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JET VELOCITIES OF OVERTOPPING WAVES ON SLOPING STRUCTURES: MEASUREMENTS AND COMPUTATION

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Abstract

Current empirical methods often predict inadequately the overtopping discharges of waves on shallow sloping seawalls. As part of the DEFRA / EA funded research project FD2410, Coastal Flooding Hazard by Wave Overtopping, physical model studies have been undertaken for structure configurations of 1:2, 1:10 and 1:15. For 1:10 and 1:15 sloping structures, no data or method is currently available for predicting accurately the overtopping discharge. Although discharge quantities are widely used for analysing the hazard of overtopping, this may not be the best way of defining a violent overtopping event. Discharge velocities may also be of key importance and it is these velocities that are reviewed here for overtopping of waves on sloping structures. Two numerical non-linear shallow water models have also been used for comparison against the physical results to see whether they can be implemented as a valid prediction tool.

Introduction

In recent years, within the UK, the design of seawalls and related coastal structures for identifying overtopping performance and relating this, with confidence, to the intended structure geometry has gained significant attention. Projects such as the Violent Overtopping of Waves at Seawalls (VOWS) (Bruce et al 2001, Pearson et al 2001) and Big-VOWS (Pearson et al 2002) have primarily reviewed and analysed overtopping of vertical, battered (5:1 and 10:1) and composite seawalls. These structures have the main purpose of protecting people, vehicles and buildings from violent sea-states and empirical methods are available to assist in their design process. For shallow sloping structures, such as clay embankment seawalls, of which there are numerous around the British coastline, no reliable method to predict overtopping is available for slopes shallower that about 1:6. A thin veneer of smooth impermeable concrete, which is highly reflective, often protects these shallow sloping seawalls. These structures are affected by changing beach levels and local scour, leading to increased wave action and potentially violent overtopping.

The test structures chosen for this study are smooth impermeable slopes of 1:2, 1:10 and 1:15. Although the testing of a smooth impermeable 1:2 slope is not new, it was tested so that the predicted and actual overtopping discharges could be compared with the available empirical methods and used as a benchmark for comparison with the previously untested structure configurations. There is no data available that describes wave overtopping at the low to no overtopping threshold level, and wave and water level conditions were chosen to provide this data for improving the accuracy, at these low discharges, of existing empirical methods. Shingle and sand slopes are common throughout the British Isles with slopes of 1:10 generally being the maximum for steep shingle slopes and 1:15 slopes being a similar maximum for steep sand slopes. Slopes of 1:15 are possibly at the threshold of structures or beaches that are likely to be overtopped, and tests on these structures have contributed a significant proportion of the new scientific data that has been collected during this project. Current methods are incapable of predicting accurately the overtopping discharge for such shallow sloping structure.

Current empirical methods of Owen (1980), van der Meer et al (1998), Hedges & Reis (1998) and Besley (1999) have concentrated on improving predictions for mean overtopping discharge and are biased towards simple sloping embankments and vertical walls. There are gaps in the data from these studies, leading to widely different predictions at the threshold level of wave overtopping. The other main empirical prediction focuses on the volume of the maximum individual overtopping event, though both Owen (1980) and Franco (1994) commented on the importance of the discharge velocity and this may also be an important criterion when defining a violent overtopping event. Overtopping jets of water have the capability, if travelling with sufficient speed, to injure individuals or damage property even if the volume of water is relatively small. Owen (1980) also commented that velocities seemed to increase on sloping structures with Owen recording the most violent on 1:2 slopes. Similar wave run-up and velocity discharge studies have previously been carried out (van de Meer & Janssen 1995, Schuttrumpf 2002, Van Gent 2002) for overtopping of dikes, though the approach slopes have often been steeper than those reviewed here. These velocity discharges are important on dikes, as they can lead to erosion to the rear of the structure, leading to possible structure failure.

Figure 1 shows an excellent example of a high velocity overtopping event on a 1:2 sloping structure, and where the jet is clearly visible to the left. Testing was conducted in the Absorbing flume, which is 40m long, 1.5m wide and has an operating range of water depths at the wave paddle of 0.5 to 1.2m. The flume is equipped with an absorbing piston paddle, which is driven by an electro-hydraulic system. The paddle is controlled by a computer enabling either regular, random or solitary waves to be generated. Two wave probes mounted on the front face of the paddle measure the water surface elevation continuously. This signal is then compared with that generated with the feedback loop adjusting the signal to the paddle to ensure that only the required incident wave train is generated, and that reflections from the structure are absorbed at the paddle. The waves used for these physical model tests were JONSWAP random waves.

