Applications of a neural network to predict wave overtopping at coastal structures

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Introduction

For design, safety assessment and rehabilitation of coastal structures reliable predictions of wave overtopping are required. Several design formulae exist for dikes, rubble mound breakwaters and vertical breakwaters. Nevertheless, often no suitable prediction methods are available for structures that do not resemble rather standard shapes. In the European research project CLASH a method is developed to provide a generic design tool to estimate wave overtopping discharges for a very wide range of coastal structures. The paper gives results from the CLASH project on this subject. It is focused on the extensive database gathered (see Verhaeghe et al., 2003), the neural network (see Pozueta et al., 2004) that has been developed on the basis of this database, and on applications of both.

Database

Significant effort has been made to generate a homogeneous database on wave overtopping consisting of more than 10,000 tests from more than 165 independent projects or test series, each described by means of 31 parameters (see Verhaeghe et al., 2003). All coastal structures, including dikes, rubble mound breakwaters, berm breakwaters, caisson structures and combinations have been considered and have been schematized by over 300,000 numbers in the database.

Within the framework of the CLASH-project specific tests on missing parameters and structures (white spots) have been performed, as well as prototype measurements and small scale simulation. The results of these tests have enlarged and homogenized the database. White spot tests concentrated on the roughness factor for all kind of armour units and on the influence of oblique wave attack. These tests were performed by the University of Edinburgh (UK) and Aalborg University (DK), respectively. Prototype measurements were performed at Zeebrugge (BE), Samphire Hoe (UK) and Ostia (IT). The small scale simulation tests were performed by most of the partners in CLASH. All these tests and additional tests from people and institutes outside CLASH enlarged the first database in 2003 (6300 tests) with almost another 4000 tests, (see Steendam et al., 2004). The database has been created in such a way that particular and confidential information on actual projects is not present. This creates the opportunity to finally release the database to all interested people.

This database has been created in several steps, see also (De Rouck et al., 2002). A summary is described below.

Gathering of data-sets

Visits were made to HR Wallingford, Delft Hydraulics and Italy (4 contributors) to gather all data available on wave overtopping. Other data were received from CLASH-partners and, more than expected, from other people from all over the world. This includes research work, but also tests on actual projects.

Screening of data

In a second phase, each particular dataset has been screened carefully for consistency. This has been done by analysing the original reports: not only information about the wave characteristics, the overtopping structure and corresponding overtopping was gathered, but also information concerning the test facility, the processing of the measurements and the precision of the work was searched for. Overtopping data were compared with existing formulae for dikes (TAW, 2002) and vertical structures (Franco et al., 1994 and Allsop et al., 1995) and judged for consistency and reliability. To account for the effect of reliability in the database, a 'reliability-factor' was defined for each test. Values from 1 to 4 can be assigned to this factor, standing for 'very reliable' up to 'not reliable'.

Determining all 31 parameters

Distinction can be made between hydraulic information (incident wave characteristics, measured overtopping volume), structural information (test section characteristics) and additional general information (reliability of the test, complexity of the structure). The method how to characterize or schematize almost every existing coastal structure by means of a certain number of parameters, was developed during the two years of work for the database. It is the first time that all kind of coastal structures can be simulated by only one limited set of parameters.

One of the main tasks for a user of the database or neural network will be to produce these structure parameters for the structure under consideration. The main structure parameters are given in Figure 1. In fact there are three groups of parameters:

- the main structure around swl (upper and down slope, $\cot\alpha_u$ and $\cot\alpha_d$, berm with width and level, B_h and h_b and roughness of the slope γ_f)
- the lower part of the structure (water depth at toe, h, toe width and toe level, B_t and h_t)
- the crest of the structure (crest freeboard R_c, armour freeboard, A_c and crest width G_c).

