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PROBABILITY CALCULATION METHOD WITH NEURAL NETWORK FOR ESTIMATING WAVE OVERTOPPING AT COASTAL STRUCTURES: LEARNING FROM REGULAR WAVE TESTS

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Key words: wave overtopping, artificial neural network, probability calculation method, vertical wall, parapet.

ABSTRACT

An exact mathematical description of the wave overtopping processes is impossible due to the complex nature of the processes. Therefore the dependency of overtopping from wave parameters and coastal structures was mostly studied by physical model tests. To avoid the uncertainties due to imperfect statistics of wave heights in the irregular wave trains performed in physical models, the mean overtopping rates of irregular waves can be determined by the probability calculation method (PCM) (Goda, 2000) based on the regular wave data. The PCM combined with an artificial neural network (NN) technique is proposed in this paper to determine the mean overtopping rates of irregular waves on coastal structures based on learning from the regular wave data. The NN is used to quantify the overtopping volumes for the individual waves and the PCM is used for calculating the cumulative wave effect of individual waves of random nature. Determination of wave overtopping at a vertical wall with a parapet is presented as an application of the present model. Good agreement with the available experimental data and the empirical formulas shows that the present model offers an alternative to determine the mean overtopping rates of irregular waves on coastal structures. The method itself allows an insight in the reasons and the extent of scatter to be expected in physical model tests.

I. INTRODUCTION

Coastal structures such as seawalls and revetments are used to prevent water flooding due to storm waves in coastal, rural, or urban areas. While breakwaters are built against waves, they provide a sheltered area in a harbour. Wave overtopping is one of the important factors in design of such coastal structures. A tolerable wave overtopping is commonly allowed in practical situations (Yu, 2000). Thus, the assessment of the amount of wave overtopping rates is a key requirement for the effective design of coastal structures.

Based on the simple steady flow over weir model, Kikkawa et al. (1968) proposed a theoretical description of wave overtopping in regular waves. However, an exact mathematical description of the wave overtopping processes is not possible due to the stochastic and complex nature of the randomness, wave breaking, wave run-up, wave reflection and various other factors. Thus, the wave overtopping rates at coastal structures were mainly determined by empirical formulas obtained from physical model experiments. Since Saville (1955), physical model tests have been conducted for various types of structure, e.g., wave overtopping at vertical structures (Franco et al., 1994; Allsop et al., 1995; Cornett et al., 1999; Franco and Franco, 1999; Oumeraci et al., 2001; Daemrich et al., 2006a), sloping structures (Allsop et al., 2005; Etemad-Shahidi and Jafari, 2014), composite breakwater (Franco et al., 1994) and rubble mound breakwaters (Bruce et al., 2009; Lykke Andersen and Burcharth, 2009) etc. Within the CLASH (Crest Level Assessment of Coastal Structures) project (De Rouck et al., 2009), field or prototype measurements of mean wave overtopping were performed as well. Based on the field or laboratory investigations, a variety of empirical formulas for wave overtopping rates have been commonly presented as a function of the relative freeboard, and an exponential decay was assumed. The European Manual (EurOtop) for the assessment of wave overtopping was issued in 2007 (EurOtop Manual, 2007). In recent years, van der Meer et al. (2013) and Bruce et al. (2013) revisited the EurOtop for sloping structures and vertical structures, respectively. Mase et al. (2013) proposed prediction formulas both for random wave runup and mean overtopping rates at seawalls constructed on land or in very shal low water using

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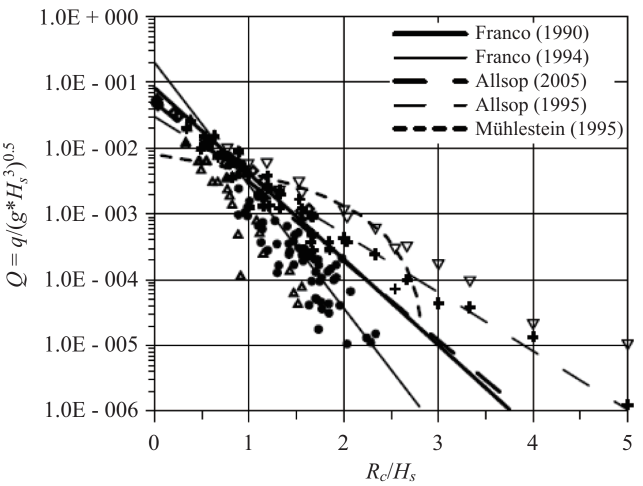

Fig. 1. Some data sets and design formulas of wave overtopping rate at the vertical wall.

the equivalent deepwater wave characteristics and an imaginary seawall slope for easy application of the formulas. A few numerical simulations of wave overtopping based on the Navier-Stokes equations have also been presented (Ingram et al., 2009).

