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Prediction of extreme and tolerable wave overtopping discharges through an advanced neural network

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ABSTRACT

This paper presents an Artificial Neural Network (ANN) to predict the wave overtopping discharge at coastal and harbour structures for a variety of wave conditions and complex geometries. The goal of this work is to provide a robust tool in both extreme and tolerable overtopping conditions, starting from the ANN recently developed by the authors for wave reflection, overtopping and transmission. Optimisation of the existing ANN is analysed: (i) by training the ANN also on very low values of the overtopping discharge: (ii) by the set-up of an architecture consisting of a classifier-quantifier scheme; (iii) through the modification of the weight factors included in the boot-strapping resampling technique. The accuracy of the optimised ANN is proved predicting new data and datasets.

1. Introduction

Most coastal and harbour structures are constructed primarily to limit wave overtopping or prevent flooding. New challenges to the risk based design of these structures are posed by the ongoing effects of climate change, with sea level rise and increasing intensity and frequency of storms (THESEUS team, 2014). Therefore the accurate estimation of overtopping discharges and volumes, together with the characteristics of the overtopping flow over the structures, are extremely important to assess and assure the safety – or at least limit the exposure – of people, activities and goods.

Formulae and methods are available to predict overtopping at particular structures, often fairly simplified geometries, under given wave conditions and water levels (EurOtop, 2007; Van der Meer et al., 2009). Numerical models do exist that can simulate the wave-by-wave process and the details of 3D flows (Higuera et al., 2013), also with some simplification and in general with a significant effort for the preparation of the required data and the need for calibration. A good option to predict wave overtopping is to use physical model tests, but they are expensive and time consuming. They should certainly be considered for a final design, but are often a way too far in a preliminary design.

For conceptual design purposes, a simple and rapid approach is to use an Artificial Neural Network (ANN), which is particularly recommended in case of complicated structure geometries and variable wave conditions (EurOtop, 2007). This kind of predictive method requires however a homogeneous and “wide-enough” database to train the ANN, based on a number of parameters for total range of possible output values. There are specific cases where an ANN cannot deal with, such as very complex walls and double promenades (Van Doorslaer et al., 2015), see for details the methodology released within the PC-OVERTOPPING calculator (http://www.overtopping-manual.com/calculation_tool.html).

The ANN developed within the CLASH (2004) project and proposed by EurOtop (2007) for the prediction of the average overtopping discharge, q, is the ANN by Van Gent et al. (2007). Further analysis and other ANNs have been delivered during and after CLASH (2004): the ANN by Verhaeghe (2005) for q and the ANN developed by the authors (Zanuttigh et al., 2014). The last one predicts the main wave-structure interaction parameters: besides q, the wave reflection, K_r, and transmission, K_t coefficients. These ANNs showed a good performance when predicting the same database used for training but were not systematically tested against new data, i.e. data that were not already used for training.

The goal of this work is to provide coastal designers with a tested robust and accurate ANN able to represent extreme and tolerable wave

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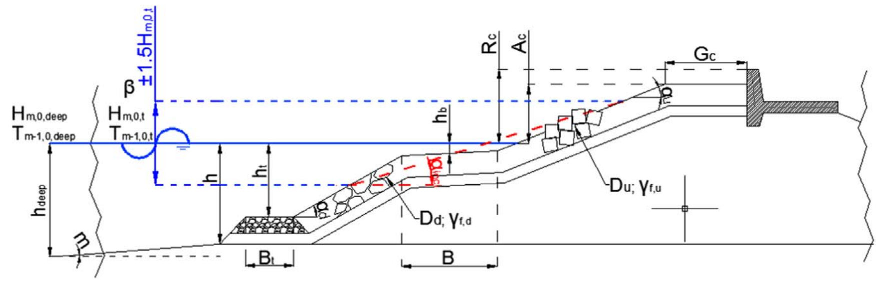

Fig. 1. Schematisation of the structure based on CLASH, including some of the geometrical and hydraulic parameters.

overtopping discharges for a wide range of structure types under a variety of wave conditions. This new ANN tool is intended to be delivered – upon registration only – to the Coastal Engineering community at www.unibo.it/overtopping-neuralnetwork, with the forthcoming publication of the updated EurOtop (2016). This work is based on the recent research carried out by the authors (Zanuttigh et al., 2014) and is going to answer key questions such as:

- How the ANN can deal with zero measured values of overtopping?
- Does the implementation of a new classifier-quantifier scheme (based on the idea by Verhaeghe, 2005; Verhaeghe et al., 2008) allow a better prediction of the extreme values or is the effect of the error propagating from the first classification dominant?
- How should weight factors be introduced in the ANN training, to let the ANN learning from the more reliable data?
- How can the results of the ANN be used in practice, accounting for model and scale effects?

