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EurOtop – overtopping and methods for assessing discharge

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ABSTRACT: This paper will describe the new Wave Overtopping Manual (EurOtop, Pullen et al., 2007) developed for EA/Defra, Rijkswaterstaat in the Netherlands and the German Coastal Engineering Research Council (KFKI). The new manual extends and updates the EA's Overtopping Manual (W178) (Besley, 1999), the Netherlands TAW manual (Van der Meer, 2002), and the German Die Küste (EAK, 2002). Considerable research since those publications prompted the production of an updated and extended manual combining European expertise. Research for Defra and the Environment Agency, by HR Wallingford, has provided techniques for predicting the overtopping discharges and consequent flood volumes for a range of seawall types. In the Netherlands and Germany there has been continuous research into overtopping at embankments and dikes, and the European research project CLASH (de Rouck et al. 2005) has expanded understanding of overtopping and scale effects.

1 INTRODUCTION

1.1 *Wave overtopping*

Wave overtopping has always been of principal concern for coastal structures constructed to defend against flooding: often termed sea defences. Similar structures may also be used to provide protection against coastal erosion: sometimes termed coast protection. Other structures may be built to protect areas of water for ship navigation or mooring within ports, harbours or marinas; often formed by breakwaters or moles. Within harbours, or along shorelines, reclaimed areas must be defended against both erosion and flooding. Some structures may be detached from the shoreline, often termed offshore, nearshore or detached, but most structures used for sea defence or similar function form a part of the shoreline.

Sloping dikes have been widely used for sea defences along the coasts of the Netherlands, Denmark, Germany, UK. Dikes or embankment seawalls are also used to defend low-lying areas in the Far East, including China, Korea and Vietnam. Historically, dikes or embankment seawalls were built along many North Sea coastlines, sometimes subsuming an original sand dune line, protecting the land behind from flooding, and sometimes providing additional amenity value. Similar structures have been formed by clay materials or even from a vegetated shingle ridge, in both instances allowing the side slopes to be steeper. All such embankments need some degree of protection against direct wave erosion, often using a revetment facing on the seaward side. Revetment facing may take many forms, but may commonly include closely-fitted concrete blockwork, cast in-situ concrete slabs, or asphaltic materials. Embankment or dike structures are generally most common along rural frontages.

A second type of coastal structure consists of a mound or layers of quarried rock fill, protected by rock or concrete armour units. The outer armour layer is designed to resist wave action without significant displacement of armour units. Under-layers of quarry or crushed rock support the armour and separate it from finer material in the embankment or mound. These porous and sloping layers dissipate a proportion of the incident wave energy in breaking and friction. Simplified forms of rubble mounds may be used for rubble seawalls or protection to vertical walls or revetments. Rubble mound revetments may also be used to protect embankments formed from relict sand dunes or shingle ridges. Rubble mound structures tend to be more common in areas where harder rock is available.

Along urban frontages, especially close to ports, erosion or flooding defence structures may include vertical, battered or steep walls. Such walls may be composed of stone or concrete blocks, mass concrete, or sheet steel piles. Typical vertical seawall structures may also act as retaining walls to material behind. Shaped and recurved wave return walls may be formed as walls in their own right, or smaller versions may be included in sloping structures. Some coastal structures are relatively impermeable to wave action. These include seawalls formed from blockwork or mass concrete, with vertical, near vertical, or steeply sloping faces. Such structures may be liable to intense local wave impact pressures, may overtop suddenly and severely, and will reflect much of the incident wave energy. Reflected waves cause additional wave disturbance and/or may initiate or accelerate local bed scour.

It is worth noting that developments along waterfronts are highly valued with purchase or rental prices substantially above those for properties not on the waterfront. Yet direct (or indirect) effects of wave overtopping have the potential to generate significant hazards to such developments and their users. Residential and commercial properties along a waterfront will often be used by people who may be unaware of the possibility, of the severity, or of the effects of wave overtopping in storm conditions. Regulatory authorities may therefore wish to impose onerous flood defence requirements on new developments. For instance, protection against flooding (including wave overtopping) for any new developments in UK is now required to the 0.5% annual probability, equivalent to 1:200 year return. Exposure to overtopping of many coastal sites will however be influenced by climate change, probably increasing wave heights and periods as well as sea level rise.