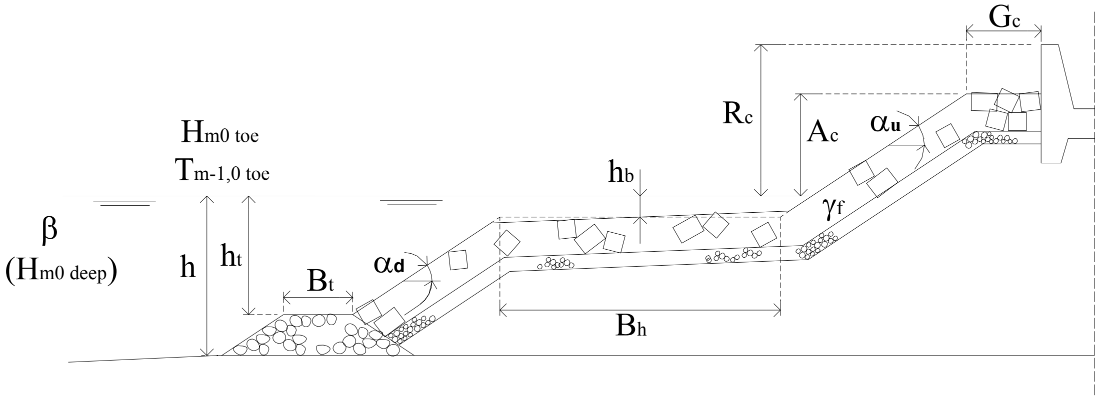


Figure 1: Most relevant structural parameters

Additional calculations were done to provide missing parameters. Missing shallow water conditions were calculated by SWAN (around 25% of all the tests). The method of Battjes and Groenendijk (2000) was used to calculate H_{m0} from $H_{1/3}$ at the toe of the structures. If required, factors were used for the ratio's between various wave period definitions like T_m, T_p and $T_{m-1,0}$.

Parameter analysis on the total database

All tests which gave overtopping (a fair number of tests gave "no overtopping") are gathered in Figure 2. The dimensionless discharge is given as a function of the dimensionless relative freeboard. This graph is only meant to give an idea of the contents of the database, it is up to the neural network to find relationships between the parameters in the database.

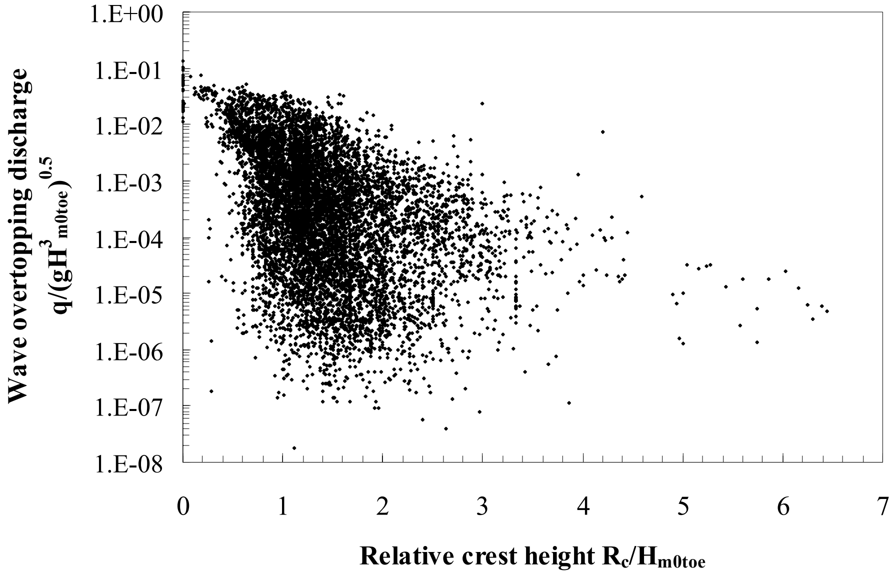


Figure 2. Dimensionless plot of all overtopping tests

A parameter analysis was performed on most of the parameters, in order to show the coverage of parameters available and to find errors in the database (outliers). Figure 3 shows the tests with oblique wave attack. Many extra tests with multi-directional waves, highlighted in the Figure, were performed within CLASH in order to give a good coverage of this parameter.

