

**MEASUREMENT AND ANALYSIS  
OF  
WAVE OVERTOPPING**

Thesis submitted in accordance with the requirements of  
the University of Liverpool for the degree of Doctor in  
Philosophy

by

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*To my precious family*

## ***ABSTRACT***

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TITLE : Measurement and Analysis of Wave Overtopping  
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Rising sea levels associated with global warming are a threat to the coasts of the UK and continental Europe. Choosing appropriate guidance is essential when designing sea defences, since building and maintaining coastal structures are difficult and expensive operations. Specifying the front slope and the crest are major factors influencing the cost of these structures and overtopping is the most important measure in fixing their values.

A number of methods have been published to predict overtopping discharges but they hardly give reliable estimates. The absence of a wholly reliable overtopping prediction method led to the present research. The Department for Environment, Food and Rural Affairs (DEFRA) funded project FD2410 and commissioned Hydraulics Research Wallingford Ltd (HRW) to perform an extensive series of physical model tests. Seconded from the University of Liverpool, the author performed all but a minor proportion of these tests. Amongst the collaborators, this project was known as SHADOW, which stands for Sea Hazard Defences against Overtopping by Waves.

Model structures with front slopes of 1:2, 1:10 and 1:15 were tested against random waves. Wave statistics and overtopping information were recorded and data saved in digital files for further analysis. In total, 219 new conditions were investigated.

Accurately recording overtopping is a difficult task, especially when it is necessary to identify individual events, many of which involve small volumes of water. For this reason, a major part of the project involved the writing of a computer program called proBAY to analyse the SHADOW data. It investigated the overtopping data, identified the recorded overtopping events and determined the individual overtopping volumes.

The proBAY results were analysed and compared with the estimated values provided by the most popular methods for predicting the mean overtopping discharge. Two of the methods were then successfully extended to incorporate the new data for the shallow front slopes of 1:10 and 1:15.

The extensive new data set on individual overtopping volumes was also used to investigate the distribution of volumes, with a view to predicting the maximum individual volume during a storm. It was shown that this task remains problematical. Nevertheless, the new data provide the opportunity for the natural variability in overtopping volumes to be incorporated in available software to assess the risks posed by overtopping.

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## ***LIST OF NOTATION***

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<b>Notation</b>	<b>Definition</b>
$a, b$	Empirical coefficients
$A, B$	Curve fitting constants
$C$	<ul style="list-style-type: none"><li>• Curve fitting constant</li><li>• Concentration of spray</li></ul>
$C_{z=0}$	Concentration of spray just above the water level
$d_b$	Water depth over the berm
$d_s$	Water depth at the toe of the structure
$f$	Frequency
$f_p$	Peak frequency
$g$	Acceleration due to gravity
$H$	Wave height
$\bar{H}$	Mean wave height
$H_{\max}$	Maximum wave height
$H_o$	Deep-water wave height

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$H_{rms}$	Root-mean-square wave height
$H_s$	Significant wave height, also written as $H_{1/3}$
$H_{so}$	Deep-water significant wave height
$K_r$	Refraction coefficient
$K_s$	Shoaling coefficient
$l_*$	Characteristic length
$L$	Wave length
$L_o$	Deep-water wave length according to linear wave theory
$\bar{L}_{om}$	Mean deep-water wave length calculated using $T_m$
$L_{op}$	Deep-water wave length calculated using $T_p$
$L_r$	Prototype / model length ratio
$m$	$\cot \alpha$ , the seawall slope is denoted 1 : $m$
$n$	Ratio of the number of run-ups to the number of incident waves
$N$	Number of incident waves
$N_o$	Number of overtopping waves
$N_R$	Number of individual run-ups

$p$	Percentage value which is not exceeded by individual run-ups
$P_o$	Exceedance probability of individual overtopping volumes
$P_{ow}$	Probability of overtopping per wave
$Q$	Mean overtopping discharge (volume per unit time per unit width)
$Q_b$	Dimensionless overtopping discharge for breaking waves
$Q_m$	Measured mean overtopping discharge
$Q_n$	Dimensionless overtopping discharge for non-breaking waves
$Q_p$	Predicted mean overtopping discharge
$Q_*$	Dimensionless overtopping discharge
$R$	Wave run-up
$R_b$	Dimensionless freeboard for breaking waves
$R_c$	Seawall freeboard (the vertical distance from the still water level to the crest of a structure)
$R_{\max}$	Maximum run-up
$(R_{\max})_{p\%,N_R}$	Value below which $p\%$ of the maximum run-ups fall in runs of $N_R$ individual run-ups
$R_n$	Dimensionless freeboard for non-breaking waves

$R_s$	Significant wave run-up
$R_{n\%}$	Wave run-up exceeded by only n% of the incident waves
$R_*$	Dimensionless freeboard
$s_m$	Wave steepness calculated using $T_m$
$s_p$	Wave steepness calculated using $T_p$
$t$	Time
$t_{st}$	Storm duration
$T$	Wave period
$T_m$	Mean zero-crossing wave period
$T_p$	Wave period corresponding to the peak of the wave spectrum
$T_s$	Significant wave period, also written as $T_{1/3}$
$V_{bar}$	Mean overtopping volume derived on the assumption of a Weibull distribution of individual overtopping volumes
$V_{char}$	Volume scale parameter
$V_{max}$	Maximum overtopping volume
$V_{mean}$	Mean overtopping volume
$V_{tot}$	Total overtopping volume

$V_{\#}$	Arbitrary individual volume
$w_b$	Berm width
$X$	Independent variable
$Y$	Linear function of variable $X$
$z$	Vertical distance above the water level
$\alpha$	Angle of seawall front slope measured from horizontal
$\beta$	Shape parameter
$\gamma$	Parameter (ranging from 0 to 1 for spray overtopping calculations)
$\gamma_f$	Reduction factor for slope roughness
$\gamma_h$	Reduction factor for a shallow foreshore
$\gamma_{\beta}$	Reduction factor for oblique wave attack
$\pi$	3.141592654...
$\theta$	Angle of wave attack (obliquity)
$\xi$	Surf similarity parameter or Iribarren Number
$\xi_m$	Surf similarity parameter calculated using the mean zero-crossing wave period
$\xi_p$	Surf similarity parameter calculated using the period of peak spectral density
$\xi_{p,eq}$	Breaker parameter based on an equivalent slope

## ***LIST OF ABBREVIATIONS***

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<b>Abbreviation</b>	<b>Definition</b>
<i>BS</i>	British Standard
<i>BSI</i>	British Standards Institution
<i>CEM</i>	Coastal Engineering Manual
<i>CIRIA</i>	Construction Industry Research and Information Association
<i>CoFloHWO</i>	Coastal Flooding Hazard by Wave Overtopping
<i>CUR</i>	Centre for Civil Engineering Research and Codes
<i>DEFRA</i>	Department for Environment, Food and Rural Affairs
<i>EPSRC</i>	Engineering and Physical Sciences Research Council
<i>H&amp;R</i>	Hedges and Reis
<i>HRW</i>	Hydraulics Research Wallingford Ltd.
<i>JONSWAP</i>	Joint North Sea Wave Project
<i>LAD</i>	Least Absolute Deviation
<i>LS</i>	Least Squares

<i>MAFF</i>	Ministry of Agriculture, Fisheries and Food
<i>MSL</i>	Mean Sea Level
<i>MWL</i>	Mean Water Level
<i>PM</i>	Pierson-Moskowitz
<i>RMS</i>	Root-Mean-Square
<i>SHADOW</i>	Sea Hazard Defences against Overtopping by Waves
<i>SPM</i>	Shore Protection Manual
<i>SWL</i>	Still Water Level
<i>TAW</i>	Technical Advisory Committee on Water Defences
<i>USACE</i>	US Army Corps of Engineers
<i>VOWS</i>	Violent Overtopping of Waves at Seawalls
<i>WSP</i>	WSP Development Ltd

# *Chapter 1*

## **INTRODUCTION**

Currently available overtopping prediction methods are not always in good agreement. To further investigate the overtopping performance of coastal structures, the UK's Department of Environment, Food and Rural Affairs (DEFRA) commissioned HR Wallingford Ltd to perform a series of physical model tests. Data obtained from these model tests have been analysed and compared with the values estimated by various prediction methods. Further investigations have also been pursued on wave-by-wave overtopping volumes.

### **1.1. Scope of the study**

Sea level rise is a well-known fact (Woodroffe, 2003) and will cause considerable problems in the near future. Moreover, building and maintaining coastal structures are difficult and expensive operations. Setting the crest level of a seawall 1.0m too high may cost in the region of an additional £1500-2000 for a metre length of the structure (Allsop *et al.* 2005). This estimate was given for relatively steep-slope structures and the figure will be higher for milder slopes. Depending on its type, a kilometre of a seawall can cost £2-10 million (Shareef, 2005).

Thousands of kilometres of man made coastal defences are built around Europe and 23% (860 kilometres) of the English coastline is protected mostly in the form of seawalls (Besley, 1999a). Local conditions (e.g. the dominant wind direction and wind speed, the fetch, the water depth in front of the proposed structure, etc.) must be carefully evaluated before designing such structures.

Over the last few decades, researchers have addressed problems caused by severe storms along the coasts. However, wave overtopping is a wide subject and, hence, it is difficult to cover in any one study. Thus, separate investigations have been done on seawalls (e.g. Battjes 1974; Owen, 1980; Hedges & Reis, 1998), on rubble-mound structures (e.g. Jensen & Sorensen, 1979; Aminti & Franco, 1988; De Waal & Van der Meer, 1992; Juhl & Sloth, 1994) and on vertical structures (e.g. Franco *et al.*, 1994; Van der Meer & Janssen, 1995, Franco & Franco, 1999; Allsop *et al.*, 2005).

Various models have been published to predict overtopping discharges. Amongst the different proposals, the overtopping prediction methods provided by Owen (1980), Van der Meer & Janssen (1995) and Hedges & Reis (1998) are the most popular ones in Europe. However, their predictions often disagree significantly. Therefore, one of the main purposes of the present study was to validate, where appropriate, one of these existing methods.

Although a study of the available literature suggests that a wide range of conditions has been covered, there remain gaps in the data for shallow slopes and low overtopping rates. Tests are reported here on 1:10 and 1:15 slopes in order to fill some of the gaps. A slope of 1:10 is a general minimum for shingle slopes and 1:15 is a general maximum for sand slopes. Such beach slopes are common throughout the British Isles. Plane



slopes have been employed for consistency with earlier benchmark tests. In addition, the focus of the study is on wave-by-wave overtopping at low overtopping rates. The model structures are tested against normally-incident waves, which generally provide higher overtopping than obliquely incident waves.

Hydraulics Research Wallingford Ltd (HRW) was commissioned by the UK Government, Department for Environment, Food and Rural Affairs (DEFRA) to perform an extensive series of physical model tests to investigate the overtopping performance of coastal defences. Seconded from the University of Liverpool, the author performed all but a minor proportion of these tests. The project, FD2410, was initially named “**C**oastal **F**looding **H**azard by **W**ave **O**vertopping” (CoFloHWO). However, amongst the collaborators, the project is known as **S**ea **H**azard **D**efences against **O**vertopping by **W**aves (SHADOW).

The “Absorbing Flume” and the “Three-foot Flume” at HRW were employed to perform the tests. Smooth surface model structures with different front slopes were tested against a wide range of wave conditions. The data were collected and recorded digitally. Beyond the mean overtopping discharge values, information about wave-by-wave overtopping volumes and their distributions was also investigated.