Fig. 1 shows a wide scatter of the test results affects the significance of design formulas derived from laboratory data of wave overtopping at vertical walls. The data scatter in model tests with irregular waves is supposed to be the statistical distribution of wave heights and related periods in the irregular wave trains, which can not be performed perfectly in the physical model tests (Daemrich et al., 2006a; 2006b). Therefore it is worth going back to the roots - performing regular wave investigations and using the measured overtopping rates in combinations with statistically firm distributions of wave heights and periods to determine mean rates in irregular waves by the probability calculation method (PCM). The PCM was proposed by Goda (2000) to estimate the overtopping volumes of irregular waves based on physical model tests with regular waves by considering the cumulative wave effect of individual waves of random nature for the rate of wave overtopping. The mean overtopping rate of irregular waves was obtained by taking the average from a summation of the individual wave overtopping rates related to the duration of the time-series. The validity of the PCM was unambiguously verified by Goda (1970) for the mean overtopping rates at vertical walls.

The overtopping rates at vertical walls are highly related to the height of free board and almost independent of the wave periods. However, for a vertical wall with parapet, the influence of wave height, period, freeboard and size of the parapet on the overtopping due to the complex processes involving wave reflections must be included (Daemrich et al., 2006b). It seems not easy to find a good fitting formula for including these parameters on the basis of regression analysis. Alternatively, the technique of artificial neural networks (NN) in this case is a convenient tool to deliver the relationship of an overtopping volume in a wave from such physical parameters. NNs have been successfully applied in the field of ocean and coastal engineering (Mase et al., 1995; Tsai and Lee, 1999; Deo et al., 2001; Tsai et al., 2002; van Gent et al., 2007; Verhaeghe et al., 2008; Tsai and Tsai, 2009; Mase et al., 2011). A program of the neural network model named NN-Overtopping was derived on the basis of CLASH database for estimating the wave overtopping; the guidance of CLASH NN-Overtopping was included in the EurOtop Manual (2007). However, the CLASH NN-Overtopping did not predict well for such structure of a vertical wall with parapet.

In this paper, we present the PCM combined with the NN technique to determine the mean overtopping rates of irregular waves on a vertical wall with a parapet. These types of structures are designed to reduce wave overtopping by deflecting water back seaward. The effectiveness of parapets on the wave overtopping process was investigated based on physical model experiments (Cornett et al., 1999; Oumeraci et al., 2001; Kortenhaus et al., 2003; Pearson et al., 2004; Daemrich et al., 2006b). In the following sections, we first briefly describe the theory of PCM for the mean overtopping rates of irregular waves. Next, the investigation of the physical model tests of the overtopping rate at a vertical wall with a parapet for using in the NN model is described. Applications of the combined PCM and the techniques of NN to determine the mean overtopping rates of irregular waves are then presented. The effects of the geometric aspects of the structures and the wave factors to the overtopping rates are demonstrated. The reduction of the overtopping rates by parapets is also discussed.

II. PROBABILITY CALCULATION METHOD

The probability calculation method was proposed by Goda (1970, 2000) to provide engineers with a practical method to estimate the random wave overtopping rate based on the regular wave data. Wave overtopping is primarily governed by the absolute heights of individual waves relative to the crest elevation of the structure. Thus, the cumulative effect of the action of individual waves of random nature should be considered in determining the rate of wave overtopping at coastal structures. The calculation of the cumulative wave effect was called the PCM (Goda, 2000).

According to Goda (2000), when a set of data on the overtopping rates by regular waves with various combinations of wave heights and periods is available, the mean rate of wave overtopping (q) can be calculated by the sum of the overtopping volumes of N_o individual waves (q_i), which is related to the duration of the time series t_o, using the following equation:

$$q = \frac{1}{t_o}\sum_{i=1}^{N_o} q_i(H_i, T_i) \cdot T_i \qquad (1)$$

where H_i and T_i are the wave height and period, respectively, of the i-th individual wave, which can be obtained using a

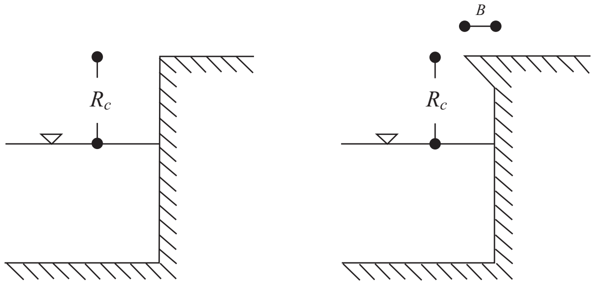

Fig. 2. Structures considered for the investigation of wave overtopping. (left: vertical wall, right: vertical wall with a 45° parapet).