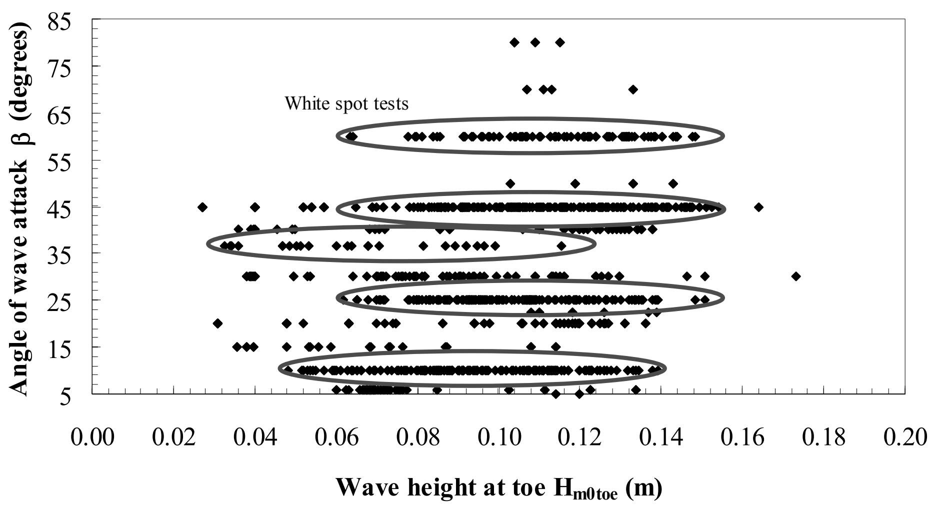


Figure 3. Tests with oblique wave attack and indication of white spot tests

Neural network modelling

Due to the rather large amount of parameters that affect wave overtopping at coastal structures it is difficult to describe the effects of all relevant parameters. For such processes in which the interrelationship of parameters is unclear while sufficient experimental data are available, Neural Network (hereafter "NN") modelling may be a suitable alternative. NN are data analyses or data driven modelling techniques commonly used in artificial intelligence. NN are often used as generalised regression techniques for the modelling of cause-effect relations. This technique has been successfully used in the past for solving difficult modelling problems in a variety of technical and scientific fields. Examples of NN modelling on coastal structures are: Mase *et al.* (1995) - stability analysis of rock slopes; Van Gent and Van den Boogaard (1998) - wave forces on vertical structures, including information on the reliability of each NN prediction; Medina *et al.* (1998, 1999, 2002) - wave run-up and wave overtopping predictions; and Panizzo *et al.* (2003) – wave transmission at low-crested structures. The approach followed in the NN developed within the CLASH project is focused on mean wave overtopping discharges at coastal structures and makes use of a much larger data set than those in the other mentioned studies. Hereafter a summary is given of this NN; a more detailed description can be found in Pozueta *et al.* (2004).

General

NN are organised in the form of layers and within each layer there are one or more processing elements called 'neurons'. The first layer is the input layer and the number of neurons in this layer is equal to the number of input parameters. The last layer is the output layer and the number of neurons in this layer is equal to the number of output parameters to be predicted. The layers in between the input and output layers are the hidden layers and consist of a number of neurons to be defined in the configuration of the NN. Each neuron in each layer receives information from the preceding layer through the connectivities, carries out some standard operations and produces an output. Each connectivity has a weight factor assigned, as a result of the calibration of the NN. The input of a neuron consists of a weighted sum of the outputs of the preceding layer; the output of a neuron is generated using a *linear activation function*. This procedure is followed for each neuron; the output neuron generates the final prediction of the NN.

The configuration of the NN model can vary. Figure 4 shows the NN configuration with 15 input parameters in the input layer (β, h, H_{m0toe}, $T_{m-1,0toe}$, h_t, B_t, γ_f, $cot\alpha_d$, $cot\alpha_u$, R_c, B, h_b, $tan\ \alpha_b$, A_c, G_c) and 1 output parameter in the output layer (i.e. mean overtopping discharge, q). This study was focused on a three-layered NN, were a configuration with one single hidden layer was chosen.

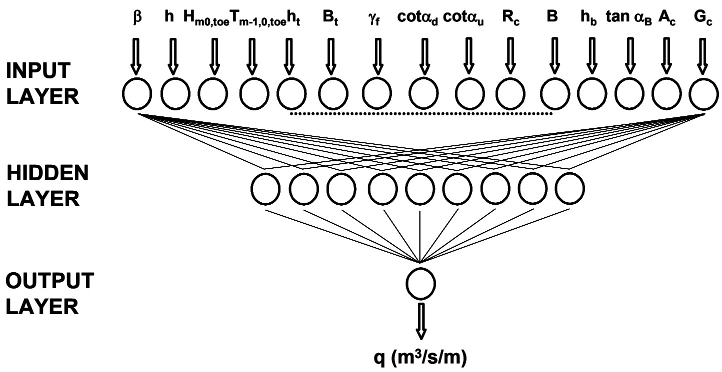


Figure 4. Configuration of a Neural Network.