Accurately recording overtopping is a difficult task, especially when it is necessary to identify individual events, many of which involve small volumes of water. For this reason, a major part of the project involved the writing of a computer program named *proBAY*, which was compiled in FORTRAN, to analyse the recorded data files and to render results in separate output files. After checks, the results from *proBAY* were found to

be reliable. Microsoft Excel workbook files incorporating macros were prepared to assist the *proBAY* software and to store the results.

The most promising overtopping prediction methods have been compared with the results of the SHADOW experiments. The wave-by-wave overtopping performances have also been investigated. It is shown that the two-parameter Weibull distribution represents the distribution of individual overtopping volumes very well. The maximum overtopping volume within a storm has also been examined but predicted values show poor agreement with measurements.

## 1.2. Objectives

The main aims of this research were:

- to collect new data on the overtopping of model seawalls with impermeable front slopes of 1:2, 1:10 and 1:15, with particular emphasis on low overtopping rates;
- to write new software to detect small overtopping volumes;
- to check the reliability of the new results by comparing the 1:2 data with previous results;
- to identify the most promising methods for predicting mean overtopping discharges;
- to investigate individual overtopping volumes;
- to make recommendations for further research.

### 1.3. Structure of the thesis

The main body of this thesis consists of five chapters.

Chapter 2 provides some basic knowledge about coasts, waves and wave action against coastal structures. Also, overtopping prediction methods and their applications are discussed in detail.

Chapter 3 gives information about the physical modelling studies. Facilities at HRW, the SHADOW project details (from its design to the physical model tests), problems that occurred while testing and solutions to these problems are given in Chapter 3. Primary results are also given in this chapter.

While testing the model structures, data were recoded on digital files for further investigation. These data files have been treated by means of a computer program called *proBAY* which was compiled in FORTRAN. The *proBAY* software, its application and details of Microsoft Excel workbooks used to assist *proBAY* software are described in Chapter 4.

The overtopping performances of simply sloping model structures with smooth front faces have been examined. Beyond the mean overtopping discharges, wave-by-wave overtopping distributions have been investigated. The *proBAY* software outputs are compared with the values predicted by existing methods. Details of the analysis are given in Chapter 5.

Finally, concluding remarks drawn from this study are presented in Chapter 6.

# *Chapter 2*

## LITERATURE REVIEW

Sea defences are expensive structures to build and to maintain. They are built relying heavily on codes of practice. However, currently available prediction methods often give unreliable forecasts of wave overtopping of coastal structures. This chapter addresses these problems. It gives some basic knowledge about the terminology and detailed information about previously developed overtopping prediction methods. These methods are mainly based on laboratory data for structures subjected to irregular waves.

### **2.1. Introduction**

Throughout the centuries, the sea has held a fascination for mankind. Humans liked living close to the sea. This can easily be seen by considering the population variations between coastal settlements and inland areas. In addition, advantages such as sea trade and fishing meant that countries having coasts wanted to use every benefit the sea could offer them. In modern times, billions of pounds worth of investments have been made in defending coastal cities. This has been accelerated by the threat of rising sea levels caused by the greenhouse effect, tsunamis caused by earthquakes, etc, and these have illustrated the threat to mankind posed by the sea.

Waves can lead to many physical processes in the coastal zone. Amongst these, run-up and overtopping play important roles for design purposes. Codes of practice for the design of coastal structures differ from one country to another. In the USA, the US Army Corps of Engineers (USACE) is responsible for the design and construction of defences. In the UK, the British Standards Institution (BSI) has issued the Code of Practice for Maritime Structures (BS 6349), and this is intended to be of direct use in the design of sea walls and similar structures. However, recent coastal flooding events have shown that codes of practice (or guidelines, etc.) have to be brought up to date with continuous development programmes.

In recent decades, researchers have performed various laboratory experiments to test the wave overtopping performance of model structures and have tried to accurately reproduce real conditions. Nevertheless, test conditions were initially limited to regular wave trains (Saville, 1955). Later, researchers started employing more realistic sea states with irregular waves conforming to defined spectral shapes. Consequently, the main focus of the literature review is on overtopping of structures by irregular waves. Furthermore, most overtopping tests have been performed for waves which are normally incident on structures. Nevertheless, the review includes some limited information on non-normal wave conditions.

## **2.2. Coasts, waves and structures**

The *coastal zone* is defined as the transition zone where the land meets the sea, the region that is directly influenced by marine hydrodynamic processes, according to the Coastal Engineering Manual (USACE, 2002). The *coast* is defined as a strip of land of indefinite width that extends from the coastline inland as far as the first major change in topography; the *coastline* is simply defined as the border between the terrestrial and the marine environments. Wave and current characteristics, and the local

characteristics of the land e.g. the geological formation, play an important role in forming the profile of a particular coast. Figure 2-1 shows a sandy beach profile. Coasts with fine sands can have very wide beaches, with slopes as low as 1:100 or even flatter. In contrast, the slope of a shingle beach ranges from 1:10 to 1:2. If the land consists of high solid rocky material, the coast will be dominated by cliffs.

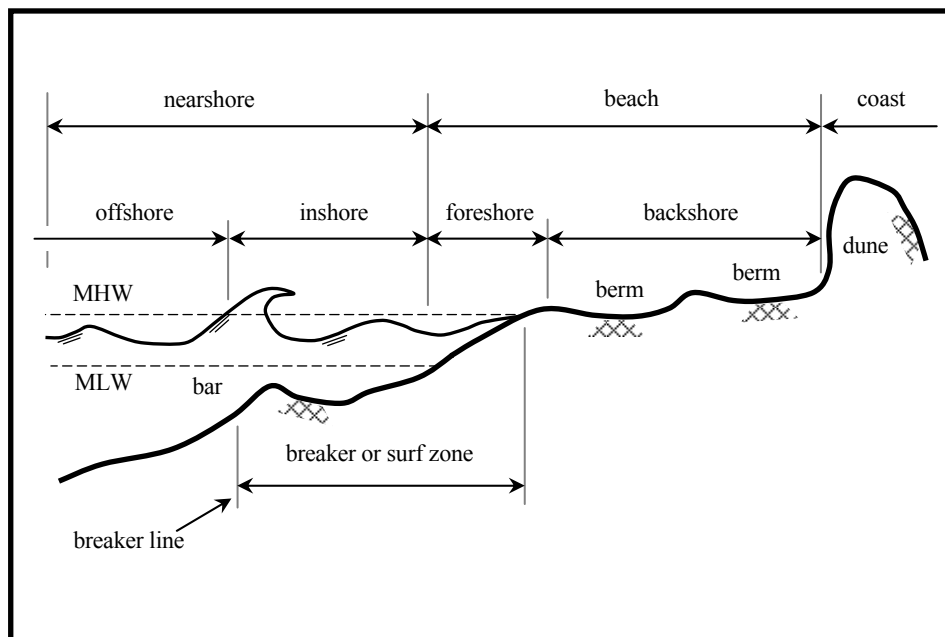


Figure 2-1 Sandy beach profile (Liverpool/Thessaloniki Network, 1996)

Waves are the major factor in determining the geometry and composition of the coastline. They influence the planning and design of harbours, shore protection measures, and other works. Waves observed at the coasts are mostly generated by the wind. Wave growth starts by the wind blowing over the sea causing a shear stress at the surface. The waves grow with increasing wind speed, increasing duration of the wind and increasing length of the generation area (also called the *fetch*). Waves will keep travelling as swell, even if the wind stops.

Wave theories are approximations to reality. They may describe some phenomena well under conditions that satisfy the assumptions made in their derivation. However, they may fail to describe other phenomena that violate those assumptions. Regular wave theories usually define waves by their heights and periods (see Figure 2-2). The **wave height**  $H$  is the vertical distance between the wave crest and the wave trough. The **wave period**  $T$  is the time that passes between two consecutive wave crests being at a given point (or the inverse of the wave frequency,  $T = 1/f$ ). The **wave length**  $L$  is defined as the distance between two wave crests.

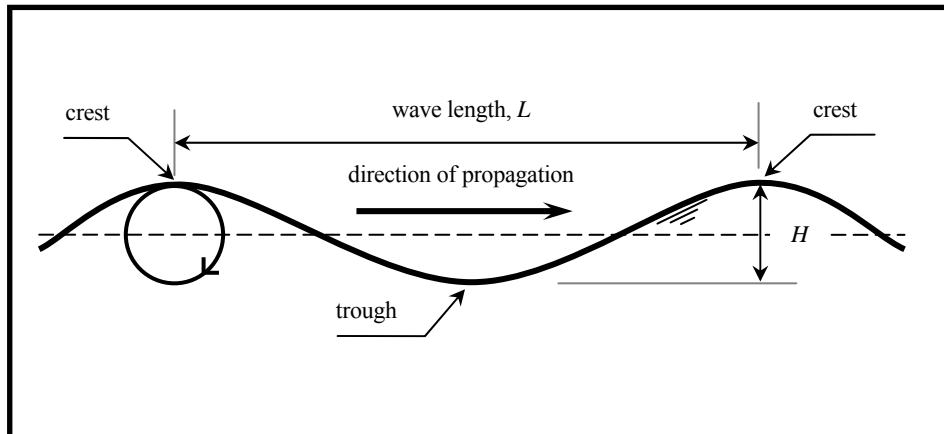


Figure 2-2 Water particle motion in linear wave theory

Unlike regular waves that result in a single value of wave height and wave period, **irregular waves** have a distribution of these characteristics. For characterisation, there are many candidate parameters which may be used to define the statistics of irregular sea states. Nevertheless, two of the most important parameters necessary for adequately quantifying a given sea state remain a characteristic wave height and period, as in linear wave theory.

Using the zero up-crossing method (recording a wave every time the water level rises across the zero line), individual waves can be detected from a continuous record of water-level variation (see Figure 2-3). Furthermore, approaches such as spectral analysis can be used to determine a graph of energy against frequency from a time-series of water surface elevation (Woodroffe, 2003).

A characteristic wave height for a random sea state may be defined in several ways. The most common in coastal engineering is the **significant wave height**, denoted as  $H_s$ . This is the mean height of the highest one third of the waves and may also be written as  $H_{1/3}$ . It characterises the short-term recorded conditions and may be used to estimate the short-term distribution of individual wave heights. Other statistical quantities are the mean of all the measured wave heights in an entire record; this is the **mean wave height**  $\bar{H}$ . The largest wave height in the record is the **maximum wave height**  $H_{max}$ . The root-mean-square of all the measured wave heights is  $H_{rms}$ .

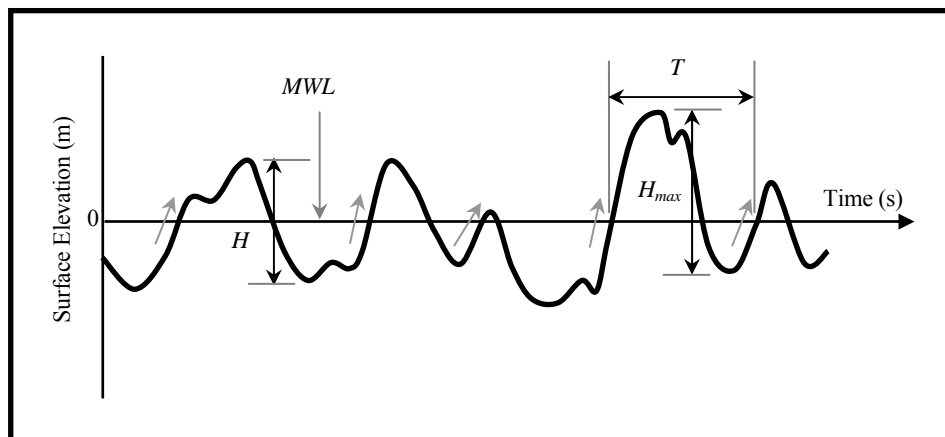


Figure 2-3 Wave parameters for random sea state



The distribution of wave heights can be expressed as a histogram. The smoothed histogram of normalized wave heights suggests the existence of some theoretical distribution function. Stochastic wave descriptions play an important role in coastal engineering and Thompson (1977) indicated how well coastal wave records often follow the Rayleigh distribution (Figure 2-4).

