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# A Comparison of field and laboratory overtopping measurements with empirical, numerical and probabilistic predictions

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# A COMPARISON OF FIELD AND LABORATORY OVERTOPPING MEASUREMENTS WITH EMPIRICAL, NUMERICAL AND PROBABILISTIC PREDICTIONS

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## Abstract

Two sets of overtopping data gathered in the field are compared with laboratory measurements, the available empirical prediction methods for these structures, a numerical Neural Network prediction tool, and a bespoke probabilistic prediction method developed for one of the field measurement sites. Descriptions of each of these are given so that a sufficient understanding of each data set can be gained. For each of the two structures examined, a total of four data sets are available from each of the different methods. These are examined individually to show how each compare, and show some justification for their use. It is concluded, at least for the two structures investigated, that the available desk methods compare well to the measured data.

## Introduction

The paper compares field and laboratory measurements of wave overtopping and compares these to existing empirical, numerical and probabilistic methods for predicting wave overtopping. The available field data are from the CLASH Samphire Hoe (Pullen et al. (2003), Pullen et al. (2004) & Pullen et al. (2009)) measurements and the recent EA funded (project code SC050069) measurements at Anchorsholme in Blackpool, England (Pullen et al., 2008). The available probabilistic model includes Ensemble surge models, offshore wave models, hydrodynamic wave transformation models and empirical wave overtopping formulae from the EA SC050069 project. The empirical methods are derived directly from original data sets, the method for recurve wave return walls with berms described by Besley (1999), and from the recent EurOtop manual by Pullen et al. (2007).

Outline descriptions of the field measurements at Samphire Hoe and Anchorsholme are given, and the corresponding 2d & 3d laboratory measurements for Samphire Hoe are also described. A more detailed description of the probabilistic model will be given, as this is a more recent innovation, and the general methodology is less well known. The empirical models will be mentioned briefly, as these methods are reasonably well known and more details can be easily obtained. The numerical calculations used the CLASH Neural Network (CNN), and this, too, will be outlined briefly with adequate references to obtain a more detailed description.

Field measurements of wave overtopping are rare, and the subsequent simulation of those measurements in the laboratory rarer still. Comparison of these data with the principal methods available for desk studies gives us the opportunity to examine the validity and applicability of each. This paper, therefore, does not seek to propose a new method or methods, rather its main purpose is to share with the wider community this unique set of data, and allow a greater level of confidence to be prescribed to some the predictions given for some of the available methods.

**Figure 1: The seawall at Samphire Hoe, and the overtopping tanks in position**

## Field Measurements

### Samphire Hoe, UK

Field studies at Samphire Hoe (see Figure 1) have been described previously by Pullen et al. (2003), Pullen et al. (2004) and Pullen et al. (2009). Samphire Hoe is an area of reclaimed land formed by 4.9M m$^3$ of chalk marl excavated from the Channel Tunnel. The area of approximately 300,000m$^2$ is enclosed by a vertical (slightly battered) seawall with a crest level at +8.22mODN and a rubble berm at -2.42mODN. The Samphire Hoe reclamation is owned by Eurotunnel, and is run on their behalf by the White Cliffs Countryside Project (WCCP) as a public recreational area. It is exposed to waves from the southwest to southeast and is subject to overtopping on approximately 30 days / year with waves breaking over the rubble berm and impacting on the seawall face.

The composite vertical seawall fronts a wide promenade onto which were bolted a series of continuously draining tanks (Figure 1), equipped to measure instantaneous volumes for individual overtopping events. These gave mean overtopping discharge rates and peak volumes, and the arrangement of the tanks also provided data on the spatial distribution of the overtopping. The method for determining the proportion of overtopping discharges landing outside of the tanks is described by Pullen et al. (2009). Overtopping at Samphire Hoe was measured during three storms on 10 March 2003, 1 May 2003 and 2 May 2003. Overtopping was very low during the first storm, so it is not discussed here, but successful measurements were made during subsequent field trips.

