MATHEMATICAL MODELLING OF WAVE OVERTOPPING AT COMPLEX STRUCTURES: VALIDATION AND COMPARISON

Cordula Berkenbrink, Ralf Kaiser and Hanz D. Niemeyer¹

A validation study for a mathematical model called OTT-1d from HR-Wallingford modified by the Coastal research Station is presented in this paper. The model is based on the one-dimensional nonlinear shallow water equations (NLSWE) on a sloping bed describing the horizontal mass and momentum balance. Demonstrating for several wave flume test data OTT-1d can be verified as a reliable tool for predicting the mean overtopping discharge at simple an complex geometries. Furthermore a comparison of the modelling results to actual used calculation methods is done to show the limits of each calculation methods relating to the complexity of the structure.

Keywords: wave overtopping; complex structures; mathematical modelling; NLSWE; model verification

INTRODUCTION

Wave Overtopping is an important design criteria for coastal structures. Water overtopping a dyke during a storm is the most common indicator for dyke failure at the German coast in the past. Against this background it is important to predict reliable results for this hydrodynamic load to make coastal structures more safety in consideration of see level rise and higher storm intensity. At present the prediction of overtopping discharge is calculated by empirical formulas, which are limited to definite structures and wave conditions. They are found by hydraulic tests for defined wave and structure parameters. For geometries or wave conditions not tested, these methods are not be valid and an underestimation cannot be excluded. Mathematical models are able to simulate wave overtopping more precisely than empirical formulas can do, because the detailed geometry of the structure and the whole spectrum of the wave field can be considered and easily changed.

DESCRIPTION AND MODIFICATION OF THE MATHEMATICAL MODEL

The mathematical model applied here is called OTT-1d from HR Wallingford (Dodd et al., 1998), which is part of the group ANEMONE (Advanced Non-linear Engineering Models for the Nearshore Environment). It bases on the nonlinear shallow water (NLSW) equations, which describe the horizon-tal mass and momentum balance. They are solved explicitly by the finite volume method. The advantage of the model OTT-1d in contrast to other similar NLSWE-Models is the use of the Godunov-type scheme. Water volumes can be treated equally in each computational node; that allows the calculation of separated water volumes. The regeneration of waves by overtopping volumes in lee of the structure can also be modelled. The wave breaking is implicitly included by building a bore. The numerical waves steepens and form shocks, with a vertical face. OTT-1d has very robust numerical solvers, it runs efficiently and stabile. The input parameters are reduced to a minimum.

Some modifications were necessary for using the model for complex or real scale structures (Berkenbrink et al. 2009). In a first step the input and output parameters and the model domain were increased. Further the still water level at the inner slope was reprogrammed to make calculating of hydrodynamic loads at the inner slope possible. Finally the modified model is able to build up different roughness sections in the model domain. Previously the roughness factor was assumed to be constant over the whole dyke, resulting in the inability to model complex revetments. The verification of the correctness of all those modifications has been done by the output signals at the crest.

DATA SET

First validation tests were done with large scale data sets from the large wave flume in Hanover. The test dyke had a simple geometry with a 1:6 seaward slope and a 1:3 landward slope (Oumeraci et al., 2001). The crest was 2 m wide and 6 m high. For sensitivity studies small scale tests from Hanover to investigate the diffusion of overtopping discharge in hydraulic models (Kanis, 2008) were reproduced with OTT-1d to compare the diffusion of hydraulic and modelled results.

For complex geometries several small scale tests from the Leichtweiss Institute at Brunswick University (Kortenhaus et al. 2004, Oumeraci and Kortenhaus 2007) and a large scale test from the Large

¹ Coastal Research Station, Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency, An der Mühle 5, 26548 Norderney, Germany

wave flume in Hanover (Oumeraci et al. 2000) were available. The geometries have different slopes, vertical walls, bermes and a s-profile (Fig. 1); the large scale tests also have different roughness sections.



Figure 1. Example for a complex geometry (Norderney Island - Westside - German Coast)

VALIDATION PROCEDURE

The first thing to do for validation is to model all available data sets from hydraulic test with OTT-1d and compare the results to the measured wave overtopping. The comparison of measured and calculated data is done in scatter plots with the measured values on the x-axis and the calculated values on the y-axis. The mark for quality is the distribution around the reference line, where in theory the measured and calculated values are exact the same. This parameter is called S_{rl} .

The same is done for other calculation methods for mean overtopping discharge. The first method chosen here is an empirical equation founding by the respective hydraulic tests. The other methods belongs to the European assessment manual (Pullen et al., 2007). There is a calculation tool based on the empirical equations of the manual called PC-Overtopping and an artificial neural network called NN_Overtopping. The network is validated by the CLASH-Database which contains a large amount of data for wave overtopping for several types of structures and wave parameters.