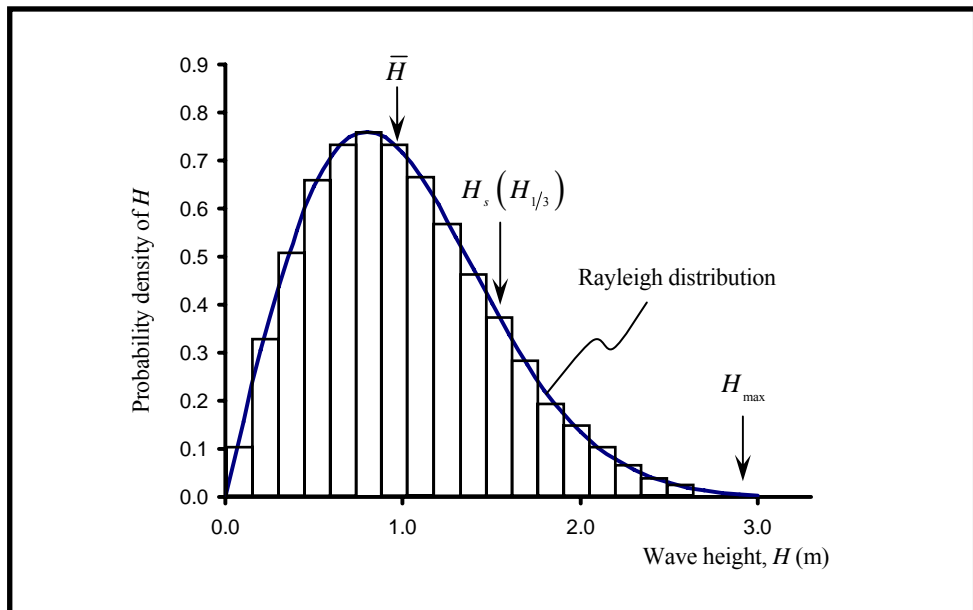


Figure 2-4 The distribution of irregular wave heights

A similar approach may be used to characterise the wave period. The **significant wave period**,  $T_s$  (or  $T_{1/3}$ ) is the average period of the highest one third of the waves.

The **mean wave period** ( $T_m$ ) is the mean period of all the waves; it may be established by counting the number of up-crossings of the mean water level (MWL, see Figure 2-3). The **peak wave period** ( $T_p$ ) corresponds to the peak of the wave spectrum and is calculated by  $T_p = 1/f_p$  (see Figure 2-5).

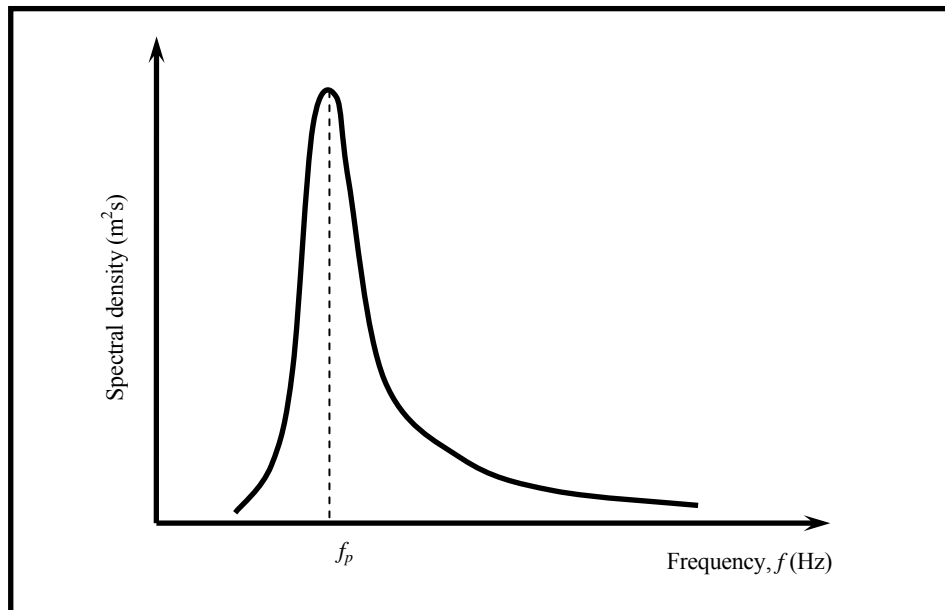


Figure 2-5 Wave spectrum

Coastal defence structures are primarily built to protect land against erosion, flooding, or any other threat by the action of the sea. Allsop (1986) has defined a *sea wall* as a structure whose primary purpose is either to provide protection against erosion, the alleviation of flooding, or a combination of both, in which wave action plays a dominant role. The purpose of *breakwaters* is to protect a harbour against wave action and to prevent sedimentation at the harbour entrance.

There are different types of breakwaters and typical ones are called rubble mound breakwaters, vertical breakwaters and composite breakwaters. Constructing a *rubble mound breakwater* is relatively simple but requires large amounts of material in deep-water. The structure consists of a core of quarry run protected by primary armour on the seaward slope, on the crest and on part of the leeside slope. A filter layer or secondary armour layer is usually needed between the core and primary armour. Quarry stone is the most commonly used material for protecting embankments from wave

attack. The maximum size of armour rock which can be economically obtained will be the principal factor in determining whether rock or concrete armour units are chosen for the primary armour. The armour size, layer thickness and slope depend on the design wave characteristics.

The seaward slope angle has an influence on wave overtopping, as do different armour types (Aminti & Franco, 1988). In the UK, the Victorians, at the beginning of the twentieth century, started a trend for seaside holidays and a consequent popularity for promenades. These promenades are walkways along the coastline which combine public amenity with coastal defence structures which are often close to vertical. *Vertical caisson breakwaters* are designed to protect harbour areas using less material than rubble mound breakwaters, often being easier to construct in areas with mild wave climates. Breakwaters are built to provide shelter for ships to dock and unload, while sea walls need to protect coasts from flooding and erosion. Obviously, both need to resist waves, but the impacts of reflected wave energy on sediment stability, which is usually not critical in harbour areas, causes problems for sea walls and their fronting beaches. Figure 2-6 illustrates a **composite breakwater** which is the combination of vertical and rubble mound breakwaters.

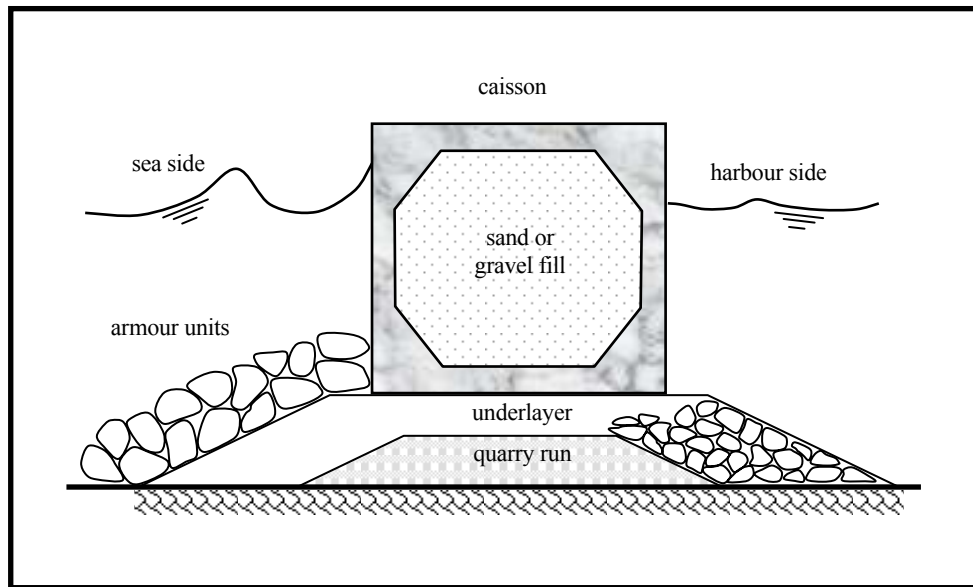


Figure 2-6 Composite breakwater

### 2.3. Factors affecting overtopping discharges

In the last few decades, various laboratory tests and field measurements have been carried out and several factors have been found to affect overtopping discharges. Coastal floods caused by the combination of high tides, storm surges and storm generated wind-waves are a major natural hazard in many parts of the world.

Nowadays, *global warming* is a well-known fact and is causing an increase in the *mean sea level* (MSL). MSL is the mean of the surface elevation over some suitably long period. The rate of sea-level rise, indeed whether there will be accelerated sea-level rise, is still subject to debate and revision (Woodworth, 1990). Note, however, that the change in local MSL also depends on local crust movements.

In addition to changes in mean sea level, *tidal effects* and meteorological conditions such as the *dominant wind direction* and its *magnitude*, and

**storm duration** have to be considered. The direct influence of wind velocity on wave overtopping and wave run-up is important and must be considered. Even when the wind velocity does not exceed 30m/s, the influence of wind setup and spray on wave overtopping rates should be considered (Yoshimichi *et al.*, 2000).

In general, the observed sea level,  $Z(t)$ , which varies with time  $t$ , is given by Pugh (1987):

$$Z(t) = Z_o(t) + T(t) + S(t) \quad (2.1)$$

$Z_o(t)$  represents the mean sea level which changes slowly with time,  $T(t)$  represents the tidal variation about the mean level and  $S(t)$  is the storm surge.

Wave characteristics have the highest importance in overtopping phenomena and they are affected by several factors as waves approach the shore. **Shoaling** is the reduction in water depth and the associated change in wave height when waves propagate shoreward. The effect is normally expressed in terms of the shoaling coefficient,  $K_s$ , which is defined as the local (unrefracted) wave height relative to the offshore (deep-water) wave height  $H_o$  (CIRIA/CUR, 1991). **Refraction** is the change in the direction of wave propagation when waves propagate in varying water depth and any associated change in wave height is expressed in terms of the refraction coefficient,  $K_r$  (CIRIA/CUR, 1991). Higher sea levels, from the effects of global warming, will result in many local changes in wave refraction patterns.

Besides the effects of shoaling and refraction, wave breaking plays an important role in run-up and overtopping. The TAW (2002) formulae consider breaking and non-breaking waves on a slope. As waves progress into shallower water, they become steeper because wave height generally increases but wave length decreases (Komar, 1998). **Steepness**, the ratio of wave height to wave length, has a maximum value of around 0.14, at which point the wave becomes unstable. However, in shallow water, it is the ratio of wave height to water depth which governs wave breaking, with the limiting value of the ratio falling in the range 0.7 to 1.3. As the velocity of the wave is dependent upon water depth, the rate of travel of the crest is faster than that of the trough (Thorpe, 2001). This is called **wave breaking** and the wave loses its height at the end of this process. Part of the wave energy is dissipated into sound, friction and turbulence, part of the energy is reflected and part proceeds in the smaller remaining wave (Liverpool/Thessaloniki Network, 1996). Depending on the bottom slope and wave steepness, breakers in the surf zone can be seen in four forms: *spilling*, *plunging*, *collapsing* and *surging* (see Figure 2-7).

