Use of equivalent slope: ratio of the dimensionless predicted to the measured overtopping versus ratio between the toe depth and the wave height in deep water conditions.**

## 6 CONCLUSIONS

The present work analyses the wave overtopping of smooth and impermeable sea dikes with very shallow and very shallow foreshores. Physical model tests have been carried at Flanders Hydraulics Research. Furthermore the CLASH database has been explored for extraction of the six datasets assumed to be representative of cases with shallow foreshores or limited toe depth. The led to 348 data in total.

The formula from Van Gent (1999), also reported in the EurOtop (2007), has been initially used but the overtopping prediction resulted inaccurate, overestimating the mean wave overtopping discharge for very shallow waters. It has been demonstrated that the inaccuracies depend on the calculation of the breaker parameter. In fact, the breaker parameter is calculated using the tangent of the slope angle and usually the slope is referring to the dike slope. The foreshore slope is not taken into account. However, if the water is very shallow at the toe of the dike, the breaking does not occur on the dike itself but on the foreshore. Therefore, the influence of the foreshore slope has been included in overtopping calculation. Here a way to include this influence is proposed: the concept of equivalent slope in shallow foreshore is introduced and defined as the average slope in between the foreshore and the dike slope.

The use of the equivalent slope to calculate the breaker parameter is proved to increase significantly the accuracy of the overtopping predictions and it allows to extend the use of the formula proposed by Van Gent (1999) to cases characterized by gentle foreshores and very shallow water conditions as those cases very typical of the Belgian and Dutch coastal zones.

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