Preparation of database used for NN

The quality of the NN depends highly on the quality of the database and erroneous data can severely degrade the performance of the NN. As a result, the initial database of more than 10,000 tests was reduced by eliminating the data that received the qualification 'non-reliable' tests (e.g. tests with a 'reliability factor' equal to 4, as defined in the previous section). Furthermore, only the tests related to overtopping events ($q \neq 0$ $m^3/s/m$) were considered in the NN. The resulting reduced database used for the NN modelling consisted of about 8,300 tests.

Since it was the aim of the NN to be applied both for small-scale and prototype situations, all the input and output parameters were scaled to $H_{m0,toe} = 1$ with Froude's similarity law. The advantage of using Froude's law, taking into account that the database was mainly based on small-scale tests, was that a better generalisation for large scale applications could be obtained. For user applications, the predicted wave overtopping discharge was then scaled to the original wave height using again Froude's similarity law.

Configuration of NN

The NN modelling technique was the Multi-layer feed-forward technique based on the standard error-backpropagation learning rule with a conjugate gradient algorithm. The configuration of the NN is performed in two phases, the *Training/Learning* phase and the *Testing/Validation* phase. The process of calibration or *training* phase of the NN involves the adjustment of its configuration based on the performance of standard operations that allows the NN to *learn* from the input-output relations for each of the parameters included in the tests selected as *training set*. Once trained, the correct performance of the resulting model is evaluated with a *testing set*, i.e. a set of input-output combinations completely new or unseen for the network. This step is called validation or *testing* phase of the NN. Further details on the NN configuration and the physics involved are described in Pozueta *et al.* (2004).

Uncertainty assessment

After obtaining the optimal NN configuration, predictions of mean overtopping discharges could be made; i.e. for a set of input parameters, a set of output parameters (overtopping discharge) could be obtained. Van Gent and Van den Boogaard (1998) developed a method to add information on the reliability of NN predictions. The method to add information on the *reliability* of NN-predictions has been developed further by Pozueta *et al.* (2004) and makes use of how the available data are spread over the entire domain of applications. Resampling techniques were used for this purpose. Resampling techniques are generic devices used for uncertainty analysis in statistics and model calibration. The use of these techniques involves the development of a set of NNs based on the original database. This implies firstly that the training and testing processes are redone many times solving the problem of representativeness of the training and testing sets; and secondly, that the set of NNs developed results in a set of predictions of overtopping discharge, allowing the estimation of the reliability of the predictions, i.e. standard deviation or 95 % confidence intervals. A set of about 500 NNs was performed.

As a result, the NN does not only give a prediction of the wave overtopping discharge but also a measure for the reliability of the prediction. For user applications, the results of the NN are given in the form of exceedance levels and can be used as first estimates in the conceptual design stage. In this respect, the NN can be viewed as a complementary tool in the design process for all those coastal structures for which no reliable prediction formula exists.

Applications of database

If a user has a specific structure, there is a possibility to look into the database and find more or less similar structures with measured overtopping discharges. This can simply be done by using filters in the Excel database. Every test of such a selection can then be considered in depth. Three examples are given here. Suppose one is interested in improvement of a *vertical wall with a large wave return wall*. The angle with the vertical should be larger than 45° ($\tan\alpha_u < -1$) and the wave return wall should at least be $0.5H_{m0}$ wide. This gives $-\cot\alpha_u * (A_c - h_b)/H_{m0} > 0.5$ and for the vertical wall $\cot\alpha_d = 0$. The database gives 93 tests from 3 independent test series. Figure 5 gives the data points with $q \neq 0$, together with the expression of Franco et al. (1994) for a vertical wall.