The data gathered from each of the two storms were determined at half hour intervals for the purpose of the analysis, and the recording was over the rise and fall of the tide from the first to the last instance of overtopping. During the storm of 1 May 2003 Storm, measurements were made in wind speeds of 15~20m/s (gale force 5). The maximum overtopping discharge was approximately $q = 1.0$ l/s/m and the maximum predicted discharge was $q = 1.4$ l/s/m. There was little wind recorded during the 2-3 May 2003 storm, and the highest recorded mean overtopping discharge during the storm was $q = 3.3$ l/s/m and the prediction according to Besley (1999) was $q = 3.1$ l/s/m, which is in excellent agreement.

### Anchorsholme, Blackpool, UK

The seawall at Anchorsholme is shown in Figure 2. It comprises a toe at approximately +1.8mODN, a 1:2 slope leading up to four steps each approximately 0.5m x 0.5m, a 2m wide horizontal berm and then a 1.7m recurve wave return wall with a crest at +7.8mODN. The overtopping tank was placed directly behind the crest and is also shown in Figure

2. It had a total capacity of 450 l divided into two compartments of 225 l. Pressure cells in each of the compartments measured the total head of water, and this was recorded as a time-series. The control box contains a data-logger and is mounted to a lid that was closed to secure the equipment between probable overtopping events. The methods, procedures and analysis methods for collecting and determining the overtopping discharges in the field are described in more detail by Pullen et al.(2003), Pullen et al. (2004) & Pullen et al. (2009), and further details on the measurements at Anchorsholme are given by Pullen et al. (2008). Three events were recorded at the field overtopping measurement site. Of these events, one recorded no overtopping when a very low probability of overtopping was predicted. For the remaining events there was a high probability of overtopping predicted, and these are discussed below.

Two events on 9 January and 24 January 2008, both spring tides, were successfully captured and recorded as overtopping discharges in the tank at Anchorsholme. The tank recorded all discharges as a continuous time series, and the total volumes recorded during each 15 minute period were derived. These volumes were then used to establish the total discharge in litres per second per metre (l/s/m) for each 15 minute period so that these would correspond to the predictions made by the probabilistic model (see below). The maximum discharge recorded during the 9 January storm was q = 0.5 l/s/m and for the 24 January storm the maximum discharge was q = 3.75 l/s/m.

## Laboratory Models of Samphire Hoe

The 2d Samphire Hoe model was constructed in a laboratory flume at a scale of 1:40 in the School of Engineering at University of Edinburgh, UK. This wave flume is 20 m long, 0.4 m wide and has an operating water depth of 0.7 m. Waves were generated by a flap type wave paddle with active absorption. For the 3d basin study at HR Wallingford, the model was constructed in a deep water basin at a scale of 1:20. The seawall was modelled over approximately 120 m, which allowed for the direction of the waves and any hydraulic affect that may be expected from waves diffracting around the corner of the walls. The bathymetry was taken down to an offshore depth of h = 18.4 m. Waves were generated by a multi-element wave paddle with active wave absorption.

**Figure 2: The seawall at Anchorsholme, and the overtopping tank in position**

Measurements were made of the offshore waves, the waves at the toe of the structure and the wave overtopping characteristics. Different equipment was used in each of the two laboratory studies, but the fundamental measurement techniques were the same for both. In particular, overtopping discharges were directed via a chute into a measuring container suspended from a load cell, which was capable of determining individual volumes to within an accuracy of 2 l/m (prototype). Individual overtopping events were detected by high gain resistance gauges that acted as a switch when closed by the water, and the volumes were measured by determining the increment in the mass of water in the collection tank after each overtopping event. The mean spatial overtopping discharges were determined in a series of individual compartments inline and set normal to the seawall; further details on these spatial measurements are given by Pullen et al. (2009).

Each of the two laboratory studies calibrated and measured the wave conditions and water levels determined for each of the two storm events. In addition, a set of parametric sets were devised to examine a greater range of wave conditions and water levels than was possible during the field deployments. All of these data sets are discussed below.