1.2 *Predicting wave overtopping*

A number of different methods may be available to predict overtopping of particular simplified sections of structures under given wave conditions and water levels. Each method will have strengths or weaknesses in different circumstances. In theory, an analytical method can be used to relate the hydrodynamics to the structure response through equations based directly on a knowledge of the physics of the process. It is however unusual for the structure, the waves and the overtopping processes to be simple enough to be described by analytical methods. Analytical methods are not therefore discussed further here.

The primary prediction methods are therefore based on empirical methods that relate the overtopping response to the main hydraulic and geometric parameters. These are by far the most commonly used methods for predicting overtopping. Two other methods have been derived during the CLASH European project based on the use of measured overtopping from model tests and field measurements. The first of these techniques uses the CLASH database of structures, waves and overtopping discharges, with each test described by 31 parameters. Use of the database complex, and considerable knowledge of the structure types and overtopping in general is normally required to use it. A simpler approach is the use of Neural Network tools trained using the test results in the database (Kingston et al, 2008). The Neural Network tool can be run automatically on a computer as a stand-alone device, or embedded within other simulation methods.

For situations for which empirical test data do not already exist, or where the methods above do not give reliable enough results, then two alternative methods may be used. A range of numerical models can be used to simulate the process of overtopping. Shallow water equation models, SPH and VOF models can all to this with varying degrees of accuracy and complexity. But generally they required advanced knowledge to use and are limited by computational constraints, and so will not be discussed further.

The final method is physical modelling, in which a scale model is tested with correctly scaled wave conditions. Typically such models may be built to a geometric scale typically in the range 1:10 to 1:5, and waves will be generated as random wave trains each conforming to a particular sea state. The model may represent a structure cross-section in a 2D wave flume, or a more complex a 3D wave basin model. Physical models can be used to measure many different aspects of overtopping such as wave-by-wave volumes, overtopping velocities and depths, as well as other responses.

1.3 *Performance requirements*

Most sea defence structures are constructed primarily to limit overtopping volumes that might cause flooding, damage or danger beyond the crest. For defences that protect people or property, designers and owners of these defences must deal with potential direct hazards from overtopping. This requires that the level of hazard and its probability of occurrence be assessed, allowing appropriate action plans to be devised to reduce risks arising from overtopping. This is discussed elsewhere in these proceedings by Allsop et al, 2008.

2 OUTLINE OF EMPIRICAL OVERTOPPING

2.1 *Mean overtopping discharge*

Empirical methods use a simplified representation of the physics of the process, usually presented in the form of dimensionless equations, to relate the mean overtopping discharge to key hydraulic and geometric parameters. The form and coefficients of the equations are adjusted to reproduce results from physical model and/or field measurements of waves and overtopping. Empirical equations may be solved explicitly, or may occasionally require iterative methods to solve.

The mean overtopping discharge, q, is the main parameter in the overtopping process. The overtopping discharge is generally calculated in m^3/s per m width, but in practical applications it may be quoted as litres/s per m width (l/s/m). It is of course not the only measure of overtopping, but it is relatively easy to measure in a laboratory wave flume or basin, and most other parameters are related in some way to the overtopping discharge by the dimensionless equations. Although it is given as a discharge, it is usually very far from a steady discharge as the actual processes of wave overtopping are much more dynamic. For most defences, only large waves will reach the crest of the structure and will overtop, but they may do so with a lot of water in a few seconds. The individual volumes in wave-by-wave overtopping are more difficult to measure in a laboratory than the mean discharge, so data on wave-by-wave volumes are much rarer.

As mean overtopping discharges are relatively easy to measure, many physical model tests have been performed all over the world, both for idealised structures and real applications or designs. The European CLASH project collected a large database worldwide with more than 10,000 wave overtopping test results on all kind of structures. Many of these tests have been used to develop empirical methods for prediction of overtopping. Such empirical methods or formulae are however only directly applicable to idealized structures, like smooth slopes (dikes, sloping seawalls), simple rubble mound structures or vertical structures (caissons) or walls, and may require extrapolation when applied to many existing structures.