RESULTS

Simple Geometries

Exemplary for simple geometries the results for the large scale tests will present here. The test dyke with the 1:6 seaward slope was build of concrete with a constant roughness. A lot of different wave heights and wave periods were tested with different kind of spectra. At the toe of the structure a wave gauge was installed, which is used as the seaward boundary for the mathematical model. The results for 46 tests with natural spectra presented in Fig. 2 show a good agreement between measured and calculated values.



Figure 2. Comparison of measured calculated overtopping discharge for a simple geometry (OTT-1d)

OTT-1d can reproduce the wave overtopping discharge for simple geometries with a low distribution around the reference line. There a two outliers identifiable marked in Fig. 2, these are the tests with the highest wave period ($T_{m-1,0} = 9,22$ s resp. 13,33 s). There is some research for validating large wave periods necessary for what more wave flume tests must build up. Without these two tests the distribution factor increases up to 86 %.

The empirical equation founded by the belonging tests bases on the often used exponential function:

$$\mathbf{Q}_* = \mathbf{Q}_0 \exp\left(-\mathbf{b} \cdot \mathbf{R}_*\right) \tag{1}$$

Within these equations R_* and Q_* are dimensionless factors describing the overtopping discharge and the freebord. Q_0 and b are empirical factors fitting by regression analyses on the belonging hydraulic tests. The comparison of the measured and calculated values shows an great underestimation especially for the higher wave overtopping rates (Fig. 3) what results in a low distribution factor $S_{rl.}$ The same outliers like before can be seen in the diagram. The empirical calculation leads in a large overestimation for long wave periods, because the wave period is a multiplier in this equation, what results in very high overtopping discharges for long wave periods.



Figure 3. Comparison of measured and calculated overtopping discharge for a simple geometry (empirical equation)

The next calculation tool is PC-Overtopping which is used in the Netherlands for calculating wave overtopping. It bases on the equations of the European assessment manual (Pullen et al., 2007). This can be seen in Fig. 4 where both methods are printed together and the results are exactly the same. For simple geometries PC-Overtopping presents a sufficient result with a low distribution around the reference line. The tool is simple in using and therefore quite useful for a rough estimation. The calculation of overtopping discharge from the manual contains two equation (Eq. 2 and 3). The basis is also the exponential function with the dimensionless factors describing overtopping discharge an freebord (Eq. 1). Additionally there are empirical parameters including oblique wave attack (γ_{β}), berms (γ_{b}), different roughness sections (γ_{f}) and wave walls (γ_{v}) not in using for this simple structure.

$$q = \frac{0.067\sqrt{g H_{m0}^{3}}}{\sqrt{\tan \alpha}} \cdot \gamma_{b} \cdot \xi_{m-1,0} \cdot \exp\left(-4.75 \frac{R_{c}}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_{b} \cdot \gamma_{f} \cdot \gamma_{\beta} \cdot \gamma_{\nu}}\right) (2)$$

$$q_{max} = 0.2 \cdot \sqrt{g H_{m0}^{3}} \exp\left(-2.6 \frac{R_{c}}{H_{m0} \cdot \gamma_{f} \cdot \gamma_{\beta}}\right) (3)$$

Eq. 3 is a limiter for the general Eq. 2. There are less factors for the structure and the breaker parameter with consider the wave period is not included. That is the reason for the position of the outliers you

seen by the calculation methods before. With this method an overestimation caused by long wave periods are not possible on the contrary there is a big underestimation for one of the values.



Figure 4. Comparison of measured and calculated overtopping discharge for a simple geometry (PC-Overtopping)

The last calculation method presented here is the artificial neural network NN_Overtopping. It was trained by the CLASH database, which is a very large database including a lot of different types of structure and sea parameters. Neural networks are very sensitive in use, if you try to calculate an object, the network didn't learn, it can fail without giving a notice. For this kind of geometry NN_Overtopping shows a good agreement between measured and calculated data (Fig. 5). The data points are near to the reference line with a low distribution. It should be said, that the two tests with the long wave period are not calculated, the neural network gives an error notice for this two tests.



Figure 5. Comparison of measured and calculated overtopping discharge for a simple geometry (NN_Over-topping)

Complex Geometries

Exemplary for complex geometries the results for the small scale test at the Leichtweiß Institute of Brunswick are shown here. The revetment of the west side of Norderney island at the German coast was build up in the wave flume and tested for different kind of wave spectra. The geometry starts with a wall and 1:15 toe protection. A s-profile with a berm follows. The berm varies from 4.8 m up to 7.8 m (nature scale). Finally there is a wall at the crest also with different heights (Fig. 6). That results in three geometries for which the results are shown separately. The tested revetment is completely build of con-



crete. At the toe of the structure a wave gauge was installed, which is used as the seaward boundary for the mathematical model.