## The Probabilistic Overtopping Model

The UK Environment Agency Research & Development Project SC050069, Coastal Flood Forecasting, ran from March 2006 to December 2008, and was undertaken by HR Wallingford, the UK Met Office and the Proudman Oceanographic Laboratory. The overall objective was to develop, demonstrate and evaluate improved probabilistic methods for surge ensemble modelling, nearshore wave, and coastal flood forecasting in England and Wales. The project investigated the relative value of different modelling refinements, and then built, demonstrated and evaluated forecasting models that could be taken up for operational use in coastal flood forecasting. The model review, classification, development and evaluation elements of the project are described in detail in Environment Agency (2007/SC050069/SR1), and the operational forecast demonstration and evaluation elements are described in Environment Agency (2008/SC050069/SR2). This section provides sufficient background information to form a basic understanding of the components of the probabilistic model and how they are integrated to predict mean overtopping discharges at Anchorsholme; more detail is given by Pullen et al. (2008).

### Surge Ensemble modelling

A traditional deterministic forecast produces a single estimate of how each output will evolve as a function of time. An ensemble modelling approach produces not one but several forecasts. Each forecast uses slightly different initial conditions, boundary conditions and/or model physics, with the aim of sampling the range of forecast results consistent with the uncertainty in observations and the modelling system itself. For storm surge forecasting, the uncertainty in meteorological forcing is expected to dominate over uncertainties in the surge model formulation and initial state. For the project, the effect of this meteorological uncertainty was sampled by driving each surge ensemble member with surface wind and pressure forecasts taken from the corresponding member of the Met Office Global and Regional Ensemble Prediction System (MOGREPS, Bowler et al, 2007). The data for the project came from the regional ensemble, which covers a North Atlantic and Europe domain at 24 km resolution, with two forecasts per day. The boundary conditions for each regional integration are obtained from the corresponding member of the lower resolution global ensemble. Both ensembles contain 23 perturbed members, sampling the uncertainty in atmospheric initial conditions and model physics, together with one unperturbed ‘control’ member. The length of the regional runs extended from 54 hours, giving a full two days of useful forecast.

## Nearshore wave modelling

The single deterministic forecast provided an initial unperturbed surge member and a single wave condition at each of the boundary nodes in the model; an ensemble wave forecasting model is expected to be developed in the near future. A SWAN wave model was used to generate lookup tables for the expected range of wave conditions that might lead to overtopping at the demonstration site. An accurate bathymetry was constructed within the model to simulate the wave transformation from the boundaries of the surge / wave forecasts to the site. For a given surge ensemble, wave condition and astronomical tide prediction, a prediction of the wave and water level conditions at the site was determined. The model included a range of parameters that were used to model the uncertainties within the SWAN model, uncertainties concerned with the offshore and nearshore bathymetry and also the level of the beach at the toe of the structure.

## Probabilistic Methods in Modelling

For given inputs of nearshore wave condition, beach profile, water level, wall crest, wall profile, empirical coefficients, etc., the best methods for the prediction of mean overtopping (EurOtop, Pullen et al., 2007) aim for order of magnitude accuracy over their appropriate ranges of applicability. The uncertainty associated with an individual model output, and the propagation of this uncertainty forward through the modelling chain is handled through Monte Carlo simulation from either discrete or continuous probability distributions, based on the information available on each of the variables involved. A Monte Carlo approach to handling uncertainty includes typical representations of uncertainties. It involves random simulations from probability distributions incorporating the surge ensemble information, the various assumed uncertainties in the source variables (waves, still water level and wind), the empirical overtopping formulae, the descriptors of sea defences and other model parameters. Uncertainty is specified in terms of a distribution, e.g. Normal, and its associated parameters, e.g. mean and standard deviation. The Monte Carlo simulations work by taking random draws from the range of offshore wave and still water level conditions, and from the parameter distributions, and following these selections through to the computation of wave overtopping rates and volumes. This process is repeated until a convergence criterion is achieved, e.g. consistency in the mean overtopping rate. This was done for each of the 24 surge members, and the results shown below are the overall probabilistic mean for each storm event.

The model includes all necessary site-specific data, including the parameters with uncertainties, and the thresholds for alerts. The model includes three principle hierarchies, an outer level main control used primarily to read in and write out data, a middle level that represents the Monte Carlo simulation control, and an inner level that represents the offshore to nearshore and shoreline modelling. Output incorporates a range of parameters, probabilities, graphical outputs and alerts, which are all related to the calculated overtopping discharges. There were two main purposes to the coastal flood forecast demonstration. One was to show that the models could work together consistently to deliver coastal flood forecasts at regular intervals, in time for them to be acted upon. The other was to check individual model elements and the modelling system as a whole against field measurements and against other forecasting methods. The demonstration was set up to mimic an existing operational system, took Met Office inputs twice daily, and generated the corresponding coastal forecasts twice daily.