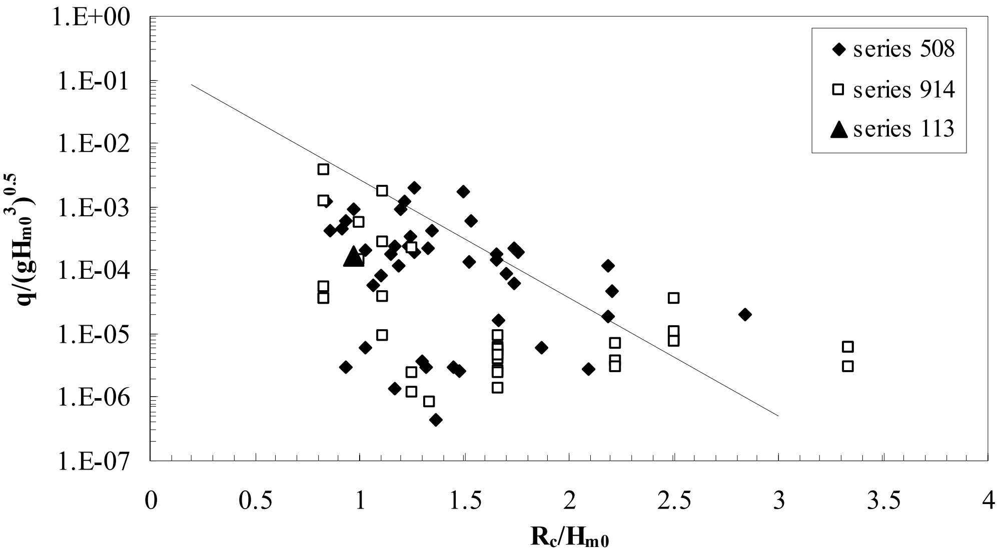


Figure 5 Overtopping for large wave return walls, compared with Franco et al. (1994) for vertical walls

There is a wide scatter in Figure 5. Many tests give very large reductions, see the lower left part of the figure. But there are also situations comparable or even worse than a simple vertical wall. A closer look into the data shows that almost horizontal wave return walls close to the still water level are not effective if the wave period is quite long. Probably the wave fills up the small area below the wave return wall and then just travels over the wall. It is clear that not all large wave return walls are effective.

A second example is the influence of a *wide crest on a rubble mound structure*. For example $\gamma_f < 0.6$ (rubble mound structure) and $G_c/H_{m0} > 5$. The database gives 84 tests in 17 independent test series. In 37 tests the overtopping $q = 0$, which means that a wide crest can be very effective. Figure 6 shows the data points with $q \neq 0$. There is a large scatter. The line in the figure gives a steep smooth structure (non-breaking or surging waves, see TAW (2002)). Many tests give a large reduction compared to the line. But a small part gives very large overtopping. A closer look reveals that all points around the line belong to a group where the wave height was only around 0.02 m and a wave period around 2 s. These small and long waves do hardly feel the porous armour crest and in many cases the crest freeboard is only 0.02 – 0.04 m, giving not very reliable tests. Also in this example a closer look is needed to explain the large scatter and find the conditions which differ in the selected data.

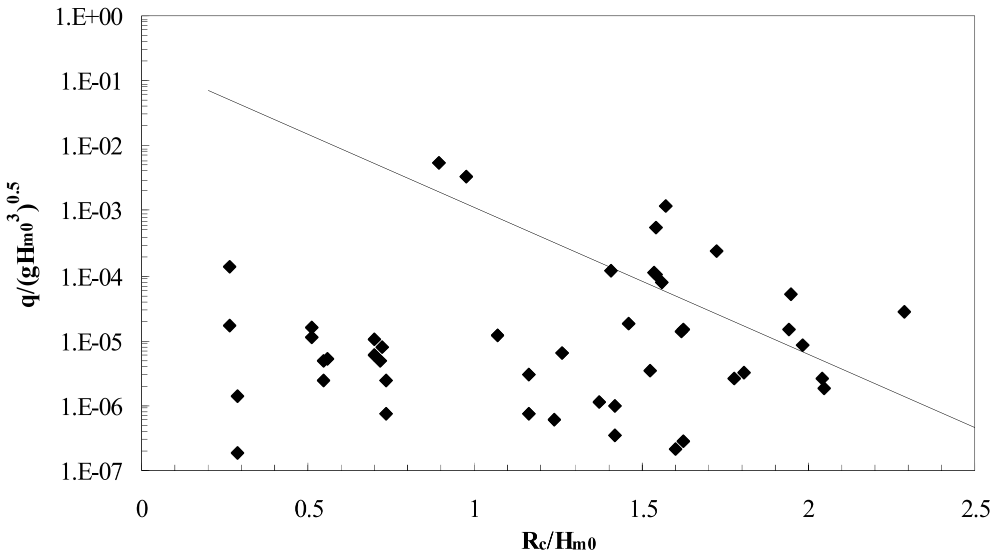


Figure 6 Rubble mound structures with a wide crest compared to smooth and steep slopes (TAW 2002)

As final example a *structure with a vertical wall and a large berm in front* with the crest of the berm above swl. As input for the database this gives: $\cot\alpha_d > 1$; $\cot\alpha_u = 0$; $B/H_{m0} > 3$; $h_b < 0$. In total 16 tests are found in 6 independent test series. From these 16 tests 11 give no overtopping, $q = 0$. Probably a berm above swl is quite effective for a vertical structure. The remaining data points with $q \neq 0$ are shown in Figure 7 and are compared with the prediction of Franco et al. (1994) for a vertical wall. The figure shows a reduction of one or two orders of magnitude compared to a simple vertical wall.