2.2 *The basic method*

There is not the space here to go into any detail on the various methods and when they should be applied. We therefore give an overview of what is possible and direct the reader to the manual itself the EurOtop Overtopping Manual (Pullen *et al.,* 2007). Here an overall view is given to compare performance of different structure types and to give insight into how wave overtopping behaves for different structures. Those structures considered here are: smooth sloping structures (dikes, seawalls); rubble mound structures (breakwaters, rock armoured slopes); and vertical structures (caissons, sheet pile walls).

The principal prediction formula for many types of wave overtopping is:

$$\frac{q}{\sqrt{gH_{m0}^3}} = a\exp(-bR_c / H_{m0}) \tag{1}$$

It is an exponential function with the dimensionless overtopping discharge $q/(gH_{m0}{}^3)^{½}$ and the relative crest freeboard R_c/H_{m0}. This type of equation shows a straight line on a log-linear graph, which makes it easy to compare formulae for different structures.

Two equations are considered for pulsating waves on a vertical structure. Vertical structures are often in shallow water, and may have a sloping foreshore in front, may become subject to impulsive forces, i.e. high impacts and water splashing high up into the air. For vertical structures under impulsive wave attack the conditions are usually achieved with a relatively steep foreshore in front of the vertical wall.

Specific formulae have been developed for these kinds of situation. For easy comparison of different structures, like smooth and rubble mound sloping structures and vertical structures for pulsating and impulsive waves, some simplifications are assumed.

In order to simplify the smooth structure no berm is considered, only normal wave attack is considered, and the sloping seawall does not feature any wave wall on top, and assumes the slope is smooth and impermeable. For rubble mound or armoured slopes, the same basi equation is used but a roughness factor is included and the coefficients a & b change, but the overall method does not. Rubble mound structures are often steep, but some rock armoured slopes may be gentler. The high roughness and permeability of a rubble mound can reduce overtopping substantially.

3 EMBANKMENTS AND DIKES

An exact mathematical description of the wave run-up and wave overtopping process for coastal dikes or embankment seawalls is not possible due to the stochastic nature of wave breaking and wave run-up and the various factors influencing the wave run-up and wave overtopping process. Therefore, wave run-up and wave overtopping for coastal dikes and embankment seawalls are mainly determined by empirical formulas derived from experimental investigations. The influence of roughness elements, wave walls, berms, etc. is taken into account by introducing influence factors. Thus, the following chapter is structured as follows.

Wave run-up is a function of the wave breaking process on the seaward slope for simple smooth and straight slopes. The overtopping is a mean overtopping discharges and individual overtopping volumes sum to determine this mean discharge. The influencing factors on wave run-up and wave overtopping like berms, roughness elements, wave walls and oblique wave attack have all been studied separately and different allowances are made with the methods to account for these. The main calculation procedure for coastal dikes and embankment seawalls is given in Chapter 5 of EurOtop.

4 ARMOURED RUBBLE SLOPE AND MOUNDS

Chapter 6 of the manual describes overtopping at armoured rubble slopes and structures. Sometimes there will be combinations and it can be difficult to place them only into one category. For example, a vertical wall or sloping embankment with a large rock berm in front. Armoured rubble slopes and mounds are characterized by a mound with some porosity or permeability, covered by a sloping porous armour layer consisting of large rock or concrete units. In contrast to dikes and embankment seawalls the porosity of the structure and armour layer plays a role in wave run-up and overtopping. The cross-section of a rubble mound slope, however, may have great similarities with an embankment seawall and may consist of various slopes. As rubble mound structures are to some extent similar to dikes and embankment seawalls, the basic wave run-up and overtopping formulae are taken from Chapter 5 and are in modified versions as mentioned above.

5 VERTICAL AND STEEP SEAWALLS

Chapter 7 presents guidance for the assessment of overtopping and post-overtopping processes at vertical and steep-fronted coastal structures such as caisson and blockwork breakwaters and vertical seawalls. Also included are composite vertical wall structures, where the emergent part of the structure is vertical, fronted by a modest berm. Also covered are the effects of including a recurve or bull-nose section, or modified parapet or wave return wall at the upper part of the defence.

Large vertical breakwaters are almost universally formed of sand-filled concrete caissons usually resting on a small rock mound. Such caisson breakwaters may reach depths greater than 100 m, under which conditions no wave breaking at all at the wall would be expected. Conversely, older breakwaters may, out of necessity, have been constructed in shallower water or indeed, built directly on natural rock outcrops. As such, these structures may find themselves exposed to impulsive conditions when the water depth in front of them is sufficiently low. Urban seawalls are almost universally fronted by shallow water, and are likely to be exposed to breaking or broken wave conditions, especially in areas of significant tidal range.