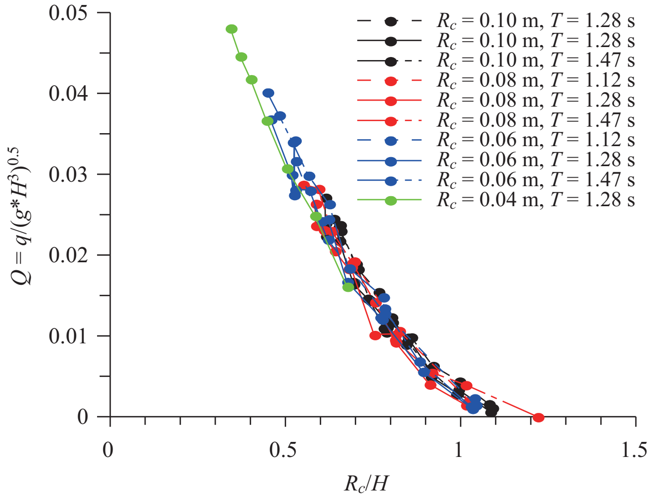

Fig. 3. Experimental results of the dimensionless overtopping rates at the vertical wall.

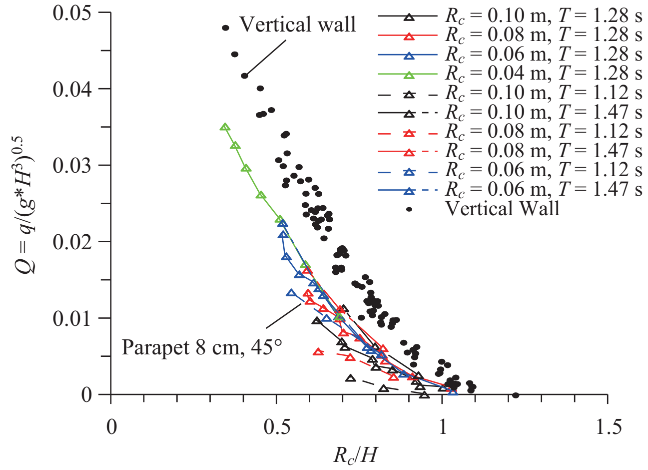

Fig. 4. Experimental results of the dimensionless overtopping rates at the vertical wall with a parapet (B = 8 cm).

firm statistical distribution function or a suitable wave train from a spectral density function.

The great advantage of PCM is that tendencies of variations in wave and period distributions of irregular wave trains, which are influenced by spectral shape and random phase setting, could be simulated. In laboratory tests, mostly we are not really able to attribute the real individual wave height and period to an individual overtopping event because of variation with location (distance to the structure) and deformation by reflection or, in case of sloped dikes, deformation by shoaling, and furthermore not knowing which location is relevant for generating the run-up/overtopping. Thus, it is worth performing regular wave investigations and using the measured overtopping rates in combinations with statistically firm distributions of wave heights and periods to determine mean overtopping rates in irregular waves by the PCM.

III. PHYSICAL MODEL TESTS

As practiced in Goda (2000), regular waves were conducted in the present model tests for applying the PCM to the determination of the overtopping rates of irregular waves. Two types of structures, a plain vertical wall and vertical wall with a 45° parapet (Fig. 2), were considered in the physical model tests for establishing the present NN model of wave overtopping.

In Fig. 2, R_c and B stand for the height of freeboard and the width of parapet, respectively. The preliminary experimental results were presented in Daemrich et al. (2006b). The model tests were conducted in a wave channel beside the wave basin of the Franzius-Institute in Hannover, Germany. The structure was placed at a distance of approximately 16 m from the wave paddle. The height of the structure was 0.75 m. The overtopping water was collected in a tank behind the vertical wall. Overtopping was excluded by a vertical plate (on top of the structure) as long as the waves at the structure are not yet quite regular (in the start-up phase). The plate was lifted for the duration of the overtopping measurements (usually 5 overtopping events) after reaching steady state conditions of the waves at the structure. The total overtopping volume was determined by measuring the increase of water level in the tank.

The wave heights (H) were ranged from 4 to 18 cm, and wave periods (T) were 1.12 s, 1.28 s, 1.47 s and 1.792 s. Water levels were 0.65 m to 0.71 m, which corresponds to freeboards (R_c) of 0.10 m to 0.04 m. Two parapets with width (B) of 4 cm and 8 cm were used in the test. The incident wave heights were measured at a distance of 4.6 m from the wave paddle. The heights were analysed in a time window after reaching constant heights at the wave gauge but before the reflected waves from the structure appeared. In a similar manner, the time of the overtopping measurements was fixed on the basis of the measurements of the waves in front of the structures.

The experimental results of the dimensionless mean overtopping rates (Q) as a function of the relative freeboard (R_c/H) are plotted in Figs. 3 and 4. The dimensionless mean overtopping rate (Q) is defined as