Figure 6. Complex geometry: revetment at the west side of Norderney island - German coast (Kortenhaus et al. 2004)

The results for the mathematical model are presented in Fig. 7. It can be seen that OTT-1d can predict overtopping discharge reliable without any additional calibration. There is a low overestimation, so the distribution factor for one structure is a quite low, but this is not an uneconomic overestimation.



Figure 7. Comparison of measured and calculated overtopping discharge for a complex geometry (OTT-1d)

The empirical equation fitted by the belonging test shows the best results (Fig. 8). All data points are near to the reference line. The equation is based on the exponential function (Eq. 1) without any additional factors. It's a very simple function for such a complex geometry; there is no parameter for the berm, the wall or even an equivalent slope (Eq. 4).

$$q = 0,0081 \cdot g \cdot H_{m0} \cdot T_{m-1,0} \cdot e^{\left(-45,447 \frac{R_c}{T_{m-1,0}\sqrt{g \cdot H_{m0}}}\right)}$$
(4)

That this equation is not universal can bee seen in Fig. 9. The formula is tested on a similar geometry on the north side of Norderney island, which was tested in the Large Wave Flume in Hanover. The structure also has the toe protection, the s-profile and the berm (Fig. 6), but it doesn't finish with a wall but with a slope with roughness elements. The equation doesn't recognize the difference in the geometry that's why it fails. There is a high distribution and an uneconomical overestimation of the measured values.



Figure 8. Comparison of measured and calculated overtopping discharge for a complex geometry (empirical equation)



Figure 9. Application of the empirical equation to a similar complex geometry

For using the calculation tool PC-Overtopping some simplifications of the geometry must be done. It's not possible to enter slopes steeper 1:1 and how the program simplify the s-profile can't be reconstruct. Nevertheless the profile is to complex for a reliable prediction of overtopping discharge with the equations from the European assessment manual (Pullen et al. 2007). The distribution around the reference line especially for one type of structure is very high (Fig. 10). For the profile with the wide berm and the low wall PC-Overtopping shows sufficient results, but the overestimation for the other profiles is serious. There is no constancy in the results, it can't be said that the program works better for lower overtopping discharges or smaller profiles.



Figure 10. Comparison of measured and calculated overtopping discharge for a complex geometry (PC-Overtopping)

The artificial neural network must be use carefully. The network is not trained for these complex structures. In the User manual (Coeveld et al. 2005) and on the associated website (http://www.overtopping-manual.com/calculation_tool.html) a lot of predictable structures are printed but a structure with an s-profile is not included. There is a similar one (Fig. 11) with horizontal berms but a slope instead of the s-profile. The results show a not expected very big underestimation (Fig. 12), the neural network fails.



Figure 11. Scheme of real geometry compared to available profile verified in the neural network



Figure 12. Comparison of measured and calculated overtopping discharge for a complex geometry (NN_Overtopping)

Finally a second structure is chosen demonstrating the reliable work of OTT-1d. Small scale tests were done for the revetment on the island Baltrum at the German coast. The structure also have the for the east Frisian islands typical s-profile, but with two berms and two walls afterwards (Fig. 13). For the hydraulic tests it is completely build of concrete.



Figure 13. Complex geometry: revetment at Baltrum island - German coast (Oumeraci and Kortenhaus, 2007)

There is no wave gauge installed in front of the toe which is need as the seaward boundary for OTT-1d. But the spectrum near to the toe is known and can easily be used in the model. Two spectra were tested for different water levels: spectrum 1 with $H_{m0} = 0.137$ m and $T_{m-1,0} = 2.28$ s and spectrum 2 with $H_{m0} = 0.236$ m and $T_{m-1,0} = 2.86$ s. For these spectra several time series were generated in the hydraulic wave flume as well as in the mathematical one. That results in various time series with different overtopping discharges, therefore it is not possible to compare measured and calculated results directly, in a scatter plot. But the measured and calculated overtopping discharges for each spectrum related to the water level must be in the same range. The modeled results are in the same range like the measured ones (Fig. 14 and Fig. 15), especially for the higher overtopping rates there is a good agreement. For PC-Overtopping and NN-Overtopping there is no range of datasets, because it works with the wave parameters H_{m0} and $T_{m-1,0}$ and not with wave signals. Nevertheless both calculation methods fail. PC-Overtopping shows a big overestimation while NN-Overtopping doing the opposite. The failure is in the same range you see before for the hydraulic tests from Norderney.