Figure 1 Overtopping event on a 1:2 sloping structure

Physical model

As previously described smooth impermeable slopes of 1:2, 1:10 and 1:15 have been tested to gather data to improve and extend the range of existing empirical prediction methods. Data for the 1:10 test structure is presented here, with Figure 2 showing the structure configuration and wave gauge positions. The crest of the structure is set at 0.650m above the flat horizontal bathymetry and two water levels, h = 0.425m and 0.525m allowed a change in the freeboard level. The water level used in the data presented later was set at the higher level. At the crest of the structure two pieces of apparatus were used in measuring the amount of water overtopping the structure and also the velocity of the overtopping jets. The overtopping chute, Figure 3, funnels the waves into the overtopping container, where a strain gauge is used to calculate the volume of overtopping events. These volumes can then be used to calculate mean overtopping and maximum individual overtopping events. The velocity detector, Figure 4, is of a simple design consisting of two wave gauges, set 0.165m apart. Once an overtopping event has left the crest of the structure the wave gauges individually record a signal in the presence of water. Calculating the time difference between the signals allows the associated velocity of the water jet to be calculated. An example of the signal readings from the two wave gauges, for a 10 second period, is shown in Figure 5. These wave gauges were recorded at a sampling frequency of 400Hz.

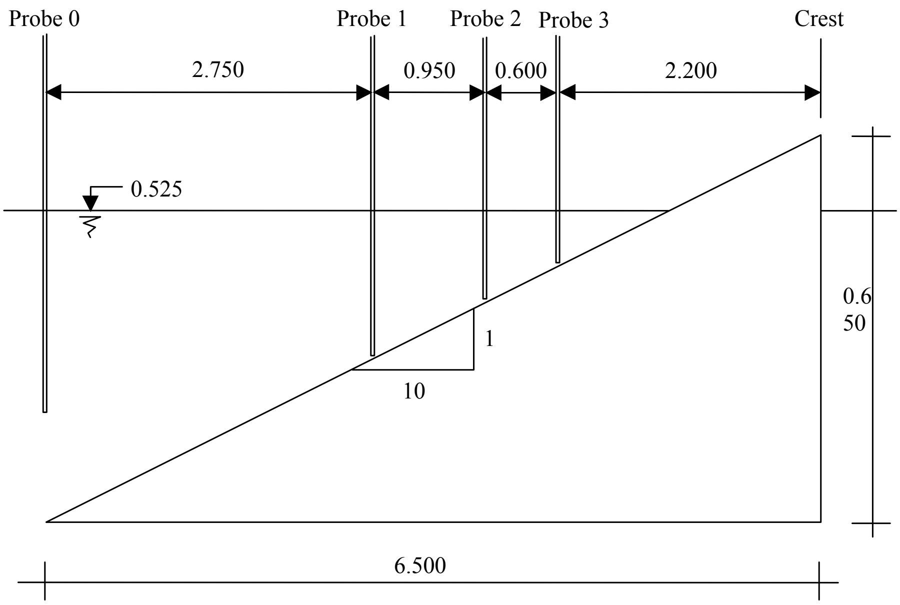

Figure 2 1:10 sloping structure with wave gauge positions shown for a water depth of 0.525m

Figure 3 Plan view of overtopping chute and container, waves approach from the left of picture

Figure 4 Velocity detector at crest of structure, comprised of two highly responsive wave gauges a set distance apart