## Empirical Models

### Composite Vertical Walls

The prediction of the overtopping performance of composite vertical walls is described in detail in EurOtop (Pullen et al., 2007), and is outlined briefly here for completeness. In deep water, waves hit the structure and are generally reflected back seawards (non-impulsive waves). As the waves become limited by water depth, they are prone to break over the sea wall (impulsive waves) and this causes a change in the overtopping performance. This lead to the formulation of a wave breaking parameter, *h**, a parameter which allows the parameterisation of the incoming wave type. *h** may is determined from the following expression;

$$h_* = 1.35\frac{2\pi h^2}{H_s g T_{m-1,0}^2} \qquad (1)$$

where $h$ is the depth at the toe, $H_s$ the significant wave height and $T_{m-1,0}$ the spectral mean wave period at the toe of the structure. Non-impulsive waves predominate when $h^*>0.3$, and impulsive predominates when $h^*<=0.3$.

For composite vertical structures including toe berms, such as that at Samphire Hoe, the *h** parameter can be modified to take account of the relative size of the berm, and is given by;

$$d_* = 1.35\frac{2\pi dh}{H_s g T_{m-1,0}^2} \qquad (2)$$

where $d$ is the water depth over the berm. The berm is classified as large when $d^*<=0.3$, whereas when $d^*>0.3$ the berm is classified as small and the wave at the structure behaves as with plain vertical walls. The formulation of *d** is essentially dependent upon the water depth and the wave steepness and reflects the fact that the waves are more likely to break if the wave length or the wave height is large compared to the water depth. The following empirical formula is then used to determine the mean overtopping discharge on a composite vertical seawall for impulsive waves and large mounds, and is given by;

$$Q_d = 4.1\text{x}10^{-4} R_d^{-2.9} \qquad (3)$$

where $Q_d$ is the dimensionless discharge, and $R_d$, the dimensionless crest freeboard, which is given by;

$$R_d = \frac{R_c d_*}{H_s} \qquad (4)$$

and where $R_d$ is valid for $0.05<R_d<1.0$, and $R_c$ is the crest freeboard.

From Equations 1 to 4, the mean overtopping discharge $q$(m$^3$/s/m) can be obtained from the following expression;

$$q = Q_d d_*^2 \left(g d^3\right)^{0.5} \qquad (5)$$

## Recurve Wave Return Walls with Berms

The prediction of the overtopping performance of recurve wave return walls with berms is described in detail by Besley (1999). The method is too complex to describe in detail here, and the reader is referred to the reference given. Nonetheless, a brief outline of the method is given here.

Essentially it is based on the classic Owen formulation for wave overtopping at simple sloping structures. Firstly a nominal dimensionless freeboard is determined for the height of the structure to the top of the slope ($A_c$), but not including the wall, and is found from;

$$A_{c*} = A_c / \left(T_{m-1,0}\left(g H_s\right)^{0.5}\right) \qquad (6)$$

from which a nominal dimensionless overtopping discharge ($Q_{b*}$) is calculated,

$$Q_{b*} = A e^{(-B A_{c*})} \qquad (7)$$

where A & B are coefficients determined by the front slope of the structure. The nominal discharge $q_b$ is then found from;

$$q_b = Q_{b*} T_{m-1,0} g H_s \qquad (8)$$

The method is complicated because the final stage of the calculation involves the determination of a discharge factor ($D_f$) for the recurve wall, which is derived using a graphical method. $D_f$ is a function of the wall height and the berm width, and can typically take a value between 1 and $10^{-3}$. Having established a value for $D_f$, the predicted overtopping discharge (q) is found from;

$$q = q_b D_f \tag{9}$$

For the empirical model component of the probabilistic model, the original data used to derive the above method was used. A subset of those data was identified that most closely represented the seawall at Anchorsholme, and to this an empirical best fit line was established to provide the coefficients A & B, that could be used with a simple $R_*Q_*$ (see Besley. 1999) type expression. The full details are extensive and are given in Environment Agency (2007/SC050069/SR1); suffice to add here that this was used for the probabilistic model prediction, but that the original empirical method was used for the analysis given below.