On very flat beaches, **spilling breakers** are found. The waves break gradually over a very long distance. On steep shores, the more spectacular **plunging breakers** can be seen. The waves break with the crest curling and falling into the preceding trough in one short impressive motion. Steeper slopes may end up with **collapsing breakers** and on extremely steep slopes, such as rocky shores, **surging breakers** can occur. In this case, the wave is reflected before the top can curl over.

Breaker type may be correlated to the **Iribarren Number**,  $\xi_p$ , which is also known as the **surf similarity parameter** (or breaker parameter) and is

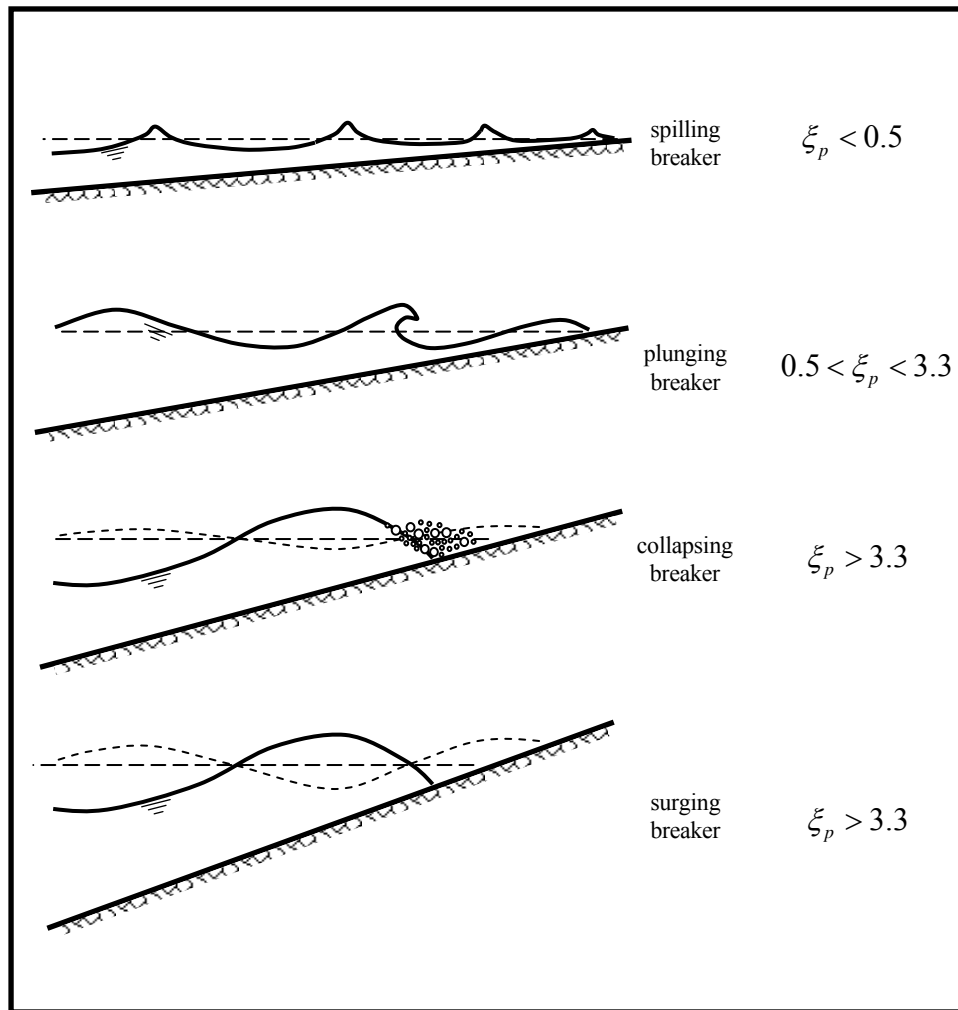


Figure 2-7 Types of breaking waves

one of the most important parameters in estimating run-up and overtopping. The relative run-up (the ratio of run-up to incident wave height) is usually given as a function of  $\xi_p$ , which is defined as:

$$\xi_p = \frac{\tan \alpha}{\sqrt{s_p}} \quad (2.2)$$

where  $\tan \alpha$  (also commonly designated  $1/m$ , see later) is the front slope of the structure (or the beach) and  $s_p$  is the wave steepness defined by  $s_p = H_s/L_{op}$ .  $L_{op}$  is the offshore wave length corresponding to the spectral peak period ( $L_{op} = gT_p^2/2\pi$ ). Although  $\xi_p$  is a good measure for run-up estimations, the use of different  $T$  values (e.g.  $T_m$ ) and  $H$  values (whether deep-water or the local values) is reported as a problem by De Rouck & Verdonck (1998).

Wave **reflection** from very steep shores leads to an increase in the wave height (almost 100% for complete reflection from vertical walls). This increase in the wave height may cause waves to break due to depth limitations and/or wave steepness.

There is a phenomenon local to the surf zone, wherein wave breaking causes a stress, or a landward push of the water which causes it to pile up against the shore until the seaward slope of the water is sufficient to oppose the wave stress. This is called **wave set-up** to distinguish it from storm set-up or storm surge and from wind set-up. Wave set-up can range from 17-50% of the incident wave height on natural beaches (Holman, 1990).

The angle of wave attack, which is known as **obliquity** is another factor influencing overtopping discharges that needs be considered in the design process; it is measured as  $\theta$  ( $\theta = 0$  for perpendicular wave attack). Owen (1982) compared the discharge levels for different angles of wave attack and stated that the discharge is reduced if the waves strike a seawall at an angle. A modified Iribarren number provided by Losada & Gimenez-Curto (1981) for oblique wave attack is cited by De Rouck & Verdonck (1998):



$$\xi = \frac{\tan \alpha \cos \theta}{\sqrt{H/L_o}} \quad (2.3)$$

where  $L_o$  is the deep-water wave length for a regular wave of period  $T$  ( $L_o = gT^2/2\pi$ ).

Juhl & Sloth (1994) ran tests with four wave steepnesses and concluded that this parameter has an influence on wave overtopping for perpendicular wave attack, whereas the influence is decreased for oblique waves. When breaking or broken waves strike the face of a structure such as a groin, bulkhead, seawall or breakwater at an oblique angle, the dynamic component of the pressure or force will be less than for breaking or broken waves that strike perpendicular to the structure (Shore Protection Manual, (SPM), 1984).

One of the most important considerations in designing coastal structures is to fix the crest level. In this respect, a good estimate of run-up is essential to establish the necessary freeboard. **Freeboard** ( $R_c$ ) is defined as the vertical distance from the still water level (SWL) to the crest of a structure.

Owen (1982) concluded that apart from raising the crest elevation, the overtopping discharge can also be reduced by flattening the seaward **slope**,  $1/m$ , by increasing the **berm width**,  $w_b$ , of composite structures or by reducing the **water depth**,  $d_b$ , over the berm, where **water depth** at the toe of the structure is  $d_s$  (see Figure 2-8).

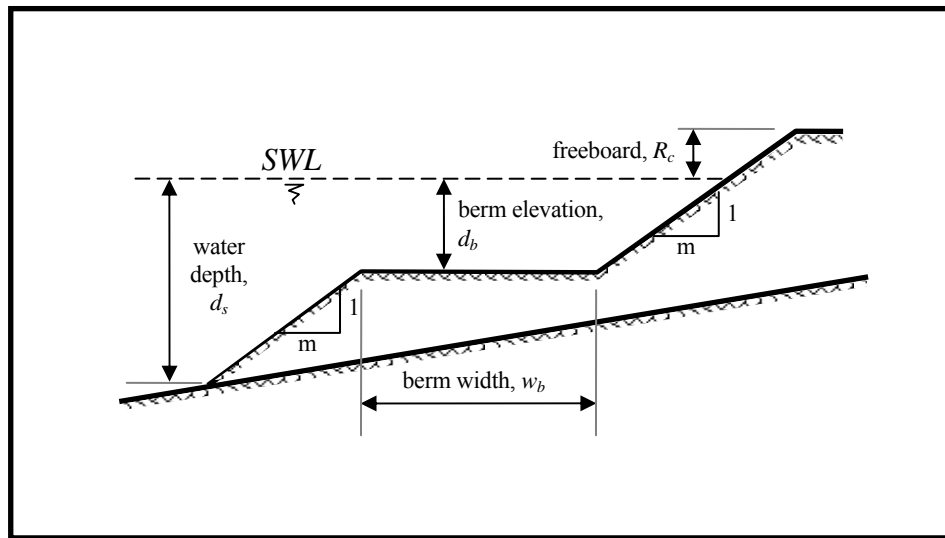


Figure 2-8 Bermed seawalls

Following a series of laboratory tests, and combining the results with the existing overtopping data provided by Owen (1980), a **recurved wave return wall** was also found to have an important effect on overtopping discharges (Herbert *et al.*, 1994). Some test conditions were found to give overtopping discharges which were reduced by almost three orders of magnitude compared to the expected situation without a return wall.

The **surface texture** and the **permeability** of a structure have crucial effects on overtopping discharges, especially for sloping structures. In this respect, rubble mound breakwaters are particularly suitable as most of the wave energy is dissipated in the armour layer. Run-up levels will therefore generally be reduced. The influence of the roughness of the top layers on wave run-up and wave overtopping for twenty-seven different types of surface texture have been investigated and tabulated in Appendix 1 of TAW (2002). Several overtopping prediction formulae, including those of Owen (1980) and Van der Meer & Janssen (1995), have been derived originally for smooth impermeable slopes. A surface roughness coefficient has then been introduced into the formulae to take into account the effect

of slope roughness. The only disadvantage of having an armoured surface on a sloping structure, rather than a smooth surface, could be the possibility of higher overtopping by spray.

Use of *artificial reefs* to reduce overtopping has been studied by Sawaragi *et al.* (1988). The idea is to cause a rapid change in the water depth and have all the biggest waves break before reaching the seawall.

## 2.4. Run-up

Water surface oscillations on the surface of a sloping structure cause water to climb up the face of the structure until its kinetic energy is converted into potential energy. Therefore, *run-up*  $R$  (see Figure 2-9) is the vertical distance between the SWL and the extreme levels reached by waves on a structure. Obviously if the run-up is higher than the structure freeboard then there is overtopping. Therefore, estimating run-up is important in overtopping predictions.