$$Q = \frac{q}{\sqrt{gH^3}} \quad (2)$$

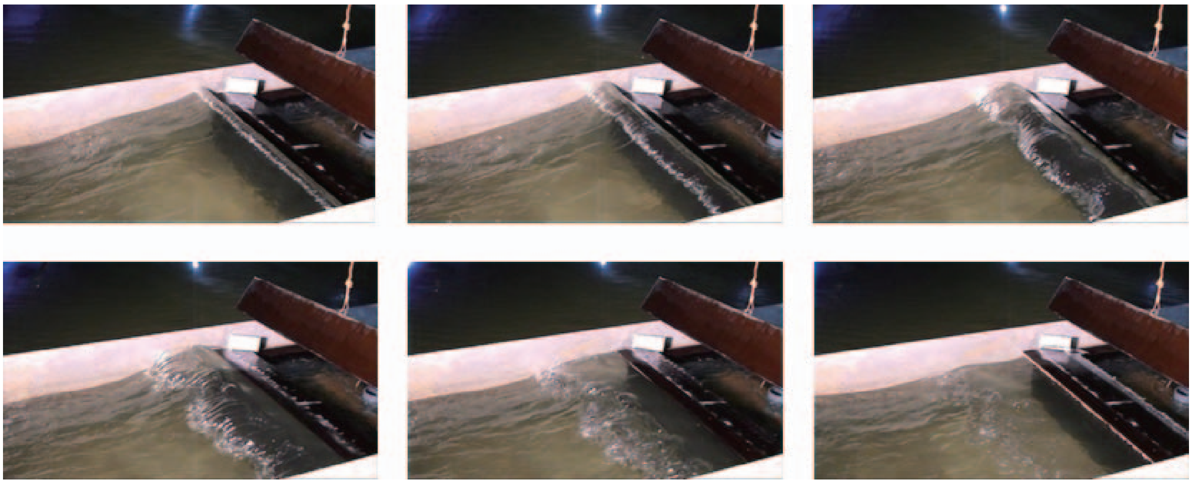

Fig. 5. A sequence of wave overtopping events at a vertical wall with a parapet in the experiments (R_c = 8 cm, B = 8 cm, H = 14 cm, T = 1.28 s).

in which q is the dimensional mean overtopping rate with unit of m^3/s.

There is no trend regarding the influence of the wave periods beyond the scatter of the data of the mean overtopping rates at the vertical wall (Fig. 3). However, adding a parapet to the wall resulted not only in a further reduction of the overtopping but also in a more distinct trend concerning the influence of the wave periods (Fig. 4). Fig. 5 shows the sequence of wave overtopping at a vertical wall with a parapet in the experiments, demonstrating the significant wave reflection from the wall.

IV. NEURAL NETWORK MODEL

Artificial neural network (NN) is an information-processing system that mimics the biological NN of the brain by interconnecting many artificial neurons. There are many types of NNs, including the supervised, unsupervised and associated learning networks, in addition to the optimisation application network. The back-propagation neural network (BPN), which is used in this study, is one of the frequently used models for solving a forecasting problem. A typical three-layered network with an input layer, a hidden layer and an output layer is considered in this study. Each layer may consist of several neurons, and the layers are interconnected by sets of the correlation weights. Each neuron receives inputs from the initial inputs or the interconnections and produces outputs by the transformation that uses an adequate nonlinear transfer function. The formulas are listed below:

$$y_j = f(net_j) \tag{3}$$

$$net_j = \sum_{i=1}^{N} W_{ij} X_i - \theta_j \tag{4}$$

where y_j is the output variable, W_{ij} is the weight between the j-th neuron and the i-th neuron, X_i is the input variable as biomimetic neuron input signal, $f(net_j)$ is the transformation function as a biomimetic non-linear function of the neurons, q_j is the theshold (bias) for the j-th neuron, and net_j is the consolidation function for the j-th neuron. The sigmoid function is commonly used as the transfer function, given using

$$f(net_j) = (1 + e^{-net_j})^{-1} \tag{5}$$

The training process of the neural network is essentially executed through the examination of a series of observed data. The interconnection weights between the neurons are then obtained from the learning process of NN based on the input and output information. The main procedure of the BPN is the error estimated at the output layer, which is propagated backward to the input layer through the hidden layer in the network, to obtain the final desired outputs. The error at the output neuron can be estimated from

$$E = \frac{1}{2} \sum_k (T_k - O_k)^2 \tag{6}$$

where T_k and O_k are the actual value and the predicted value for the k-th output neuron, respectively.

The gradient descent method is often utilized to calculate the weight of the network and to adjust the weight of interconnections to minimize the output error. The details of the BPN algorithm can be found in Rumelhart et al. (1986).

Before training a neural network, a scaling function was used to pre-process the input data to ascertain the inputs and targets falling in the range of [-1, 1] and [0, 1], respectively. The scaling function is defined as

$$x_{\text{new}} = \left[D_{\min} + \frac{x_{\text{old}} - x_{\min}}{x_{\max} - x_{\min}} \times (D_{\max} - D_{\min}) \right] \tag{7}$$

Table 1. The performance of NNs using different input vari-ables to determine the dimensionless over-topping rates Q.

Input variables	NN structures	Agreement indices	
		RMSE	R^2
R_c/H	$I_1H_3O_1$	0.004243	0.8363
R_c/H, B/H	$I_2H_5O_1$	0.001542	0.9582
R_c/H, B/H, H/L_o	$I_3H_5O_1$	0.001194	0.9871

in which $D_{\min}$ and $D_{\max}$ represent the range of linear mapping, $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of the data, respectively, and x_{old} and x_{new} are the data before and after transformation, respectively.