Figure 14. Comparison of measured and calculated overtopping discharge for spectrum 1



Figure 15. Comparison of measured and calculated overtopping discharge for spectrum 2

SUMMARY AND CONCLUSIONS

A reliable tool for calculating overtopping discharge is presented. The mathematical model OTT-1d from HR-Wallingford modified by the Coastal Research Station based on the NLSW-Equations, it is fast and stable in calculating and easy to handle.

Representative for several validation tests the results for three types of geometries were shown starting with a simple geometry with a constant slope up to a very complex one with berms, walls and a sprofile, which is a typical part of the revetments on the East Frisian islands. Scatter Plots with calculated values depending on the measured ones were chosen for illustrating the agreement. The same was done for several actually used calculation methods summarized in the European assessment manual (Pullen et al. 2007) and for the empirical equation founded by the belonging tests.

The comparison of the different calculation methods emphasises the advantages of the mathematical model especially for calculating the mean overtopping discharge for complex geometries. The empirical equations founded by the belonging tests are sometimes very well fitted, but it is not possible to use them for other geometries or wave parameters they are not verified for. The European assessment manual gives more general calculation tools. There is PC-Overtopping which is based on the empirical equations printed in the manual and NN_Overtopping, an artificial neural network trained with the CLASH-Database. PC-Overtopping is a user friendly tool available in the internet, but this paper demonstrates the limits. For complex geometries it tends to uneconomic overestimations. For a rough estimation of the mean overtopping discharge on simple geometries. It is well trained on these kind of structures and the quality of the results is similar to the modelling results. But it cannot be used for geometries which are not illustrated on the website, the underestimation is serious.

The validation of the mathematical model generated a universal calibration equation, which gave reliable results for every type of geometry and wave condition tested in the context of the project "Integrated Design of Sea- and Estuarine Dykes". It can be said that OTT-1d is a universal and reliable calculation tool for simple and complex structures for mean overtopping discharge. It is simple in application and fast in calculation, so it can be used routinely for the design of coastal structures.

ACKNOWLEDGMENTS

The work presented here is part of the research project "Integrated Design of Sea- and Estuarine Dykes" (INTBEM) within the framework of the programme of the German Committee on Coastal Engineering Research (KFKI) and sponsored by the German Federal Ministry of Education and Research (BMBF) – project code: 03 KIS 061/062. We thank the German Committee on Coastal Engineering Research for sponsoring a part of the conference participation. Finally we thank HR Wallingford and especially Nick Dodd for developing such a well working model.

REFERENCES

- Berkenbrink, C., R. Kaiser and H.D. Niemeyer. 2009: Prototype Overtopping Measurements and Model Verification. *Proceedings of 31st International Conference on Coastal Engineering*, 3009–3019.
- Coeveld, E.M., M.R.A. van Gent and B. Pozueta. 2005. Manual NN_Overtopping 2 Clash: Workpackage 8. Report, WL | Delft Hydraulics
- Dodd, N. 1998. Numerical model of wave run-up, overtopping and regeneration. ASCE J. Water-Ways, Port, *Coastal and Ocean Eng. Div.*, Vol. 124, Ww2, New York.
- Dodd, N., C.C. Giarrusso and S. Nakamura. 1998. ANEMONE: OTT-1d A User Manual Report TR 50 HR Wallingford.
- Kanis, J. 2008. Über die Streuung von mittleren Überlaufmengen in hydraulischen Modellversuchen von Seedeichen. Diploma thesis. Franzius Institute of Hydraulics, Waterways and Coastal Engineering, Hanover.
- Kortenhaus, A., M. Brühl and F. Brinkmann. 2004. Theoretische und versuchstechnische Bearbeitung der Wellenüberlauf- und Belastungssituation der Strandmauer am Weststrand von Norderney. Leichtweiss Institute for Hydraulic Engineering, Brunswick.
- Oumeraci, H. and A. Kortenhaus. 2007. Theoretische und versuchstechnische Bearbeitung des Wellenüberlaufs und der Wellenbelastung des Deckwerks auf Baltrum (Abschlussbericht), LWI-Report No. 953, Brunswick.
- Oumeraci, H., H. Schüttrumpf, A. Kortenhaus, M. Kudella, J. Möller and M. Muttray. 2000. Untersuchungen zur Erweiterung bzw. Umbau des Deckwerks am Nordstrand von Norderney (Abschlussbericht), LWI-Report No. 853, Brunswick.
- Oumeraci, H., H. Schüttrumpf, J. Möller and M. Kudella. 2001. Loading of the Inner Slope of Seadykes by Wave Overtopping Results from Large Scale Model Tests, LWI-Report No. 858, Brunswick.
- Pullen, T., N.W.H. Allsop, T. Bruce, A. Kortenhaus, H. Schüttrumpf and J.W. van der Meer. 2007. EurOtop – Wave Overtopping of Sea Defences and Related Structures: Assessment Manual, Die Küste – Heft 73.