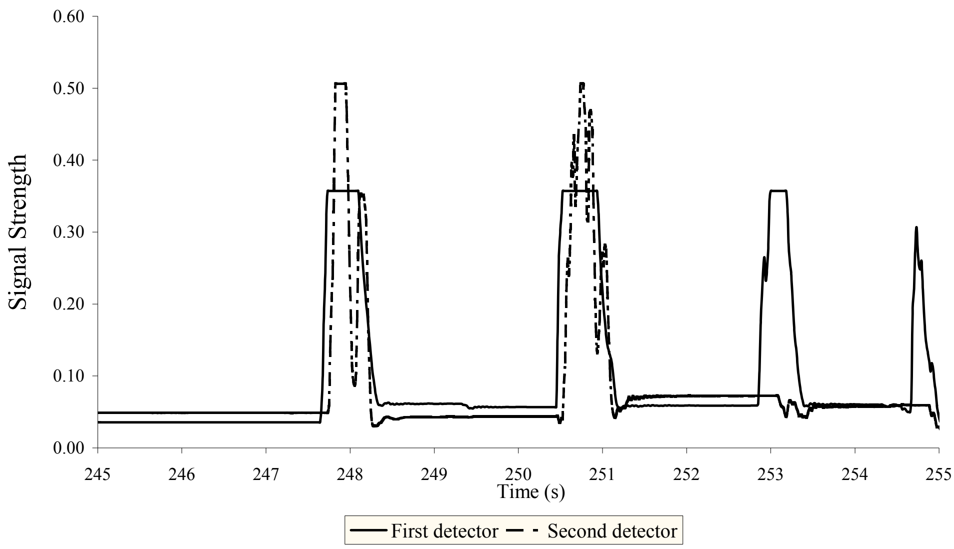

Figure 5 Time series of signal readings from the two wave gauges in the velocity detector

Numerical models

Two numerical shallow water models were used within this study, to simulate the physical model tests. The first is a well established model for one-dimensional wave run-up, overtopping and regeneration, ANEMONE OTT 1D (Dodd 1998) used at HR Wallingford and the second, AMAZON 1D (Mingham & Causon 1998) is part of the CMMFA AMAZON suite. Both models solve the one-dimensional non-linear shallow water equations, written in differential conservation form as:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} = \Omega$$

where

$$\mathbf{U} = \begin{bmatrix} \phi \\ \phi u \end{bmatrix}, \qquad \mathbf{F} = \begin{bmatrix} \phi u \\ \phi u^2 + \dfrac{\phi^2}{2} \end{bmatrix}$$

and where $\phi = gh$; h is water depth; g is acceleration due to gravity; u is the depth-averaged velocity in the x-direction; $\mathbf{F}$ is the convection flux; and Ω is the vector of source terms. These source terms could include bed slope, friction losses and Coriolis forces, though in this study only bed terms were included to represent the impermeable sloping structures. Both models are upwind finite volume schemes and have been extended in to two-dimensions, though only the one-dimensional schemes are presented.

ANEMONE OTT-1D solves the non-linear shallow water equations for the swash zone using the fast approximate Roe-type Riemann solver (for a full description see Dodd, 1998). The method used allows the simulation of water motions over surface-piercing structures with the subsequent regeneration of waves in the lee of the structure. The characteristics approach is used at both the seaward and landward open boundaries with reflected waves allowed to leave the model domain across the seaward boundary. A simple transmissive boundary condition allows waves to leave the landward end of the model region.

AMAZON 1D is a high resolution, second order Godunov method that is fully conservative. The method uses the MUSCL-Hancock finite volume, two-step scheme (van Leer 1984). Discontinuities at cell interfaces are solved using the HLL approximate Riemann solver (Harten et al 1983). For dry bed, shallow water problems, the wave speed estimates, for the HLL approximate solver, are altered (Fraccarollo and Toro 1995). The Surface Gradient Method (SGM) (Zhou et al 2000) is used in the treatment of the source terms and unlike conventional data reconstruction methods the water surface level, rather than water depth, is chosen as the basis for data reconstruction.

Both numerical models are driven by the water surface elevation from wave gauge 1, which is the first probe along the sloping structure in Figure 2, and satisfies the shallow water criteria at that point. Both numerical models recorded a time series of water surface elevation at wave gauge 2, 0.95m in front of wave gauge 1. This water surface elevation, for a twenty second period can be seen against the recorded physical model output in Figure 6. Figure 6 shows that both numerical models reproduce and preserve the correct wave heights and lengths generated within the physical model.

At the crest of the structure the velocity of the overtopping wave was recorded in both numerical models. Initially the minimum water depth, to identify whether the structure was wet or dry was set to 0.01m within both numerical models. Figure 7 shows the recorded discharge velocities for a 160 second period of a 1000 wave sequence with H_s = 0.175m, T_m = 2.75s. Only overtopping velocities in excess of 1ms^{-1} were analysed for the physical model results as these were of principal interest. Additionally, the recorded signal is affected by noise, which can make the identification of lower velocities a difficult task. Many of the overtopping velocities were below this threshold and this is evident within Figure 7, as only four physical results are plotted. The estimated numerical velocities are also below those recorded in the physical model, though if the minimum depth is reduced to 0.001m then better estimates are achieved, Figure 8. Only results from AMAZON 1D are shown in Figure 8 for a minimum depth of 0.001m. These results show that as the minimum water depth is decreased slightly higher velocities are recorded, as might be expected. These are only an initial look at the result though and further tests and analysis is required.