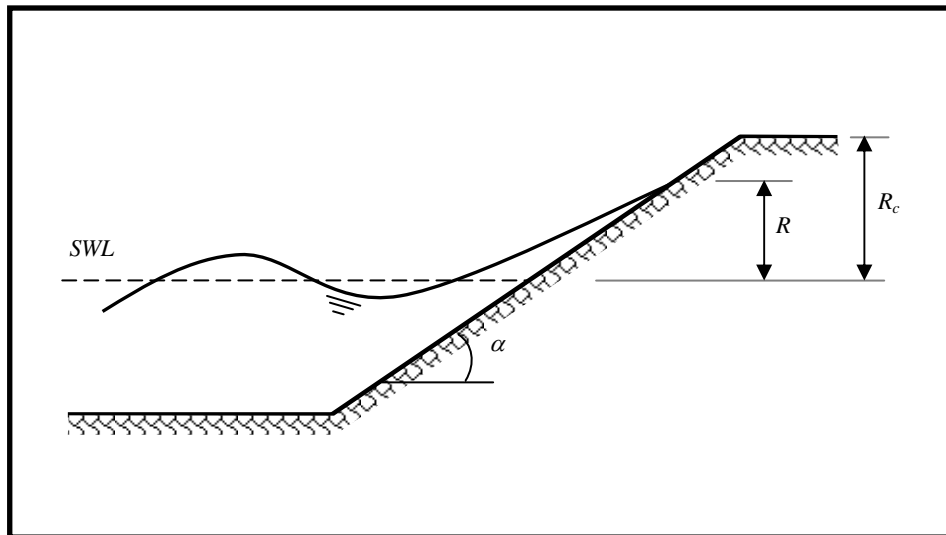


Figure 2-9 Wave run-up

Random wave run-up can be characterised by the significant wave run-up,  $R_s$ , the average of the highest one-third of the run-ups, and by  $R_{2\%}$ . This latter parameter is defined as the vertical distance between the SWL and the elevation exceeded by two percent of the individual run-up values. In other words, for every 100 waves running up a slope, two waves on average would have a run-up elevation exceeding the level estimated as  $R_{2\%}$ . Van der Meer & Stam (1992) give a formula for  $R_{2\%}$  which was provided by Wassing (1957) and was used in the Netherlands for many years:

$$R_{2\%} = 8H_s \tan \alpha \quad (2.4)$$

Battjes (1974) later modified Hunt's formula (Hunt, 1959) to give the 2% run-up level:

$$\frac{R_{2\%}}{H_s} = C \xi_m = \frac{C \tan \alpha}{\sqrt{\frac{2\pi H_s}{g T_m^2}}} \quad (2.5)$$

in which  $\xi_m$  is the surf similarity parameter based on the mean wave period,  $T_m$ , and  $C$  is a constant. Limits for the coefficient  $C$  were given as 1.49 for fully developed seas and 1.87 for very young seas. These formulae were derived from the data obtained by Van Oorschot (1968) and by Fuhrboter *et al.* (1989), mainly based on large scale measurements. Considering that  $T_p$  is often used instead of  $T_m$ , Van der Meer & Stam (1992) re-analysed the available information by adding Ahrens (1981) data for smooth slopes and provided an equation for plunging waves with  $0.5 < \xi_p < 2$ :

$$\frac{R_{2\%}}{H_s} = 1.5\xi_p \quad (2.6)$$

De Waal & Van der Meer (1992) modified equation (2.6) to include the influences of a berm, roughness, shallow water and obliquity:

$$\frac{R_{2\%}}{H_s} = 1.5\gamma_f\gamma_h\gamma_\beta\xi_{p,eq} \quad (2.7)$$

where the influence factors for roughness, shallow water and oblique wave attack are given by  $\gamma_f$ ,  $\gamma_h$  and  $\gamma_\beta$ , respectively, and  $\xi_{p,eq}$  is the breaker parameter based on an equivalent slope accounting for the presence of a berm.

Further studies were carried out by Van der Meer & Janssen (1995) using the same formula. By adding a factor of safety to the constant, they recommended the use of 1.6 and limited the validity of the formula to a maximum of 3.2 for dikes (see Figure 2-10).

Figure 2-11 shows the relative run-up levels versus the surf similarity parameter. It contains the data from Ahrens (1981) and Allsop *et al.* (1985) for smooth slopes, and Delft Hydraulics data for rock slopes. The equations were given in CIRIA/CUR (1991), which is known as the Rock Manual:

$$R_s/H_s = \begin{cases} 1.35\xi_p & \text{for } 0 < \xi_p \leq 2 \\ 3.00 - 0.15\xi_p & \text{for } 2 < \xi_p \leq 12 \end{cases} \quad (2.8)$$

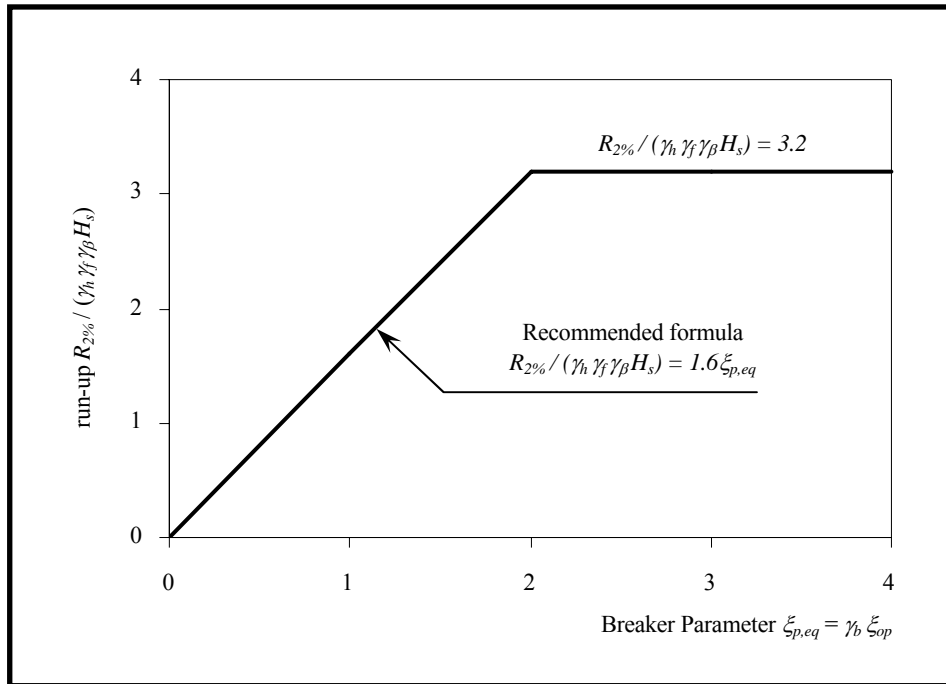


Figure 2-10 Wave run-up as a function of the breaker parameter

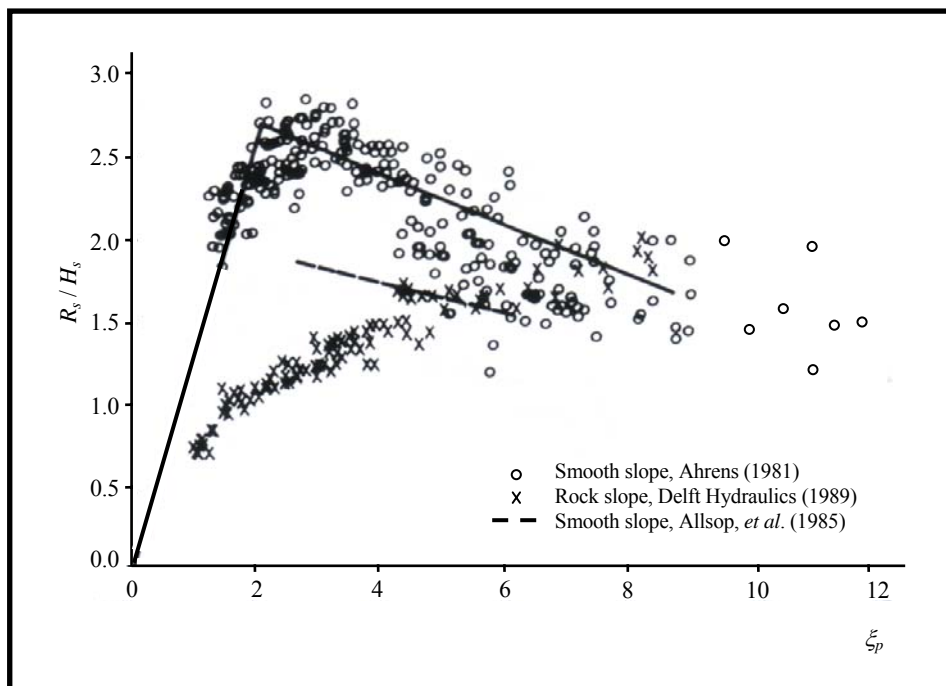


Figure 2-11 Relative run-up (CIRIA/CUR, 1991)

Recently, Mase *et al.* (2003) updated equations (2.8) by adding Japanese data. Particularly for small values of  $\xi_p$ , agreement between the equations and the run-up data was improved (see Hedges & Mase, 2004). Figure 2-12 and equations (2.9), provided by Mase *et al.* (2003), are shown below:

$$R_s/H_s = \begin{cases} 0.25 + 1.10\xi_p & \text{for } 0.0 < \xi_p \leq 2.2 \\ 3.00 - 0.15\xi_p & \text{for } 2.2 < \xi_p \leq 9.0 \\ 1.65 & \text{for } 9.0 < \xi_p \end{cases} \quad (2.9)$$

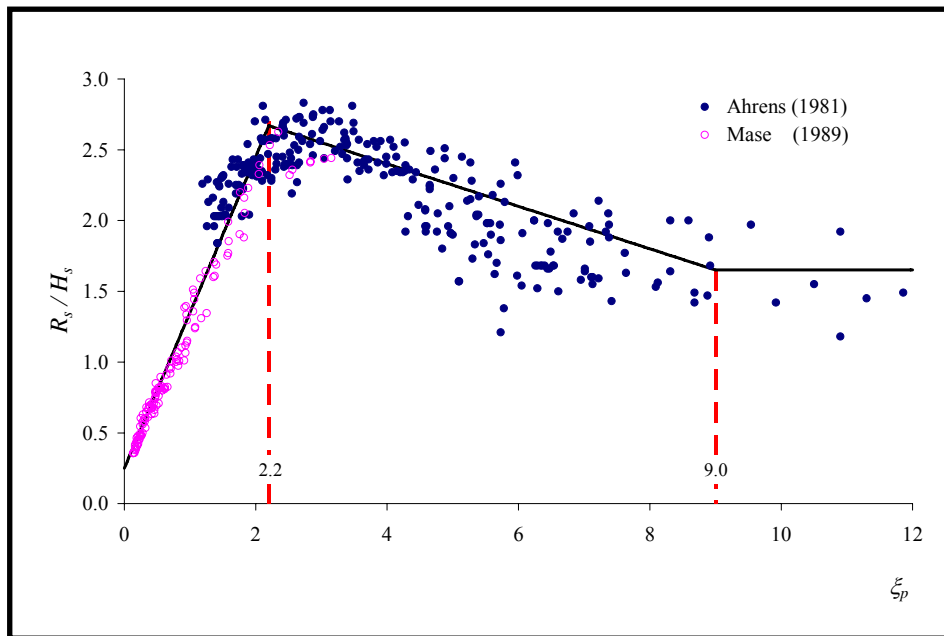


Figure 2-12 Relative significant run-up for smooth slopes (Mase *et al.*, 2003)

#### 2.4.1. Number of run-ups

The number of individual run-ups,  $N_R$ , has been studied for gentle slopes and compared with the number of incident waves,  $N$ , by Mase & Iwagaki (1984). A wave coming to the shoreline cannot run up if the back-rush of a preceding wave is large. Furthermore, a wave running up the beach face may be overtaken and captured by a subsequent wave before it reaches its

maximum run-up. Therefore, the number of run-ups may be reduced compared to the number of incident waves.