The paper structure is as follows. Section 2 describes the new extended database for wave overtopping, including the explanation of the differences and updates with respect to CLASH (2004). Section 3 focuses on the optimisation of the existing ANN (Sub-Section 3.1) with respect to the training process and the representation of the extreme values. The analysis of extreme conditions accounts for (i) the low values ($q<10^{-6}$ m^3/s/m), which are at present overestimated in previous works by Van Gent et al. (2007) as well as Verhaeghe et al. (2008); and (ii) the high values ($q>10^{-3}$ m^3/s/m), whose accurate estimate is essential to assess the potential impacts of disasters. As for the first objective, the training of the ANN including all the non-zero values of the discharge is examined (Sub-Section 3.2) and its capacity to deal specifically with zero values is discussed (in Sub-Section 3.3). The definition of the weight factors affecting the training process is also analysed and a new way to evaluate them is proposed (Sub-Section 3.4) to assure a more balanced assessment of the data reliability and complexity. As for the second objective, the architecture of the ANN is modified into a classifier-quantifier scheme, which is inspired by the work of Verhaeghe et al. (2008), but is very different both as purpose and as set-up (Sub-Section 3.5). Section 4 provides the accuracy of the final ANN (Sub-Section 4.1) when predicting either datasets excluded from the training database (Sub-Section 4.2), or new data and datasets (Sub-Section 4.3). The limitations of the optimised ANN with regard to the model (i.e. wind, currents) and scale (i.e. permeability) effects are also discussed (Sub-Section 4.4). Conclusions are finally drawn in Section 5.

2. The new database: parameters and schematisation of the structure

The wave overtopping Data Base (DB hereafter) employed in this work is composed by more than 13,500 tests mainly derived from the CLASH DB (Van der Meer et al., 2009), which consists of more than 10,000 irregular tests on dikes, rubble mound breakwaters, berm breakwaters, caissons and combinations of these structures resulting in complicated geometries. The following datasets have been added to the existing CLASH DB:

- 170 tests on vertical walls (Oumeraci et al., 2007);
- 56 tests on rubble mound with cobs (Besley et al., 1993);
- 75 tests on smooth structures with berms (private communication);
- 103 tests on harbour caissons (private communication);
- 249 tests on reshaping berm breakwaters (of which 30 from Lykke Andersen et al., 2008 and the remaining 219 from private communication);
- 366 tests on smooth steep slopes by Victor and Troch (2012);
- 671 tests on smooth slopes in combination with walls by Van Dorslaer et al., (2015).

This extended DB is part of a DB recently assembled to gather all the available data on wave overtopping, reflection and transmission (Zanuttigh et al., 2014).

The DB set-up follows the original CLASH DB, by adopting the same schematisation of the structures (see Fig. 1) and maintaining the same geometric and hydraulic parameters. In addition, the following parameters have been included.

- K_r and K_t where available,
- the average unit size D representative of the structure elements around the water level. It could be the D_{n50} for rock armour, D_n for concrete armour, but it could also be the height of a step of a staircase geometry.

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A new original procedure has been developed to evaluate few parameters (D, γ_f, $cot\,\alpha_{incl}$) in such a way to be consistent through the DB. D is calculated as the weighted average of the characteristic downslope D_d and upslope D_u sizes of the elements in the run-up/down area, i.e. within $\pm 1.5\ H_{m0,t}$ above and below the still water level, following the formula:

$$D=\frac{D_d\bullet(h_{sub}-h_b)+D_u\bullet(h_b+h_{em})}{h_{sub}+h_{em}},\qquad(1)$$

where $h_{sub}=\min(1.5\bullet H_{m0,t};h);h_{em}=\min(1.5\bullet H_{m0,t};A_c)$.

Consistently, also the roughness factor γ_f and the average slope $cot\,\alpha_{incl}$ that is the average slope in the run-up/down area are now respectively evaluated as

$$\gamma_f=\frac{\gamma_{fd}\bullet(h_{sub}-h_b)+\gamma_{fu}\bullet(h_b+h_{em})}{h_{sub}+h_{em}},\qquad(2)$$

$$\cot\alpha incl=\frac{\cot\alpha_d\bullet(h_{sub}-h_b)+B+\cot\alpha_u\bullet(h_b+h_{em})}{h_{sub}+h_{em}},\qquad(3)$$

Eq. (3) is valid for $|h_b|<1.5{\cdot}H_{m0t}$; otherwise $cot\,\alpha_{incl}= cot\alpha_d$ ($h_b>0$) or $cot\alpha_{incl}= cot\alpha_u$ ($h_b<0$).

The ANN tool that has been prepared and is going to be delivered through the website requires the users to enter –through an interface - the correct values of $cot\,\alpha_d$ and $cot\,\alpha_u$, D_d and D_u, of γ_{fd}, γ_{fu}, as well as the other input parameters for the ANN to be described in Section 3.