The root-mean-squared error (*RMSE*) between the observed and predicted values is used in the agreement index to estimate the accuracy in the paper, which is defined as

$$RMSE = \sqrt{\frac{\sum_{k=1}^{n}(y_k - \hat{y}_k)^2}{n}} \tag{8}$$

in which n is the number of samples, $\hat{y}_k$ is the value of the observation and y_k denotes the value of the prediction. The other agreement index used in this work is the correlation coefficient (R^2), which is defined as

$$R^2 = \frac{\left[\left(\sum_{k=1}^{n} y_k \cdot \hat{y}_k\right) - n \cdot \bar{y}_k \cdot \bar{\hat{y}}_k\right]^2}{\sum_{k=1}^{n}(y_k - \bar{y}_k)^2 \cdot \sum_{k=1}^{n}(\hat{y}_k - \bar{\hat{y}}_k)^2} \tag{9}$$

where $\bar{y}_k$ and $\bar{\hat{y}}_k$ are the average values of y_k and $\hat{y}_k$, respectively.

The present NN first configures the optimum network architecture based on the physical model tests in regular waves. There were a total of 221 sets of data obtained from the experiments, from which half of the data were used in the learning process of the NN and the other half of the data were used to test the NN model.

In the present NN model, the input and output physical parameters are normalized in a dimensionless form for the applications to the field. Table 1 shows the performance of the NNs using different input variables for the dimensionless overtopping rate, in which $I_lH_mO_n$ indicates l neurons in the input layer, m neurons in the hidden layer and n neurons in the output layer of the network. The best agreement was obtained when the grouped variables of the relative freeboard, R_c/H, the relative width of parapet, B/H, and the wave steepness, H/L_o (L_o is the wavelength defined as L_o=1.56 T^2, T is the wave period) were used as the inputs. The results of *RMSE* and R^2 imply that the free board related to the wave height is the main parameter governing the mean overtopping rate, but the relative width and wave period also affect the overtopping rate. Note that the learning constant (= 0.1), the momentum factor (= 0.3) and the Epochs (= 3000) were used in the NN model. Figs. 6-8 demonstrate the quality and plausibility of the trends of the present NN model. Fig. 9 shows that a very high cor-

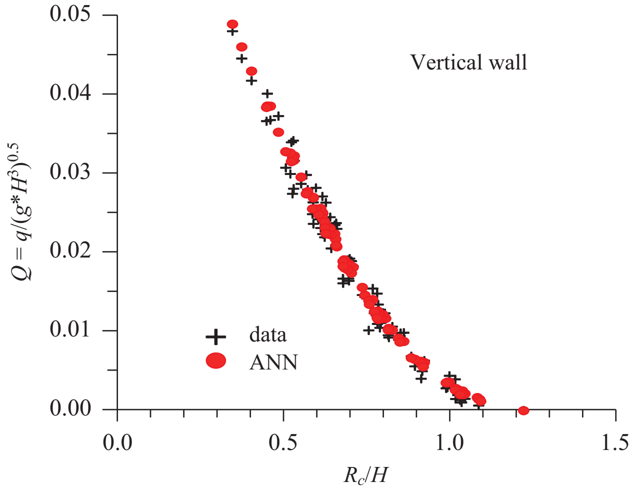

Fig. 6. Verifications of NN for a vertical wall.

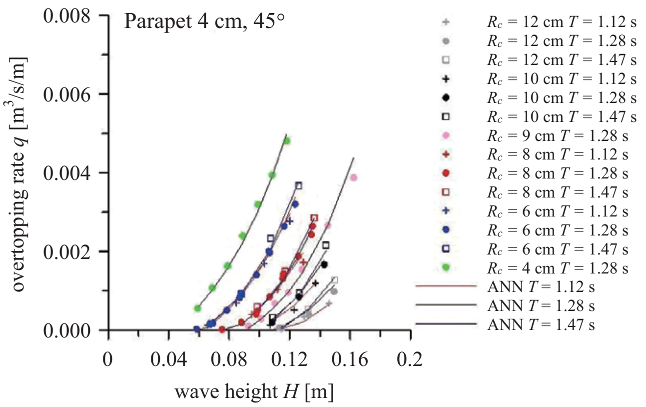

Fig. 7. Verifications of NN for a vertical wall with a parapet (*B* = 4 cm).

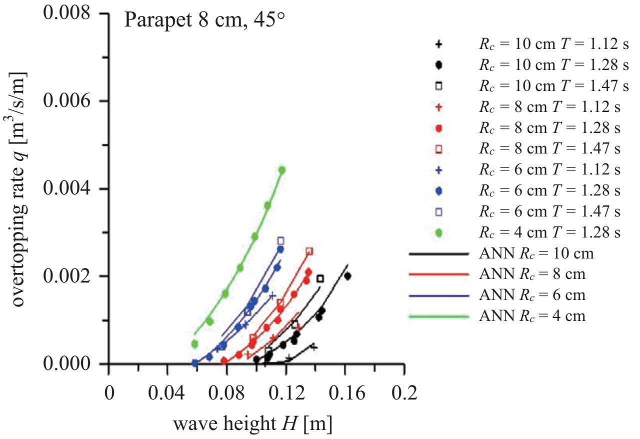

Fig. 8. Verifications of NN for a vertical wall with a parapet (*B* = 8 cm).