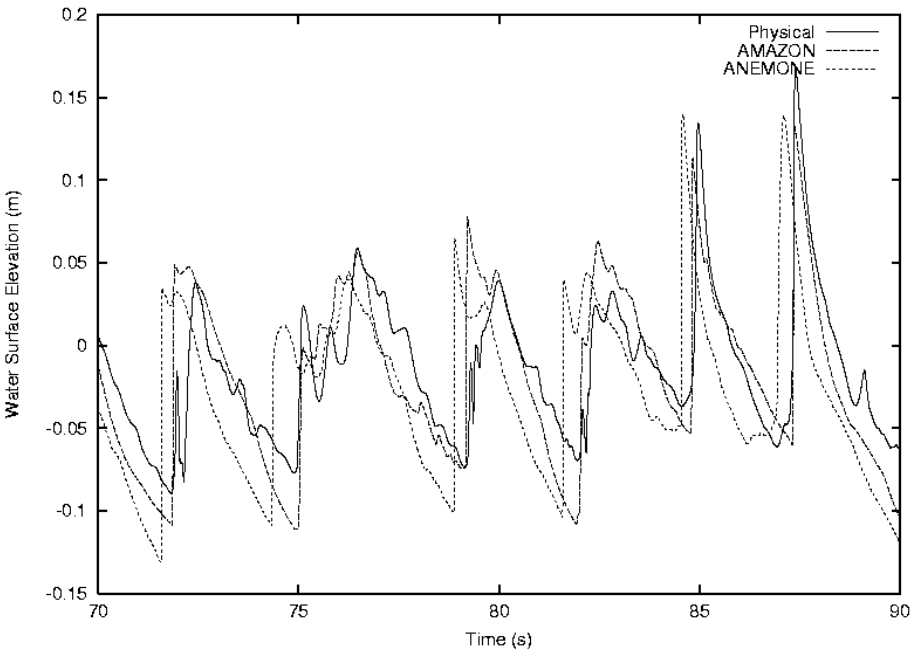

Figure 6 Comparison of water surface elevation at wave gauge 2 for physical and numerical models

Results

As the individual overtopping velocities are extreme events these results can be plotted against a Weibull distribution:

$$P(V) = \exp(-(V / A)^B)$$

where *P(V)* is the probability of exceedance and *A* and *B* are empirical coefficients. The Weibull distribution is fitted to the results from the physical model test and the numerical model tests. Figure 9 shows the Weibull probability plot produced by MINITAB™ for the physical and numerical models of the sea-state described above. The physical model data appears skewed, though this is due to the fact that all overtopping events with velocities less than $1ms^{-1}$ were not calculated. The calculated Anderson Darling goodness of fit statistic (to the right of the Weibull plot) shows that the fit of the numerical models results are actually relatively good and the data appears to follow this distribution. Further sea-states will be examined and the top 2% of velocities plotted.