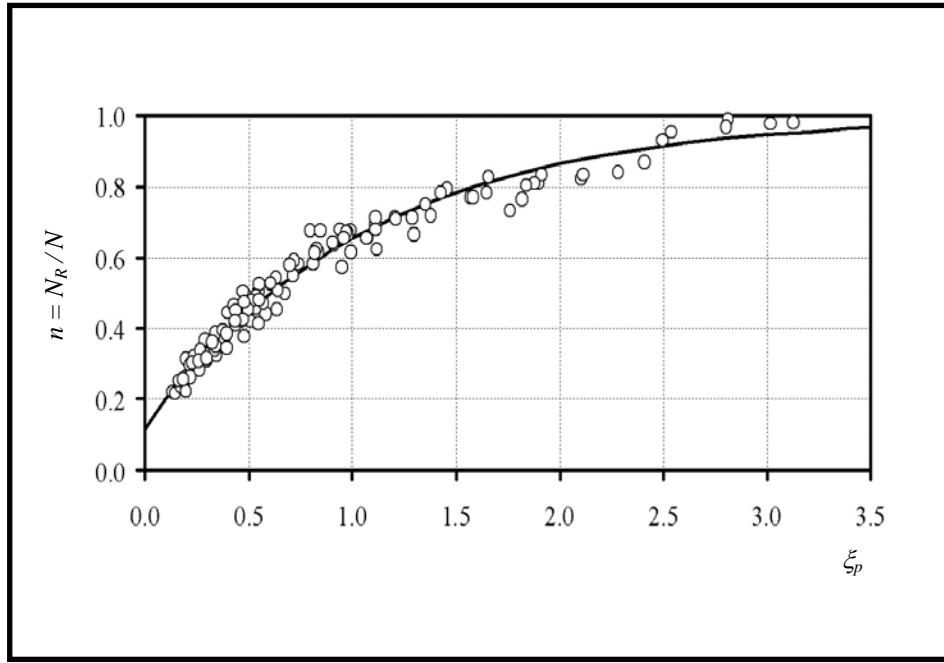


Figure 2-13 Relationship between  $n$  and  $\xi_p$  (data from Mase & Iwagaki, 1984)

Figure 2-13 shows the relationship. The ratio of the number of run-ups to the number of incident waves is:

$$n = \frac{N_R}{N} \quad (2.10)$$

in which  $0 < n < 1$ . A function fitted to the data in Figure 2-13 is (Bay *et al.*, 2005):

$$n \approx \tanh \left[ 0.07 + \left( \frac{\xi_p}{1.5} \right)^{0.8} \right] \quad (2.11)$$



### 2.4.2. Maximum run-up

The run-up on gentle, smooth and impermeable slopes has been evaluated for  $1/30 \leq \tan \alpha \leq 1/5$  and  $H_{so}/L_o \geq 0.007$  by Mase (1989). His empirical formula is in the form:

$$\frac{R}{H_{so}} = a\xi^b \quad (2.12)$$

in which  $H_{so}$  is the deep-water significant wave height and  $a$  and  $b$  are experimental coefficients determined by the least squares method. They were found to be:

$$\begin{aligned} a &= 2.32 \text{ and } b = 0.77 \text{ for } R_{\max}; \\ a &= 1.86 \text{ and } b = 0.71 \text{ for } R_{2\%} \end{aligned}$$

If a Rayleigh distribution applies to individual run-ups, then  $p\%$  of the maximum values,  $R_{\max}$ , in runs of  $N_R$  individual run-ups will fall below  $(R_{\max})_{p\%,N_R}$  given by (Hogben, 1990):

$$(R_{\max})_{p\%,N_R} = \left[ \frac{1}{2} \left\{ \ln N_R - \ln \left( -\ln \frac{p}{100} \right) \right\} \right]^{1/2} R_s \quad (2.13)$$

## 2.5. Overtopping

The run-up phenomenon has been discussed in the previous section. Run-up levels exceeding the crest of a coastal structure result in water reaching the protected area by passing over the top of the structure. This process is called **green water overtopping** (see Figure 2-14). It is one of the most important hydraulic responses at the coast and the primary

concern in designing structures to meet desired performances against flooding, and then relating the required performances to suitable structure geometries.

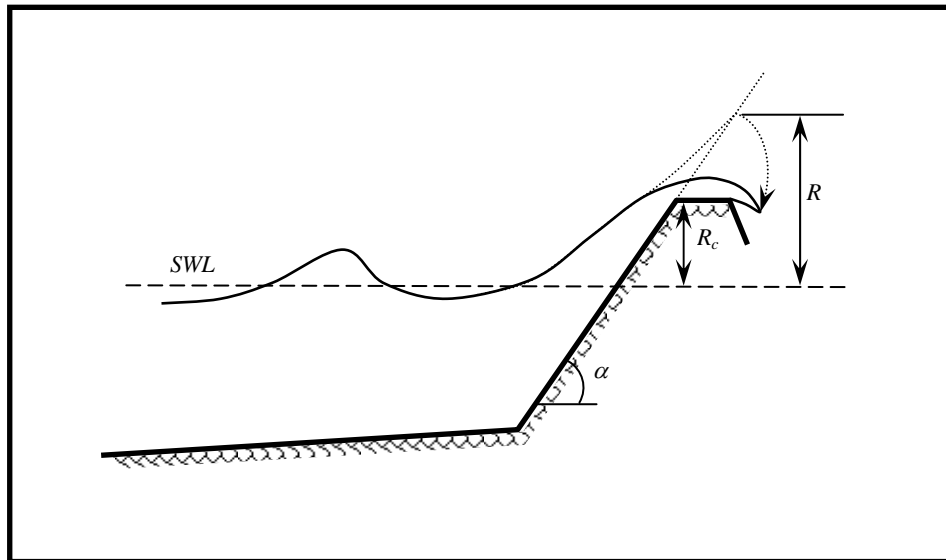


Figure 2-14 Wave overtopping of a coastal structure

The results of hydraulic model tests using random waves to determine overtopping discharges for various profiles of impermeable sea walls are given by Owen (1980). Other hydraulic model test results for seawalls include those given by Jensen & Sorensen (1979). Although many laboratory-based physical model studies have been carried out over the last few decades, and various theoretical approaches have been proposed, there are, at present, no satisfactory analytical methods for determining the quantity of overtopping water.

Close to a seawall, much of the overtopping water falls as a continuous mass and its throw is comparatively independent of the wind speed, whereas further away it falls as spray which is carried by the wind (BSI,

1999). Pullen *et al.* (2003) showed the spatial distribution of overtopping across the promenade at Samphire Hoe, using field data.

If overtopping takes place as a continuous sheet then it is defined as **green water overtopping**. This type of overtopping mainly happens with surging waves. The second form of overtopping is **spray overtopping**, discussed in Section 2.5.2.

### 2.5.1. Acceptable discharges

Wave overtopping can cause inconvenience or danger to people and vehicles, interruption to operations, and flooding, and it can induce instability to the crest and rear side of structures. Even though tolerable limits for overtopping have been investigated by a number of researchers, because of variability in design conditions (e.g. roughness, slope, sensitivity of the object on the leeside, etc.), there are still no confirmed guidelines regarding the exact limits.

Design guidance for admissible overtopping is based on the work of Fukuda *et al.* (1974). Owen (1980) developed guidance on tolerable limits by using the Japanese work and this guidance was later cited in the CIRIA/CUR (1991) manual. Franco *et al.* (1994) revised the limits for pedestrians and vehicles based on vertical breakwater tests and studies provided by Dutch researchers on dikes (see Figure 2-15). However, the suggested limits applied to trained personnel, ready and equipped to get wet, but probably not to the general public (Allsop *et al.*, 2003).

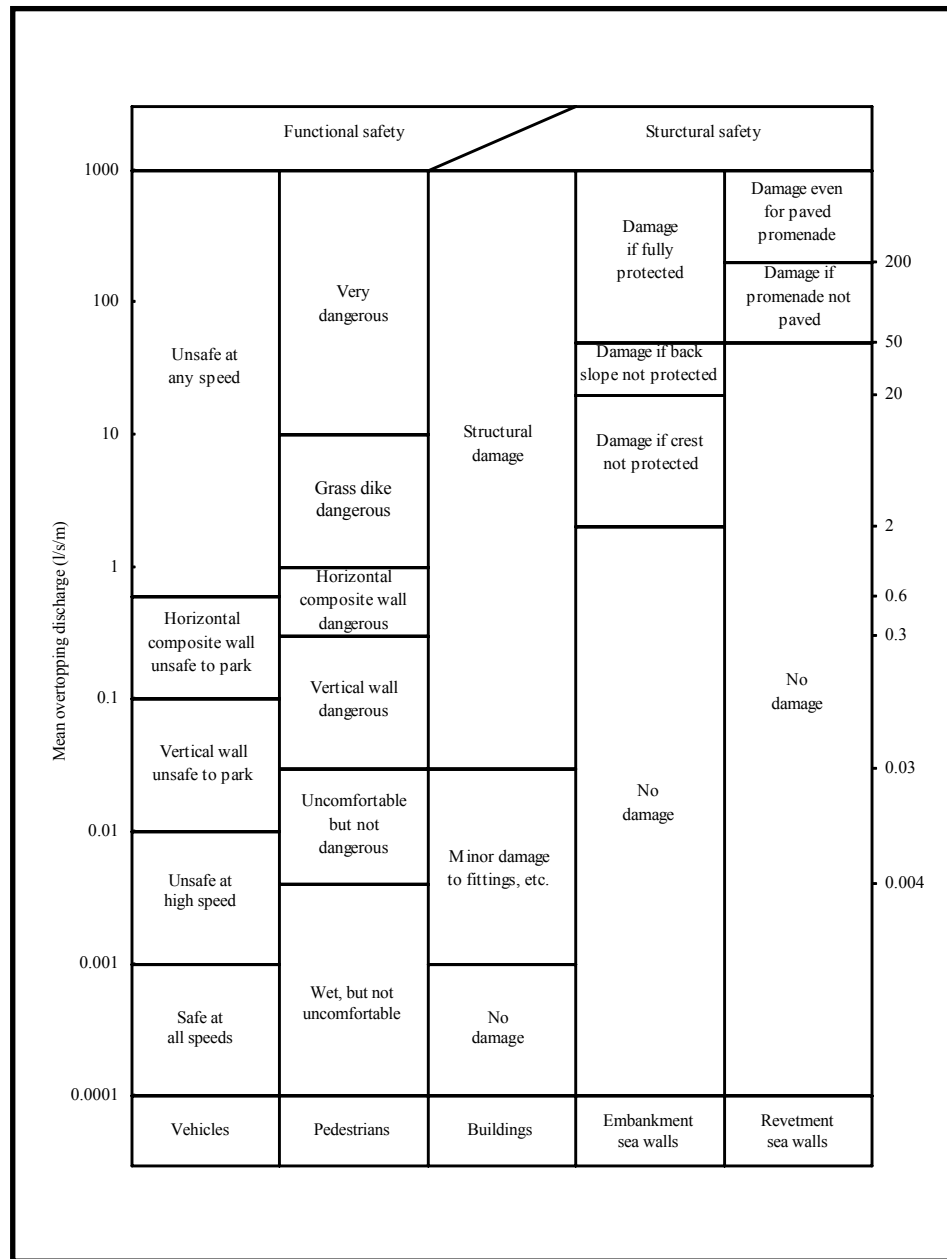


Figure 2-15 Suggested tolerable mean overtopping discharges (Franco *et al.*, 1994)

Reeve *et al.* (2004) pointed to a misconception that the overtopping discharges reduce by an order of magnitude for every 10m behind the crest or wave wall of a structure. In fact, Owen (1980) referred to Fukuda *et al.* (1974) and stated that the tolerable limits for damage (and therefore safety)

could be increased by a factor of 10, at a distance 10m behind the crest or wave wall.