## CLASH Neural Network

Artificial neural networks (ANN) fall into the field of artificial intelligence and can in this context be defined as systems that are analogous to the structure of the human brain. An ANN is a nonlinear statistical model that has been trained on a set of related data, so that generic patterns and/or solutions can be obtained from the ANN. ANNs are particularly useful where a large data set is available on a particular phenomenon, but where there is no single expression or model that is capable of describing the phenomenon in a generic way. In particular, within EurOtop (Pullen et al. 2007) several empirical prediction methods are described, but there is no generic method, and there are several classes of structure type that do have an empirical model associated with them.

During the CLASH (see de Rouck et al. 2005) project, a collection of 10,000 overtopping tests were gathered to form the CLASH overtopping database. The database was used to train the CLASH NN (CNN), and produce a generic prediction method for assessing wave overtopping. The CNN allows overtopping predictions to be made for structures where there is little or no data available, or more particularly, no calibrated empirical prediction method. The CNN consists of 11 structural parameters and 4 hydraulic parameters. The hydraulic parameters are wave height, wave period, wave angle and the water depth at the toe of the structure. The structural parameters describe almost every conceivable structural configuration with two toe parameters, two structure slope parameters, two berm parameters and four for the configuration of the crest. The eleventh structural parameter is the roughness factor for the structure and is the average roughness for the whole structure. To run the model the fifteen input parameters are entered in and a mean (and percentile) overtopping discharge is predicted. A more detailed description of the CNN is given by van Gent et al. (2004).

## Discussion of Results

The results and the predictions from Samphire Hoe are shown in Figure 3 and those from Anchorsholme in Figure 4. The Samphire Hoe data includes: two sets of field data; two sets of laboratory data of the field simulations; one set of 3d parametric laboratory tests; a set of CNN predictions covering the complete range of tested and recorded wave conditions and water levels; and the generic empirical prediction from EurOtop (Pullen et al., 2007). The Anchorsholme data includes: two sets of field data; two sets of probabilistic model predictions; two sets of CNN predictions covering the complete range of recorded wave conditions and water levels; and empirical predictions from Besley (1999). Flume tests on the Anchorsholme seawall are due to place during the autumn of 2009.

In Figure 3 it can be seen that most of the data are clustered around, and either side of, the empirical prediction line. This scatter is quite within the anticipated range and is consistent with a 'best fit' prediction method. The field and laboratory simulation data are more densely clustered and this is because the range of wave conditions and water levels was limited to the two storms. For the parametric tests we see that the greatest departure from the prediction line is for the lower discharges, and again it is generally known that a wider scatter in the data should be anticipated at lower discharges.

The best data fit is that for the CNN prediction. This is to be expected since composite vertical walls have been tested many times and most of this data went into training the CNN; indeed much of the data shown here was included in the training database. EurOtop (Pullen et al. 2007) explains how to choose between a deterministic or probabilistic approach when determining which prediction to use, and the best fit line (± standard deviation) may often be adjusted to encompass all the data or allow for a more conservative approach. The empirical prediction method and the CNN prediction are not entirely decoupled, but this shows an excellent agreement between the two separate methods. In particular, it is a convincing demonstration of the ability of the CNN to predict overtopping for this complex structure type.

For the Anchorsholme Seawall results, shown in Figure 4, the most obvious observation is the divergence between the probabilistic model predictions and those of the field measurements, empirical and CNN predictions. The probabilistic model was specifically calibrated to be able to predict probable flooding events, and the empirical equation within the model used a simplified method as described above. It can be seen though, that the model predictions are in agreement with other methods for the higher discharges that affect flood warnings, even though the method under-predicts for the lower discharges.