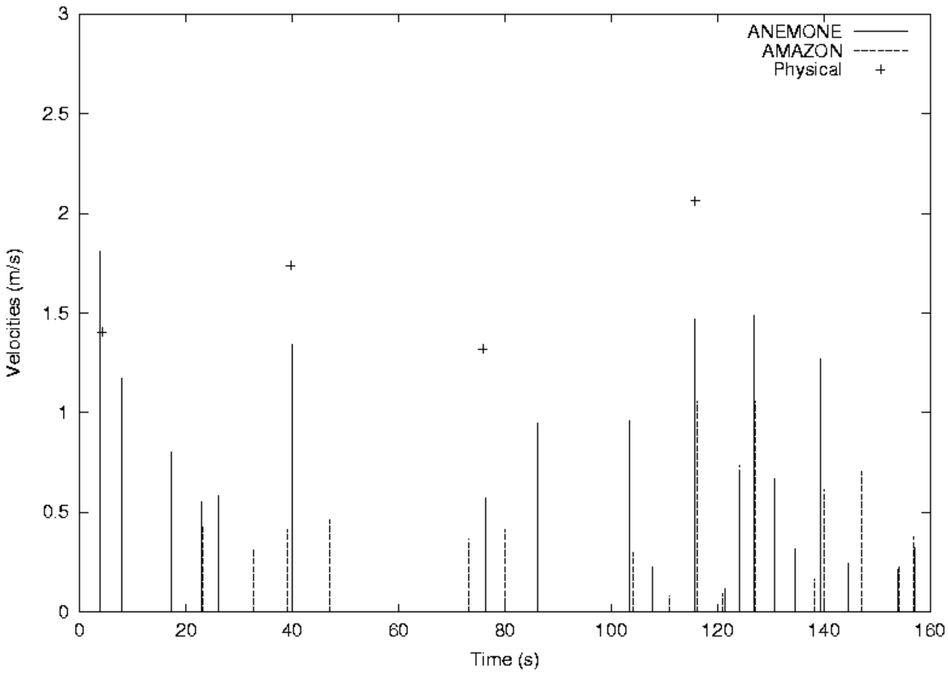

Figure 7 Comparison of recorded overtopping velocities with minimum depth set to 0.01m

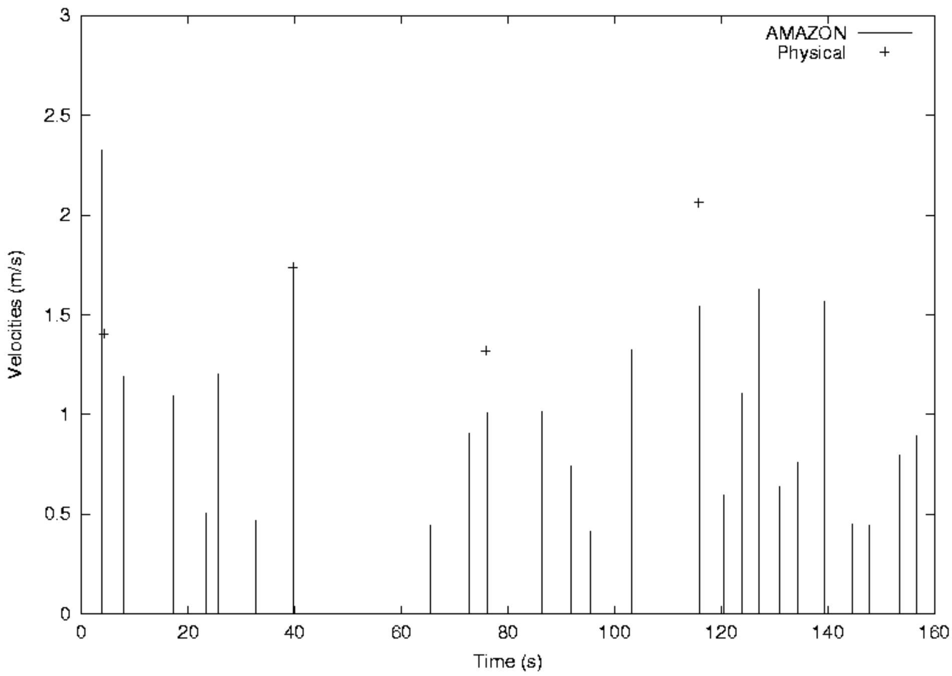

Figure 8 Comparison of recorded overtopping velocities with minimum depth set to 0.001m