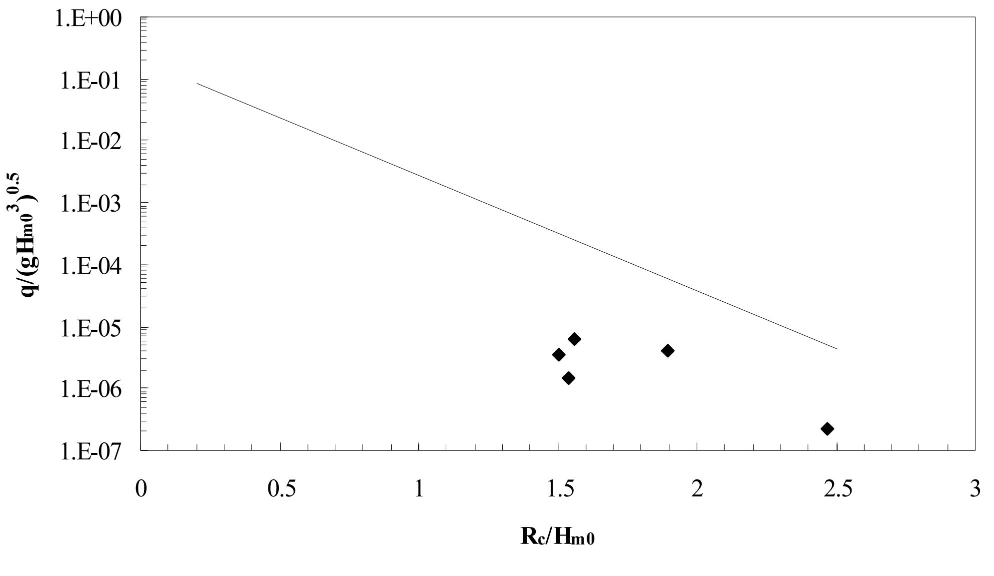
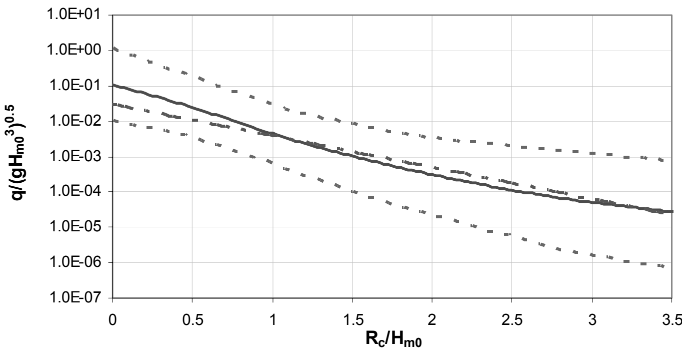


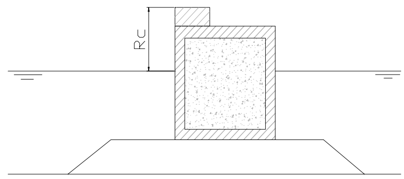
Figure 7 A vertical wall with a large berm in front with the crest above swl, compared to a simple vertical wall (Franco et al. (1994))

Applications of Neural Network

A sensitivity analysis can demonstrate the influence of the parameters on the outcome of the predictions by the NN, including the reliability. In the following, four examples of the application of the NN for different types of structures are given.

Figure 8 shows the influence of an increase of the relative crest freeboard on the predictions of overtopping discharge for a vertical structure. As expected, an increase of the relative crest freeboard results in a decrease of the wave overtopping discharge predicted by the NN model. The reliability of these predictions given by the 95% confidence band indicates a maximum of a factor of 10 difference. Additionally, the influence of the crest freeboard was also studied with the empirical formula proposed in Allsop *et al.* (1995). For structures with a low freeboard $R_c/H_{m0} < 1$, the dimensionless overtopping discharge predicted with the NN is slightly higher than that predicted by Allsop *et al.* (1995). For structures with relatively higher freeboard $1 < R_c/H_{m0} < 3$ (where the range covered by the empirical formula is $0.03 < R_c/H_{m0} < 3.2$), and therefore relatively lower overtopping discharges, the NN predictions of wave overtopping are very similar to those by Allsop *et al.* (1995).