The descriptions follow approximately the same sequence as the chapters of sloping structures, though certain differences should be noted. In particular, run-up is not addressed, as it is not a measure of physical importance for this class of structure—indeed it is not well-defined for cases when the wave breaks, nearly breaks or is broken when it reaches the structure, under which conditions an up-rushing jet of water is thrown upwards.

6 CALCULATION TOOLS

6.1 *PC Overtopping*

The programme PC-OVERTOPPING was made on the results of the Technical TAW Report “Wave run-up and wave overtopping at dikes” and is used for the 5-yearly safety assessment of all water defences in the Netherlands. The TAW Report has now been subsumed into EurOtop’s chapters 5 (dikes and embankments) & 6 (rubble mounds). The programme was mainly based on a *dike type structure*. It means that the structure should be sloping, although a small vertical wall on top of the dike may be taken into account. Also roughness and permeability are different from smooth, and can be taken into account, but not a crest with permeable and rough rock or armour units. In such a case the structure should be modelled up to the transition to the crest and other formulae should be used to take into account the effect of the crest.

The programme was set-up in such a way that almost *every sloping structure* can be modelled by an unlimited number of sections. Each section is given by x-y coordinates and each section can have its own roughness factor. The programme calculates almost all relevant overtopping parameters: such as 2% run-up level; mean overtopping discharge; percentage of overtopping waves; overtopping volumes per wave; and required crest height for given mean overtopping discharges.

The main advantages of PC-OVERTOPPING are that you can model each sloping section, including different roughness along the slope, and calculation of most overtopping parameters, not only the mean discharge. The main disadvantage is that it does not calculate vertical structures and/or a rough or permeable crests.

The programme also provides a check of whether the results of the 2%-runup level and mean overtopping discharge fall within measured ranges. It generates graphs that show the actual measured run-up or overtopping, including the effect of reductions due to roughness, berms, etc. The curve gives the maximum, which means a smooth straight slope with perpendicular wave attack. The programme then plots the calculated point in these graphs.

6.2 *Neural network tools*

Artificial neural networks fall in the field of artificial intelligence and can in this context be defined as systems that simulate intelligence by attempting to reproduce the structure of human brains. Neural networks 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 connections, carries out some standard operations and produces an output. Each connectivity has a weight factor assigned, as a result of the calibration of the neural network. 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 neural network.

Artificial neural networks have applications in many fields and also in the field of coastal engineering for prediction of rock stability, forces on walls, wave transmission and wave overtopping. The development of an artificial neural network is useful if the process to be described is complicated with a lot of parameters involved and there is a large amount of data.

Less complicated processes may be described by empirical formulae. This is also true for the process of wave overtopping, where many formulae exists, but always for a certain type of structure. Wave overtopping on all kind of structures can not be covered by only one formula, but a neural network is able to do this. A neural network needs a large amount of data to become useful for prediction. If the amount of data is too small, many predictions might be unreliable as the prediction will be out of range. But specially for the topic of wave overtopping there is an overwhelming amount of tests on all kinds of coastal structures and embankments.

The application of the neural network is providing an Excel or ASCII input file with parameters, run the programme and get a result file with mean overtopping discharge. Such an application is as easy as getting an answer from a formula programmed in Excel and does not need knowledge about neural networks. The advantages of the neural network are it works for almost every structure configuration, and it is easy to calculate trends instead of just one calculation with one answer.

The input exists of 10 structural parameters and 4 hydraulic parameters. The hydraulic parameters are wave height, wave period, and wave angle and water depth just in front of the structure. The structural parameters describe almost every possible structure configuration by a toe (2 parameters), two structure slopes (including vertical and wave return walls), a berm (2 parameters) and a crest configuration (3 parameters). The tenth structural parameter is the roughness factor for the structure (γ_f) and describes the average roughness of the whole structure.

7 CONCLUDING REMARKS

This paper has attempted to introduce the EurOtop overtopping manual, but the manual is 180 pages and so only a rudimentary introduction has been possible here. The manual may however be downloaded for free from http://www.overtopping-manual.com/EurOtop.pdf

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