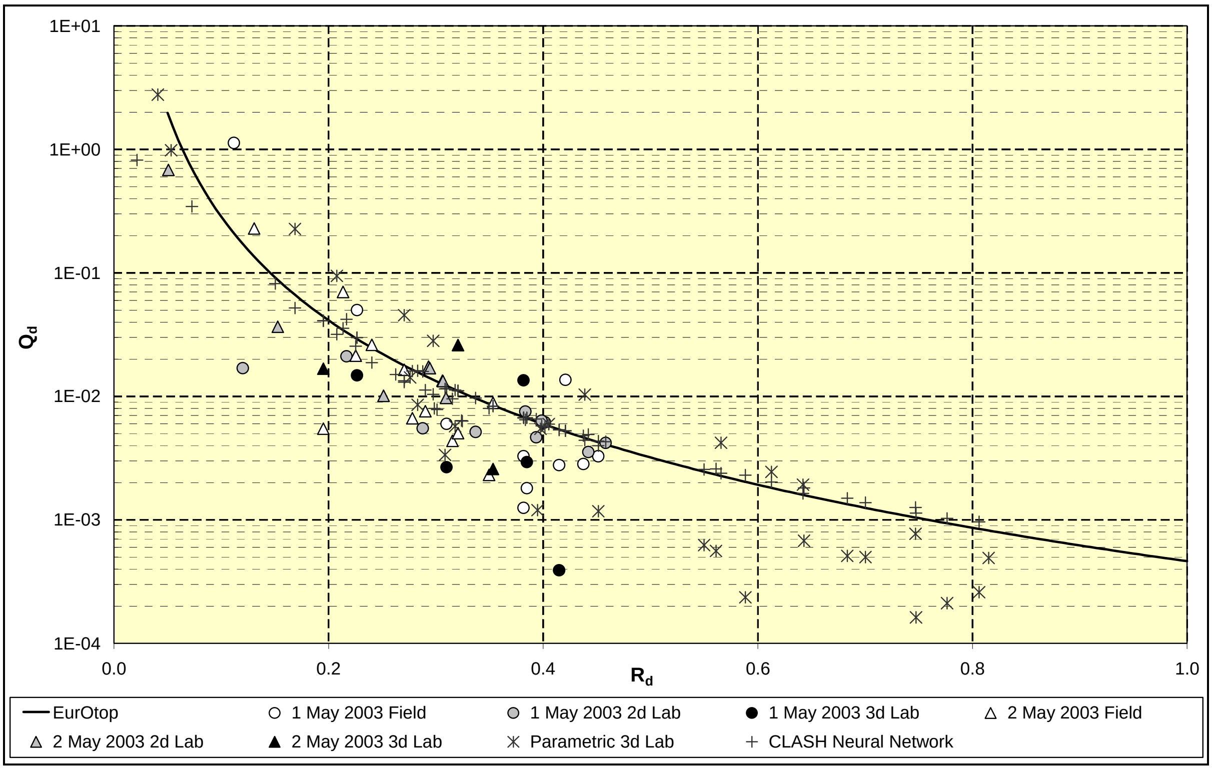

**Figure 3: Overtopping analysis for Samphire Hoe**

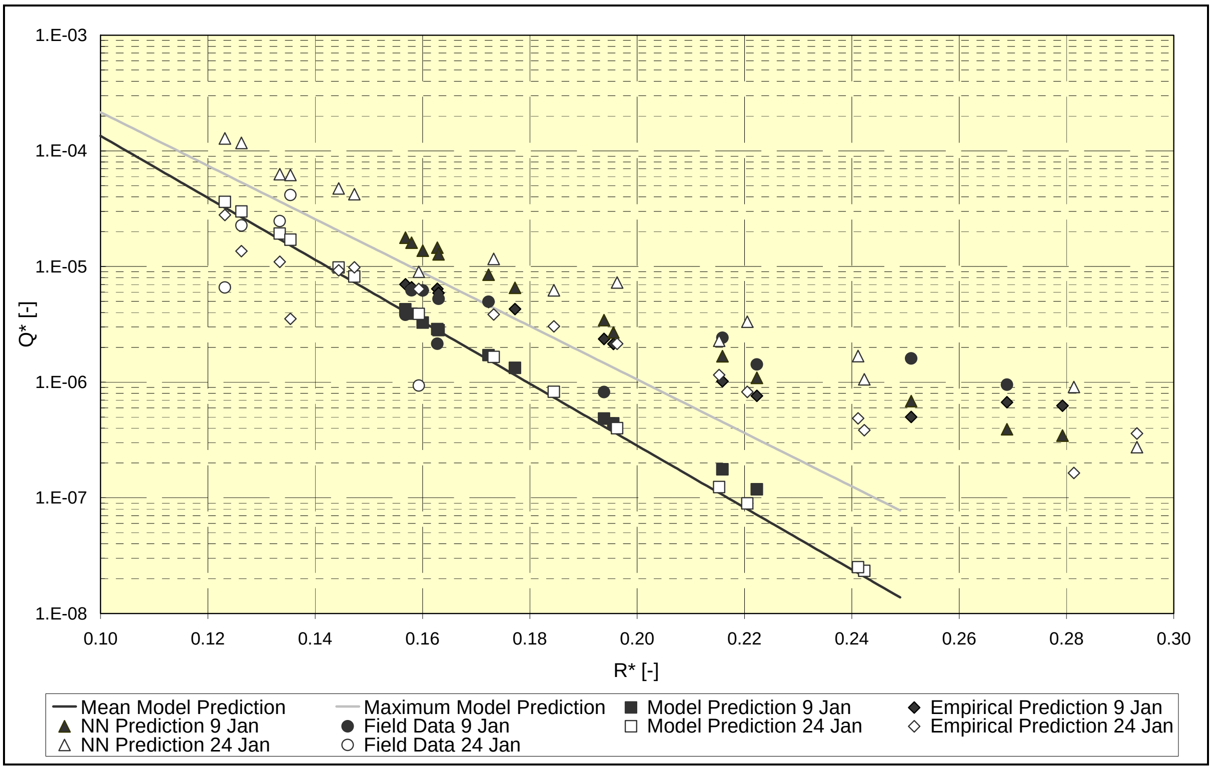

**Figure 4: Overtopping analysis for Anchorsholme**

Of greater interest is the close agreement among the data from the empirical predictions, the CNN predictions, and the field data. As with the earlier case, the CNN prediction is based to a certain degree on the original test data for recurve wave return walls with berms. The CNN does not know that it is this type of structure *per se*, but it demonstrates how it can predict for a structure with this complex geometry. In fact, it is remarkable in that the selection of the parameter values would not actually describe the structure in its entirety, merely that the armour and crest freeboards are different ($A_c$ & $R_c$) and that there is an upper berm.