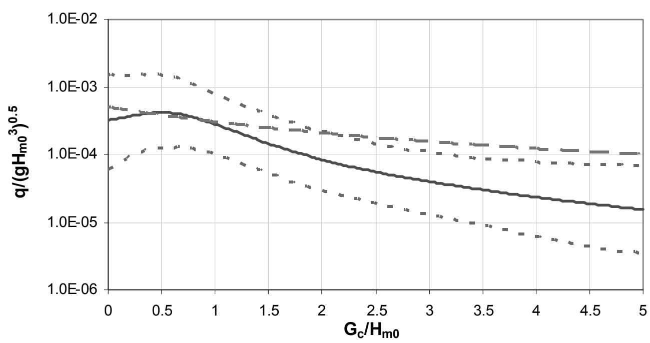


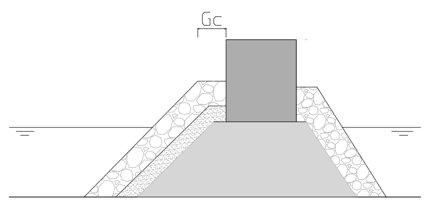


Example 1: Vertical structure

Figure 8 Sensitivity of wave overtopping to relative crest freeboard. Vertical structure
(—— NN predictions; ······ 95% confidence interval; – · · Allsop *et al.* 1995, predictions)

Figure 9 shows the influence of an increase of the relative armour width in front of the crest wall on the predictions of overtopping discharge for a conventional rubble mound structure. As expected, the general trend indicates a decrease of the dimensionless wave overtopping discharge predicted by the NN model with increasing armour crest widths. For structures with a crest wall directly next to the end of the armour slope ($G_c/H_{m0} = 0$) the overtopping discharge is similar as for structures with a relative armour width of $G_c/H_{m0} = 0.5$. The influence of the armour width was also studied with the TAW guidelines for the design of dikes (TAW, 2002). In general, for structures with relative armour widths $G_c/H_{m0} > 1$, the NN predictions are lower than those provided by the TAW guidelines.

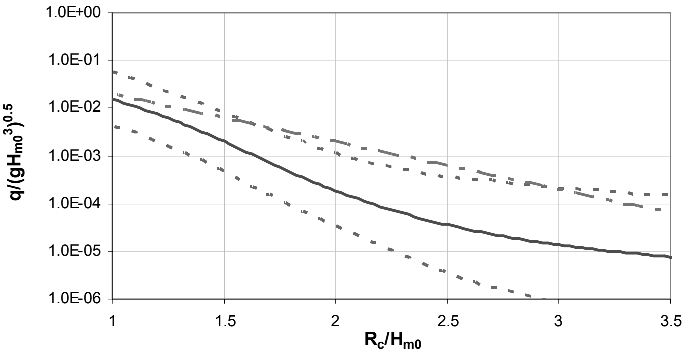


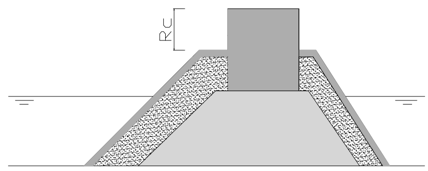


Example 2: Rubble-mound structure

Figure 9 Sensitivity of wave overtopping to relative armour width
(—— NN predictions; ······ 95% confidence interval; – · · TAW predictions)

Figure 10 shows the influence of an increase of the relative crest freeboard on the predictions of overtopping discharge for a smooth structure. In the same way as in Figure 8, an increase on the relative crest freeboard results in a decrease of the dimensionless wave overtopping discharge predicted by the NN model. The influence of the relative crest freeboard was also studied with the TAW guidelines for the design of dikes (TAW, 2002). For structures with a relative crest freeboard of $R_c/H_{m0} \sim 1$, the NN predictions are similar to those provided by the TAW guidelines. For structures with a relatively high crest freeboard $R_c/H_{m0} > 1$, the NN predictions are lower than those provided by the TAW guidelines.