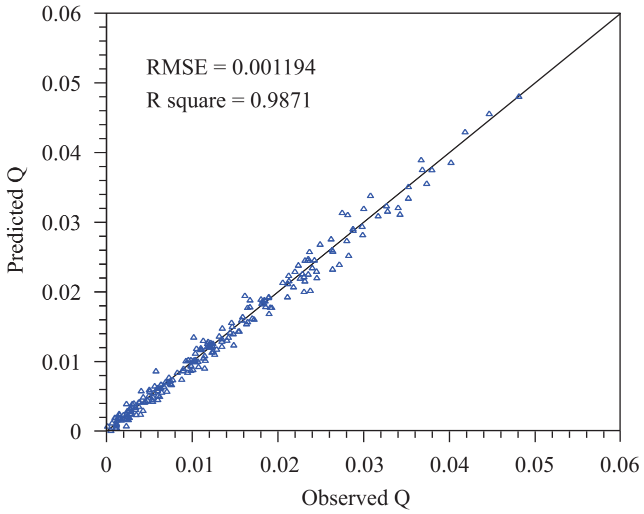

Fig. 9. The correlation between the measured and calculated overtopping rates.

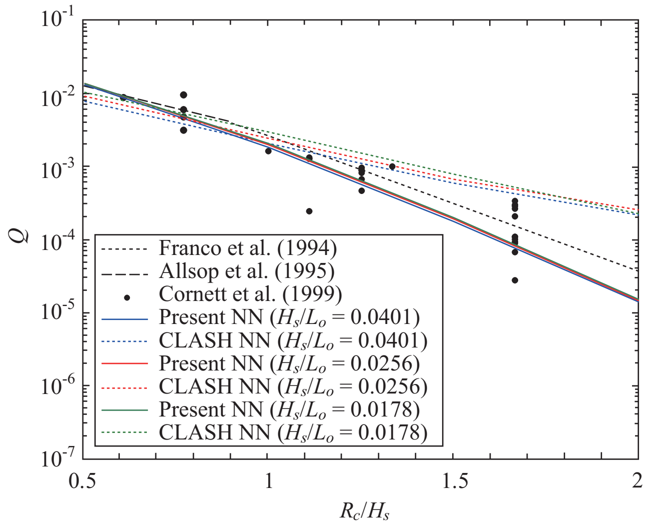

Fig. 11. Results of the overtopping rates for a plain vertical wall.

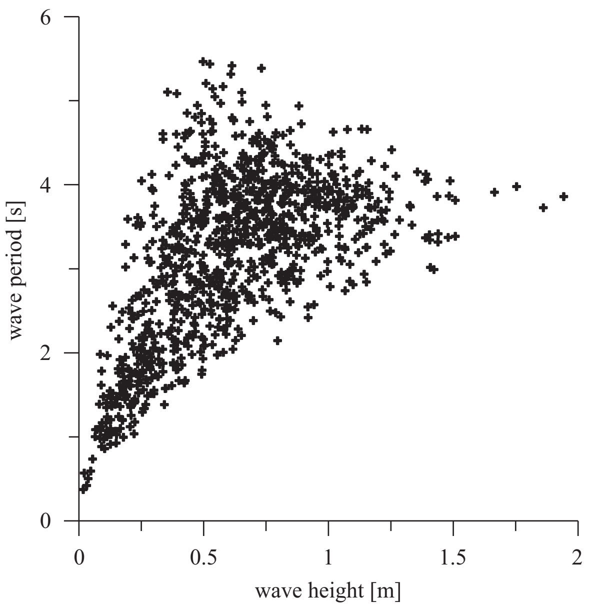

Fig. 10. Scatter plot of the individual wave heights and periods of the time-series (H_s = 1.0 m, T_s = 4 s).

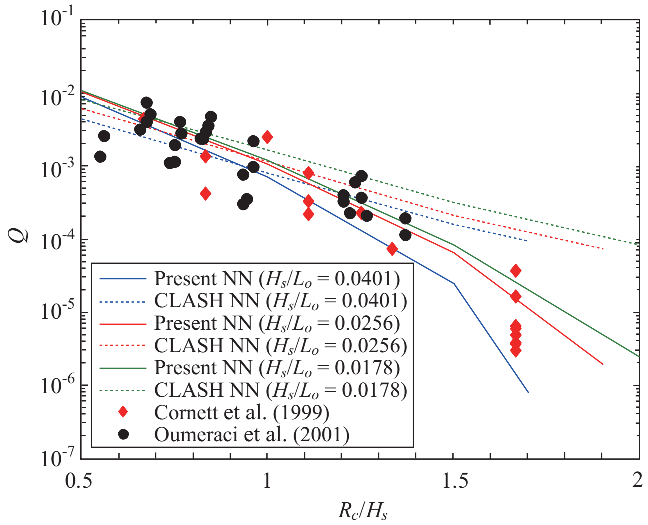

Fig. 12. Results of the overtopping rates for a vertical wall with a parapet (B/H_s = 0.5).

relation between the measured and calculated overtopping rates of all the data was observed.