## Concluding Remarks

The main purpose here has been to examine two very different structures and then compare overtopping data from both. This included empirical, field, laboratory, numerical predictions, and a bespoke site specific probabilistic model. It has been shown that where physical data have been collected these are in agreement with the relevant empirical model. The two structures are particularly useful for demonstrating the use of the CNN, especially as it is best used for structures where there are either no data, or where there is a complex geometry. In all cases there is a good agreement among the data, and it has been shown that, when chosen well, methods to predict overtopping discharges may be within the anticipated performance of the structure.

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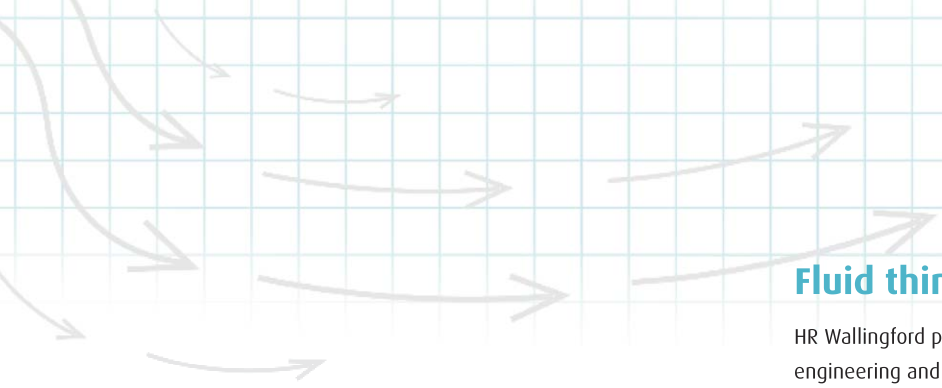

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