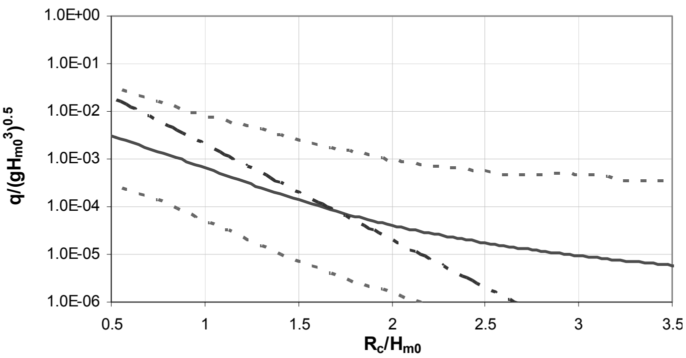


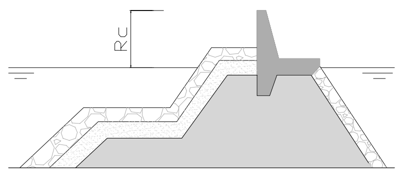


Example 3: Smooth structure

Figure 10 Sensitivity of wave overtopping to relative crest freeboard
(—— NN predictions; ······ 95% confidence interval; — · · TAW predictions)

Finally, Figure 11 shows the influence of an increase of the relative crest freeboard on the predictions of overtopping discharge for a rubble-mound structure with a berm and a crest element. The influence of the relative crest freeboard was also studied with the TAW guidelines for the design of dikes (TAW, 2002) and the influence of a berm.





Example 4: Rubble-mound structure with berm

Figure 11 Sensitivity of wave overtopping to relative crest freeboard
(—— NN predictions; ······ 95% confidence interval; — · · TAW predictions)

These examples demonstrate that the NN is capable to detect from the data-set the influence of particular parameters for a wide range of structure types, together with an indication of the reliability of the NN-predictions.

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REFERENCES

Allsop, N.W.H., P. Besley and L. Madurini (1995). *Overtopping performance of vertical and composite breakwaters, seawalls and low reflection alternatives*. Paper 4.6 in Final Proceedings of MCS-project, MAS2-CT92-0047.

Battjes, J.A. and H.W. Groenendijk (2000). *Wave height distributions on shallow foreshores*. Coastal Engineering 40, p161-182

De Rouck, J., J.W. van der Meer, N.W.H. Allsop, L. Franco and H. Verhaeghe (2002). *Wave overtopping at coastal structures: development of a database towards up-graded prediction methods.* Proc. ASCE, 28th ICCE, Cardiff, UK, pp. 2140-2152.

Franco L., de Gerloni M. and Van der Meer J.W. (1994). *Wave overtopping on vertical and composite breakwaters.* ASCE, proc. 24th ICCE, Kobe, Japan, pp. 1030-1045.

Mase, H., M. Sakamoto and T. Sakai (1995), *Neural network for stability analysis of rubble-mound breakwaters*, J. of Waterway, Port, Coastal and Ocean Engrg, ASCE, nov/dec 1995, pp. 294-299.

Medina, J.R, J.A. González-Escrivá, J. Garrido and J. De Rouck (2002), *Overtopping analysis using neural networks*, ASCE, Proc. ICCE 2002.

Panizzo, A., R. Briganti, J.W. van der Meer and L. Franco (2003), *Analysis of wave transmission behind low-crested structures using neural networks,* ASCE, Proc. Coastal Structures 2003, Portland.

Pozueta, B., M.R.A. van Gent, H.F.P. van den Boogaard and J.R. Medina (2004), *Neural network modelling of wave overtopping at coastal structures.* Proc. ASCE, 29th ICCE, Lisbon, Portugal.

Steendam, G.J., J.W. van der Meer, H. Verhaeghe, P. Besley, L. Franco and M.R.A. van Gent (2004). The international database on wave overtopping. Proc. ASCE, 29th ICCE, Lisbon, Portugal.

TAW (2002). *Technisch rapport golfoploop en golfoverslag bij dijken* (Technical report on wave run-up and wave overtopping at dikes - in Dutch). Technical Advisory Committee on Water Defences.

Van Gent, M.R.A and H.F.P. van den Boogaard (1998), *Neural network modelling of forces on vertical structures*, ASCE, Proc. ICCE 1998, Vol. 2, pp. 2096-2109.

Verhaeghe, H., J.W. van der Meer, G.-J. Steendam, P. Besley, L. Franco and M.R.A. van Gent (2003), *Wave overtopping database as the starting point for a neural network prediction method,* ASCE, Proc. Coastal Structures 2003, Portland.