V. APPLICATIONS TO IRREGULAR WAVES

An irregular wave train, e.g., generated by inverse Fourier-transformation, can be analysed by using the zero-crossing definition. Each "zero-crossing wave" is considered to correspond to an individual regular wave. According to Eq. (1), the mean overtopping rate can be calculated by the summation of the overtopping volumes of the individual waves related to the duration of the underlying time-series, for which the overtopping volumes of the individual waves are provided by the NN model trained as described above.

To perform the calculations of each irregular wave, a time series of a wave train containing 1000 waves was created from a JONSWAP spectrum density function. By the inverse Fourier transformation and the zero-down crossing analysis, Fig. 10 shows that 1000 individual wave heights and their related periods are created for the random wave with a significant height H_s = 1.0 m and a period T_s = 4 s. In the following, the mean overtopping rates of irregular waves of height H_s = 1.0 m combined with four wave periods T_s = 4 s, 5 s and 6 s, i.e., three cases of wave steepness H_s/L_o = 0.0401, 0.0256 and 0.0178, were calculated and analysed for the different combinations of B/H_s and R_c/H_s.

Based on the NN calculations and Eq. (1), Figs. 11 and 12 show the present results of the dimensionless mean overtopping rates Q against the relative freeboards R_c/H_s for a plain vertical wall and a vertical wall with a parapet for $B/H_s = 0.5$, respectively. The overtopping rates at a plain vertical wall are almost independent of the wave steepness/period, as expected. But there is a distinct dependence of the overtopping rates on the wave period for the vertical wall with a parapet. In shorter waves the efficiency of the parapet is clearly increasing.

Bruce et al. (2013) revisited EurOtop for vertical structures based on new analysis of existing data, and recommended the empirical formulas of Allsop et al. (1995) and Franco et al. (1994) for lower and higher freeboards of vertical wall without foreshore, respectively. The description of wave overtopping is given by:

For $R_c/H_s < 0.91$ (Allsop et al., 1995),

$$Q = 0.05\exp\left(-2.78\frac{R_c}{H_s}\right) \tag{10}$$

For $R_c/H_s > 0.91$ (Franco et al., 1994),

$$Q = 0.2\exp\left(-4.3\frac{R_c}{H_s}\right) \tag{11}$$

Fig. 11 shows that the present NN combined PCM results are good comparable with the experimental data of Cornett et al. (1999) and in agreement with the recommendations of Bruce et al. (2009), that is, close to Allsop et al. (1995) for smaller R_c/H_s and close to Franco et al. (1994) for larger R_c/H_s. However, it can be seen that the CLASH NN-Overtopping overpredicts overtopping for higher freeboards and underestimates overtopping for lower freeboards.

For the overtopping of the vertical wall with parapets, Fig. 12 also shows that the present NN results are in good agreement with the experimental data of Cornett et al. (1999) and Oumeraci et al. (2001) but CLASH NN-Overtopping gives higher values for higher R_c/H_s. The experimental data of Cornett et al. (1999) and Oumeraci et al. (2001) shown in Figs. 11 and 12 are extracted from the series 113 and series 914 of the CLASH database, from which the cases of cot $\alpha_u = 0$ and -1 of the database are selected for the vertical wall and for the vertical wall with parapet, respectively.

The representative curves of the mean overtopping rates of irregular waves for a vertical wall with a parapet in comparison to a plain vertical wall are plotted in Fig. 13. It shows that the present results are comparable with the experimental data, from which the reasonable reduction of the overtopping by the use of a parapet is observed.

The effectiveness of the use of a parapet in reducing overtopping is indicated in Fig. 14, where the reduction factor is defined as

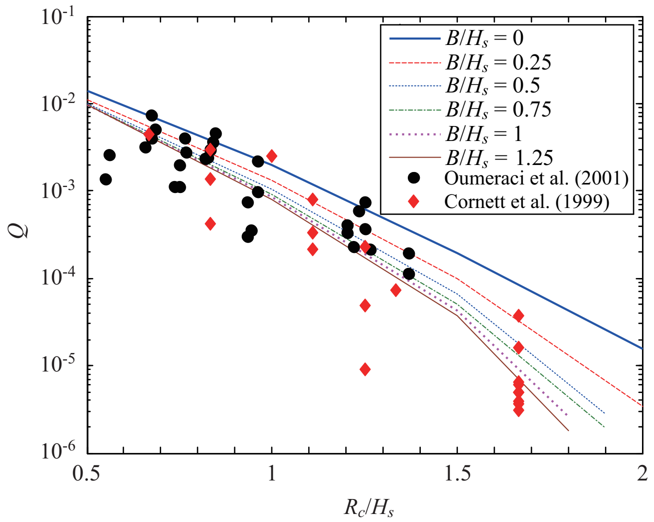

Fig. 13. Results of the overtopping rates for various widths of the parapets ($H_s/L_o = 0.0256$).