### 2.5.2. *Spray Overtopping*

Plunging waves on smooth surfaces (especially steeper slopes or vertical walls) or wave action on rough surfaces may cause significant volumes of splash. Water particles may then be carried over the top of the structure by the wind. This form of overtopping is known as *spray overtopping*.

Wind effects on spray overtopping are rarely studied. Winds have a relatively small effect on green water overtopping but they may influence spray overtopping considerably (De Waal & Van der Meer, 1996).

It is obvious that the damage caused by spray overtopping is not as severe as the damage caused by green water overtopping. But the numbers of spray overtoppings may be well above the number of green water overtoppings and this may result in an uncomfortable environment as well as unsafe conditions for vehicles. Existing overtopping prediction methods were developed by using laboratory-based experimental data provided for green water overtopping, where spray cannot be correctly modelled because of the effects of viscosity and surface tension. However, spray is not presently believed to contribute significantly to overtopping volumes, and it generally causes little hazard except by reducing visibility and extending the spatial extent of salt spray effects (Allsop *et al.*, 2003).

Concentration of spray near a sea wall was found to decrease exponentially in the vertical upward direction and in the horizontal landward direction by Hashida *et al.* (1996). Matsunaga *et al.* (1994) also investigated the concentration of spray formed at the crests of breaking waves. Equation

(2.14) was suggested for the variation of concentration in the vertical direction while the horizontal variation was found to be much smaller than the vertical variation.

$$\frac{C}{C_{z=0}} = \exp \left\{ \frac{1}{1-\gamma} \left( 1 - \left( 1 + \frac{z}{l_*} \right)^{1-\gamma} \right) \right\} \quad (2.14)$$

where  $C$  is the concentration of spray,  $C_{z=0}$  is the concentration for spray just above the water level,  $z$  is the vertical distance above the water level,  $\gamma$  is a parameter ranging from 0 to 1 and  $l_*$  is a characteristic length.

### 2.5.3. Mean overtopping discharge

Predicting the mean overtopping discharge is one of the main concerns in designing coastal defence structures. Hazards and damage caused by overtopping have to be kept at a minimum and the mean overtopping discharge is a good measure for making these assessments.

It has been stated in BSI (1999) that the measurement of overtopping quantity should be made over periods of about 50 to 100 waves and tests should be repeated to obtain sufficient results for proper statistical analysis of the overtopping discharge. However, this suggestion can only be regarded as a minimum recording period, as longer sequences will provide better stability of the mean value. Owen (1980) ran experiments for 100 waves and repeated each test condition five times. Besley's (1999) improvements and the Hedges & Reis (1998) prediction method were based on Owen's (1980) data. However, in more recent investigations, researchers have preferred to record longer tests of up to 1000 waves (or more in some special cases).

As noted above, the mean overtopping discharge per unit length of sea wall,  $Q$  ( $m^3/s/m$ ), is the most common way of representing overtopping. Several factors influence its value:

$$Q = \text{function}(H_s, T_m, \theta, R_c, \alpha, d_s, g, \dots) \quad (2.15)$$

Researchers have used different combinations of these parameters to achieve appropriate non-dimensional forms of  $Q$ . Owen used:

$$\frac{Q}{T_m g H_s} = \text{function}\left(\frac{R_c}{T_m \sqrt{g H_s}}, \frac{H_s}{g T_m^2}, \frac{d_s}{H_s}, \alpha, \theta, \dots\right) \quad (2.16)$$

However, many other arrangements are possible.

Two types of dimensionless formulae dominate the literature:

$$Q_* = A \exp(-BR_*) \quad (2.17)$$

and

$$Q_* = A(R_*)^B \quad (2.18)$$

in which  $A$  and  $B$  are curve-fitting constants provided by the authors,  $Q_*$  is a dimensionless overtopping discharge and  $R_*$  is a dimensionless freeboard. Various formulae relating  $Q_*$  to  $R_*$ , provided by different researchers, are given in Table 2-1.

Table 2-1 Overtopping discharge prediction methods

Reference	Structure types	Overtopping model
<b>Owen (1980)</b>	impermeable smooth, rough, simple and bermed slopes	$Q_* = A \exp(-BR_*)$
Bradbury & Allsop (1988)	rock armoured, impermeable slopes with crown walls	$Q_* = A \exp(R_*)^{-B}$
Ahrens & Heimbaugh (1988)	seven different seawall/revetment designs	$Q_* = A \exp(-BR_*)$
Sawaragi <i>et al.</i> (1988)	artificial reef-fronted vertical sea-dikes	-
Aminti & Franco (1988)	rock cube and tetrapod double layer armour on rather impermeable slopes with crown walls	$Q_* = A \exp(R_*)^{-B}$
Pedersen & Burcharth (1992)	rock armoured rather impermeable slopes with crown walls	$Q_* = A \exp(R_*)^{-B}$
De Waal & Van der Meer (1992)	smooth with and without bermed rough slopes	$Q_* = A \exp(-BR_*)$
Van der Meer, Smith <i>et al.</i> , <b>Van der Meer &amp; Janssen (1995)</b>	impermeable smooth, rough, simple and bermed slopes	$Q_* = A \exp(-BR_*)$
Franco <i>et al.</i> (1994)	vertical wall breakwater with and without perforated front	$Q_* = A \exp(-BR_*)$
<b>Hedges &amp; Reis (1998)</b>	impermeable smooth slopes	$Q_* = A(1 - R_*)^B$ for $0 \leq R_* < 1$ = 0 for $R_* \geq 1$



Table 2-1 continued

Reference	Dimensionless discharge, $Q_*$	Dimensionless freeboard, $R_*$
<b>Owen (1980)</b>	$\frac{Q}{T_m g H_s}$	$\frac{R_c}{T_m \sqrt{g H_s}}$
Bradbury & Allsop (1988)	$\frac{Q}{T_m g H_s}$	$\frac{R_c^2}{T_m \sqrt{g H_s^3}}$
Ahrens & Heimbaugh (1988)	$\frac{Q}{\sqrt{g H_s^3}}$	$\frac{R_c}{(H_s^2 L_p)^{1/3}}$
Sawaragi <i>et al.</i> (1988)	$\frac{Q}{\sqrt{g L_s H_s^2}}$	$\frac{R_c}{H_s}$
Aminti & Franco (1988)	$\frac{Q}{T_m g H_s}$	$\frac{R_c}{H_s}$
Pedersen & Burcharth (1992)	$\frac{Q T_m}{L_m^2}$	$\frac{R_c}{H_s}$
De Waal & Van der Meer (1992)	$\frac{Q}{\sqrt{g H_s^3}}$	$\frac{R_c - R_{2\%}}{H_s}$
Van der Meer, Smith <i>et al.</i> , Van der Meer & Janssen (1995)	$\frac{Q}{\sqrt{g H_s^3}} \frac{\sqrt{\tan \alpha}}{\xi_p}$ for $\xi_p < 2$  $\frac{Q}{\sqrt{g H_s^3}}$ for $\xi_p > 2$	$\frac{R_c}{H_s} \frac{1}{\xi_p} \frac{1}{\gamma}$ for $\xi_p < 2$  $\frac{R_c}{H_s} \frac{1}{\gamma}$ for $\xi_p > 2$
Franco <i>et al.</i> (1994)	$\frac{Q}{\sqrt{g H_s^3}}$	$\frac{R_c}{H_s}$
<b>Hedges &amp; Reis (1998)</b>	$\frac{Q}{\sqrt{g (C H_s)^3}}$	$\frac{R_c}{C H_s}$

Herbert *et al.* (1994) revised equation (2.17) and provided:

$$Q_* = A \exp\left(\frac{-BR_*}{\gamma_f}\right) \quad (2.19)$$

where  $\gamma_f$  is the reduction factor for slope roughness and its value varies with the type of armour units.

Hedges & Reis (1998) recently developed a more promising prediction method for sloping structures (which will be discussed in detail in section 2.6.5) and the dimensionless formula was provided in another form:

$$Q_* = \begin{cases} A(1-R_*)^B & \text{for } 0 \leq R_* < 1 \\ 0 & \text{for } R_* \geq 1 \end{cases} \quad (2.20)$$

Equation (2.20) satisfies the requirement that no overtopping (apart from wind blown spray) occurs if the sea-wall freeboard exceeds the maximum wave run-up on the face of the structure.

#### 2.5.4. Individual wave overtopping volumes

Although mean overtopping discharges have been investigated by many researchers, only a few of them worked on individual overtopping volumes. Franco *et al.* (1994) studied the probability distribution of individual overtopping volumes for vertical walls. They considered test conditions with the number of overtopping waves,  $N_o$ , bigger than 30 and the exceedance probability of each overtopping volume,  $P_o$ , was calculated accordingly. The limit, 30, for the number of overtopping volumes, was

chosen arbitrarily. The three-parameter Weibull distribution function was found to be the best fit to the data and the equation was given as:

$$P_o = P[V \geq V_{\#}] = \exp \left[ - \left( \frac{V_{\#} - V_{\min}}{V_{char}} \right)^{\beta} \right] \quad (2.21)$$

in which  $V_{\#}$  is a particular volume,  $V_{char}$  and  $\beta$  are fitted constants and  $V_{\min}$  is the lower limit of the data, representing the minimum individual volume that the experimental method could distinguish. The shape parameter,  $\beta$ , was found to have little variability around the mean value of 0.75.

Van der Meer & Janssen (1995) eliminated  $V_{\min}$  to account for all overtopping volumes and used the two-parameter Weibull distribution. They gave the scale parameter  $V_{char}$  as:

$$V_{char} = 0.84 V_{bar} = \frac{0.84 T_m Q}{P_{ow}} \quad (2.22)$$

where  $V_{bar}$  is the mean overtopping volume derived on the assumption of a Weibull distribution of individual overtopping volumes and  $P_{ow}$  is the probability of overtopping per wave ( $P_{ow} = N_o / N$ ).

Van der Meer & Janssen (1995) investigated the individual overtopping volumes for dikes (as opposed to vertical walls), but, nevertheless, found the same constant value for  $\beta$  of 0.75 given by Franco *et al.* (1994). In addition, Franco *et al.* (1999) investigated the variability of the distribution

of overtopping volumes with respect to wave obliquity and multidirectional sea states. After analysing the dependency, they reported no clear trend for the shape parameter,  $\beta$ , with its value remaining approximately 0.75.

### 2.5.5. Number of waves overtopping

Factors affecting the mean overtopping discharge were discussed in section 2.3. They also influence the number of overtopping waves,  $N_o$ . Owen (1982) examined the number of overtopping waves on smooth and impermeable slopes. He found that the overtopping of one wave had little effect on the run-up of the next wave for steeper slopes.

Assuming that wave heights, and hence run-up levels are Rayleigh distributed, then the proportion of waves overtopping to the number of incident waves for sloping structures is given by Besley (1999) as:

$$N_o/N = \exp\left[-C\left(R_*/\gamma_f\right)^2\right] \quad (2.23)$$

where  $\gamma_f$  is the roughness coefficient. Therefore, with  $\gamma_f = 1$  for smooth surfaces, equation (2.23) can be re-written for simply sloping smooth structures as:

$$N_o/N = \exp\left(-CR_*^2\right) \quad (2.24)$$

Curve fitting constant  $C$  values were calculated for impermeable smooth 1:1, 1:2 and 1:4 slopes and given as 63.8, 37.8 and 110.5, respectively,

where the dimensionless freeboard,  $R_*$ , was calculated from

$$R_* = R_c / \left( T_m (gH_s)^{0.5} \right).$$

Besley (1999) also provided expressions for estimating the number of overtoppings for other sloped structures (including structures with crest walls, berms, etc.) by using an empirical relationship between the proportion of waves overtopping and the dimensionless discharge. He suggested predicting  $Q_*$  first, then calculating  $N_o$  using one of the following equations:

$$\frac{N_o}{N} = \begin{cases} 55.41 Q_*^{0.634} & \text{for } 0 < Q_* < 0.0008 \\ 2.502 Q_*^{0.199} & \text{for } 0.0008 \leq Q_* < 0.01 \\ 1 & \text{for } Q_* \geq 0.01 \end{cases} \quad (2.25)$$

$Q_*$  in equation (2.25) is the dimensionless discharge calculated as  $Q_* = Q / (T_m g H_s)$ .