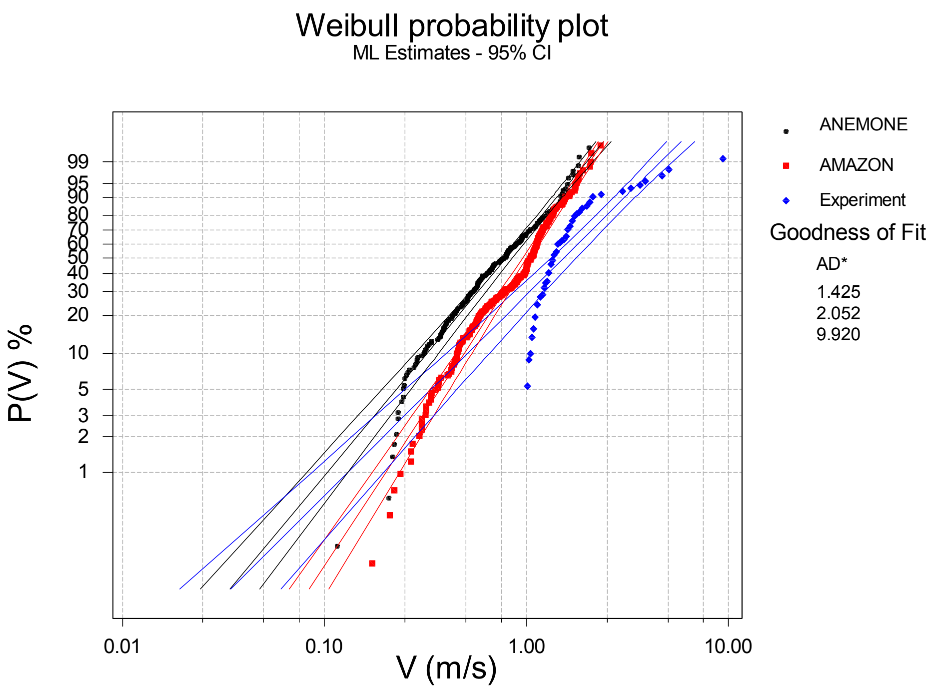

Figure 9 Weibull Distribution of discharge velocities

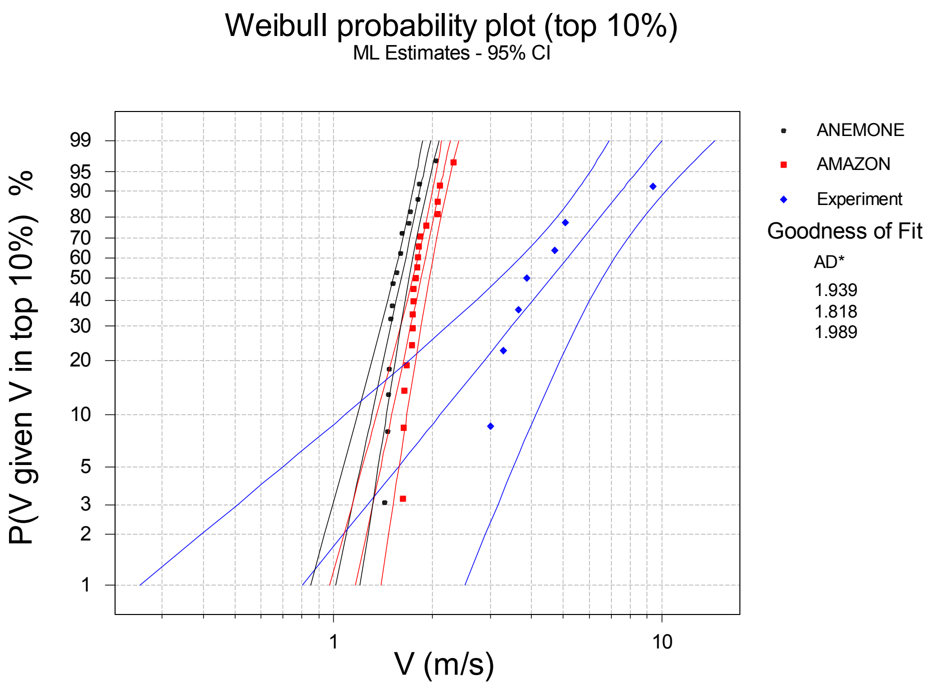

Figure 10 Weibull Distribution of top 10% of discharge velocities

As we are looking at extreme events we also reviewed the top 10% of the numerical and physical discharge velocities and these are plotted in Figure 10. If we review the Anderson Darling statistic as before, we can clearly see that the fit of the physical data to the distribution has vastly improved; though the confidence intervals for the physical data are significantly greater than those of the numerical models.

MINITAB also produces the maximum likelihood estimates for the Weibull parameters, *A* and *B*. These values are given in Table 1 and once these values are known, probabilities can be predicted for resulting specific velocities. These values are only for one test condition and more tests require performing to validate these results.

Table 1 Maximum Likelihood Estimates for Weibull Distribution Parameters

	A	*B*
Physical Model	0.413	5.34
AMAZON Model	0.521	9.21
ANEMONE Model	0.599	9.16

Conclusions

The initial results presented within this paper are the preliminary observations for overtopping jet velocities from the physical and numerical models undertaken and further study within this area is now required. It has been shown that within both the physical and numerical models the recording of such overtopping discharge velocities can be achieved, though the determination of the initial instance of an event at the experimental velocity detector is subjective. The high velocities of the overtopping jets achieved within the physical flume seem unlikely to be achieved within the current numerical shallow water models, though these models do provide an insight into the overtopping waves. It is felt that the physics of such violent overtopping events would be better modelled by a VOF method (Hirt and Nichols 1981) or a Surface Capturing method (Ingram et al 2002). The data generated under the tests described in this paper will be fed into the CLASH project, along with the VOWS data and this will, hopefully, help in improving the understanding of wave overtopping and empirical prediction formulae.

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