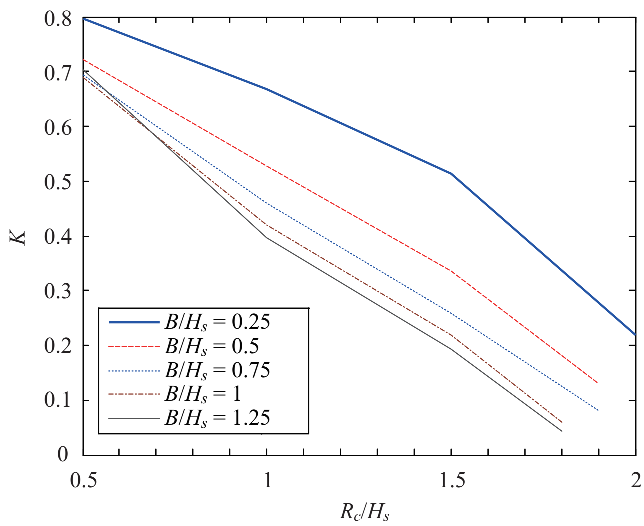

Fig. 14. The effectiveness of the use of a parapet in comparison to a plain vertical wall ($H_s/L_o = 0.0256$).

$$K = \frac{Q_{parapet}}{Q_{vertical\ wall}} \tag{12}$$

The results indicate that the use of a larger relative freeboard R_c/H_s or a larger relative width of a parapet B/H_s is more effective in suppressing overtopping. Fig. 15 shows the influence of wave steepness H_s/L_o on the K value for $B/H_s = 0.5$, indicating that the K value decreases with an increasing H_s/L_o value. This observation shows that the use of a parapet is more effective for a shorter wave period with a fixed wave height. The K value against R_c/H_s using the "Decision chart" presented in Pearson et al. (2004) are also plotted in Fig. 15, which shows that their K values are independent of the wave

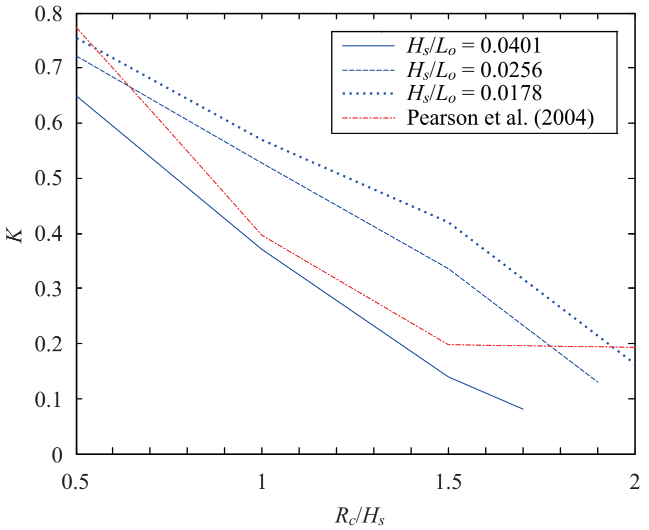

Fig. 15. The influence of the wave steepness on the effectiveness (B/H_s = 0.5).

steepness and are close to the case of shorter wave (H_s/L_o = 0.401) of the present results as 1.0 < R_c/H_s < 1.5.

VI. CONCLUSIONS

The PCM combined with the artificial NN model for the determination of the wave overtopping rates of irregular waves at a vertical wall with a parapet was presented. The NN model was first configured by the learning process based on the physical model of regular waves, from which the optimum NN model for predicting the dimensionless overtopping rate is established by three major physical parameters, the relative freeboard, the relative width of the parapets and the wave steepness. The present NN results demonstrated a very good agreement between the predicted and measured values of the dimensionless overtopping rate. For an irregular wave train, the time series of 1000 individual waves was created from a JONSWAP spectrum density function. The trained NN was applied to determine the overtopping volumes of individual waves of an irregular wave train, from which the mean overtopping rate over the duration of the time series was obtained by the PCM. The different wave steepness values combined with the various relative free board lengths and widths of parapets to the wave heights were calculated for the overtopping rates of irregular waves. As comparing with the previous experimental data for the overtopping of the vertical wall, the present results are in agreement with the recommendations of Bruce et al. (2013). For the overtopping of the vertical wall with parapets, the present results are also comparable with the experimental data of Cornett et al. (1999) and Oumeraci et al. (2001), and have better performance than CLASH NN-overtopping for the illustrative examples. The comparable results with the experimental data and available formulas demonstrate that the present NN model combined with the PCM allows an alternative to determine the mean overtopping rates of irregular waves on coastal structures.

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