Based on the same governing equation (2.23), Franco *et al.* (1994) and Van der Meer & Janssen (1995) have done further work on finding  $N_o$ . They used different symbolic representations but the theory was the same as given in Besley's (1999) manual.

### 2.5.6. Peak discharges

The maximum overtopping volume,  $V_{\max}$ , was studied and reported in Besley's (1999) manual. If the mean overtopping discharge and the number of overtopping waves within a storm can be predicted, it is,

therefore, possible to estimate the largest overtopping volume. Using equation (2.21),  $V_{\max}$  may be predicted as:

$$V_{\max} = V_{\min} + V_{char} \ln(N_o)^{1/\beta} \quad (2.26)$$

Besley (1999) commented that the quantity of available data on individual overtopping volumes was very limited but there was reasonably consistent behaviour of the data for a range of structures. Besley also suggested using equation (2.26) only if  $N_o \geq 5$ .

## 2.6. Overtopping prediction methods

Table 2-1 lists some of the currently available methods for predicting the mean overtopping rate. Owen's (1980), Van der Meer & Janssen's (1995) and Hedges & Reis's (1998) prediction methods, shown in bold, are investigated later in this study.

### 2.6.1. Owen's prediction method

Owen (1980) conducted comprehensive work on simply sloping and bermed seawalls. His equations were developed from physical model tests representing storm wave conditions in the Severn Estuary, UK.

Owen tested his model structures, with a foreshore slope of 1:20, using random waves conforming to the JONSWAP spectrum. He investigated the effects of berms (both their elevation and width), wave steepness, and angle of wave attack for a range of significant wave heights and mean wave periods. He ran his tests to record 100 waves and each test condition was run five times.

Owen (1980) defined his dimensionless freeboard,  $R_*$ , and dimensionless discharge,  $Q_*$ , as:

$$R_* = \frac{R_c}{T_m \sqrt{gH_s}} \quad (2.27)$$

$$Q_* = \frac{Q}{T_m g H_s} \quad (2.28)$$

He used an exponential relationship between equation (2.27) and (2.28):

$$Q_* = A \exp(-BR_*) \quad (2.29)$$

Equation (2.29) may thus be re-written as:

$$\frac{Q}{T_m g H_s} = A \exp \left[ -B \frac{R_c}{T_m \sqrt{gH_s}} \right] \quad (2.30)$$

Table 2-2 lists values of the  $A$  and  $B$  coefficients provided by Owen for the simply sloping smooth structures.  $A$  and  $B$  values were determined for 1:1, 1:2 and 1:4 slopes, and either interpolated or extrapolated for other slopes. Owen regarded them as valid if:

$$0.05 < R_* < 0.30$$

$$10^{-6} < Q_* < 10^{-2}$$

$$1.5 < d_s/H_s < 5.5$$

$$0.035 < H_s/\bar{L}_{om} < 0.055$$

where  $\bar{L}_{om}$  was defined as the mean deep-water wave length ( $\bar{L}_{om} = gT_m^2/2\pi$ ).

Table 2-2 Values of A and B coefficients (Owen, 1980)

Seawall slope	A	B
1:1.0	$7.94 \times 10^{-3}$	20.12
1:1.5	$1.02 \times 10^{-2}$	20.12
1:2.0	$1.25 \times 10^{-2}$	22.06
1:2.5	$1.45 \times 10^{-2}$	26.10
1:3.0	$1.63 \times 10^{-2}$	31.90
1:3.5	$1.78 \times 10^{-2}$	38.90
1:4.0	$1.92 \times 10^{-2}$	46.96
1:4.5	$2.15 \times 10^{-2}$	55.70
1:5.0	$2.50 \times 10^{-2}$	65.20

### 2.6.2. Besley's (improved Owen's) model

After Owen's work, the overtopping performances of different types of structures, such as embankments and vertical walls, were studied by other researchers. Besley (1999) was then funded by the Department for Environment, Food and Rural Affairs (DEFRA), formerly known as the Ministry of Agriculture, Fisheries and Food (MAFF), to gather this information into a manual on Overtopping of Seawalls (Project Record W5/006/5).



Table 2-3 Values of revised *A* and *B* coefficients (Besley, 1999)

Seawall slope	A	B
1:1.0	$7.94 \times 10^{-3}$	20.10
1:1.5	$8.84 \times 10^{-3}$	19.90
1:2.0	$9.39 \times 10^{-3}$	21.60
1:2.5	$1.03 \times 10^{-2}$	24.50
1:3.0	$1.09 \times 10^{-2}$	28.70
1:3.5	$1.12 \times 10^{-2}$	34.10
1:4.0	$1.16 \times 10^{-2}$	41.00
1:4.5	$1.20 \times 10^{-2}$	47.70
1:5.0	$1.31 \times 10^{-2}$	55.60

The data were analysed and values of the *A* and *B* coefficients provided by Owen (1980) were revised by Besley (1999). Table 2-3 summarizes the *A* and *B* values suggested by Besley (1999).

Besley considered the advantages and disadvantages of both Owen's method and Van der Meer's method, given in Van der Meer & de Waal (1992), and concluded that the errors in Owen's method are on the conservative side (i.e. Owen's method overestimates overtopping rates).

### 2.6.3. Extension to Owen's model for milder slopes

Following completion of further tests, Allsop & Pullen (2003) added the SHADOW data (reported in this thesis) to Owen's data and provided interim guidance on new values of *A* and *B* for use in Owen's model (see Table 2-4).

Table 2-4 New coefficients for use in Owen's model (Allsop & Pullen 2003)

Seawall slope		New coefficients (Allsop & Pullen, 2003)
1:2	A	0.01
	B	21.6
1:4	A	0.01
	B	43
1:6	A	0.01
	B	65
1:8	A	0.01
	B	86
1:10	A	0.01
	B	108
1:15	A	0.01
	B	162

Values in Table 2-4 for slopes not tested in experiments were found by simple interpolation.

#### 2.6.4. Van der Meer & Janssen's prediction method

Van der Meer & Janssen (1995) came up with a new distinctive method. Besides evaluating the overtopping performances of dikes and similar structures, i.e. revetments and seawalls, they studied the influences of berms, shallow foreshores (for depth-limited waves), surface roughness elements on sloping structures and obliquely incoming waves for both short and long-crested seas. They provided two separate overtopping formulae: one for breaking waves ( $\xi_{op} < 2$ ) and one for non-breaking waves ( $\xi_{op} > 2$ ).

##### 2.6.4.1. Breaking wave conditions:

The dimensionless overtopping discharge for breaking waves,  $Q_b$ , is:

$$Q_b = \frac{Q}{\sqrt{gH_s^3}} \sqrt{\frac{s_{op}}{\tan \alpha}} \quad (2.31)$$

and the dimensionless freeboard  $R_b$  (application range  $0.3 < R_b < 2$ ) is:

$$R_b = \frac{R_c}{H_s} \frac{\sqrt{s_{op}}}{\tan \alpha} \frac{1}{\gamma_b \gamma_h \gamma_f \gamma_\beta} \quad (2.32)$$

$\gamma_b, \gamma_h, \gamma_f$  and  $\gamma_\beta$  are the reduction factors for the influences of a berm, a shallow foreshore, roughness and angle of wave attack, respectively, with a minimum value of 0.5 for the combination of all factors. Therefore, for simply-sloping smooth structures under normal wave attack ( $\theta = 0$ ), the combination of the reduction factors can be taken as “1” and equation (2.32) may be re-written as:

$$R_b = \frac{R_c}{H_s} \frac{\sqrt{s_{op}}}{\tan \alpha} \quad (2.33)$$

By using equations (2.31) and (2.33), Van der Meer & Janssen (1995) provided a dimensionless overtopping model for breaking waves, ( $\xi_{op} < 2$ ):

$$Q_b = 0.06 \exp(-5.2R_b) \quad (2.34)$$

#### 2.6.4.2. Non-breaking wave conditions:

For non-breaking waves ( $\xi_{op} > 2$ ), the proposed overtopping model is:

$$Q_n = 0.2 \exp(-2.6R_n) \quad (2.35)$$

where the dimensionless overtopping discharge,  $Q_n$ , and the dimensionless freeboard,  $R_n$ , provided for non-breaking waves are as follows:

$$Q_n = \frac{Q}{\sqrt{gH_s^3}} \quad (2.36)$$

$$R_n = \frac{R_c}{H_s} \frac{1}{\gamma_b \gamma_h \gamma_f \gamma_\beta} \quad (2.37)$$

Again, for simply-sloping smooth structures under normal wave attack, equation (2.37) may be re-written as:

$$R_n = \frac{R_c}{H_s} \quad (2.38)$$

For design purposes, rather than using equations (2.34) and (2.35), more conservative formulae recommended by Van der Meer & Janssen (1995) are given as:

$$Q_b = 0.06 \exp(-4.7R_b) \quad (2.39)$$

$$Q_n = 0.2 \exp(-2.3R_n) \quad (2.40)$$

### 2.6.5. Hedges & Reis's (H&R) prediction method

Hedges & Reis (1998) re-analysed the data provided by Owen (1980) and introduced a new model to predict wave overtopping for simply-sloping coastal structures. The idea behind their study was fairly simple and

logical: “no overtopping occurs (other than wind-blown spray) if the seawall freeboard exceeds the maximum wave run-up on the face of the structure”. Therefore, the primary condition to have no overtopping is  $R_c \geq R_{\max}$ . In other words, there is no need to construct an infinitely high sea defence to have no overtopping as is implied by exponential relationships between the overtopping discharge and the freeboard. Therefore, the maximum run-up level governs the discharge and needs to be estimated.

In their analysis, Hedges & Reis (1998) fitted their regression coefficients using the Least Absolute Deviations (LAD) procedure instead of the Least Squares (LS) method which is commonly used for curve fitting.

With the above background, the H&R model provided a regression equation of the following form:

$$Q_* = \begin{cases} A(1-R_*)^B & \text{for } 0 \leq R_* < 1 \\ 0 & \text{for } R_* \geq 1 \end{cases} \quad (2.41)$$

in which

$$Q_* = \frac{Q}{\sqrt{gR_{\max}^3}} = \frac{Q}{\sqrt{g(CH_s)^3}} \quad (2.42)$$

$$R_* = \frac{R_c}{R_{\max}} = \frac{R_c}{CH_s} \quad (2.43)$$

This is the only model with the advantage that  $Q_* = 0$  when  $R_* \geq 1$  and  $Q_* = A$  when  $R_* = 0$ . In other words, the model predicts zero overtopping

for freeboards higher than the maximum run-up level and if the freeboard is zero, the predicted overtopping rate is still finite. Figure 2-16 illustrates the influences of coefficients  $A$ ,  $B$  and  $C$  in the model.

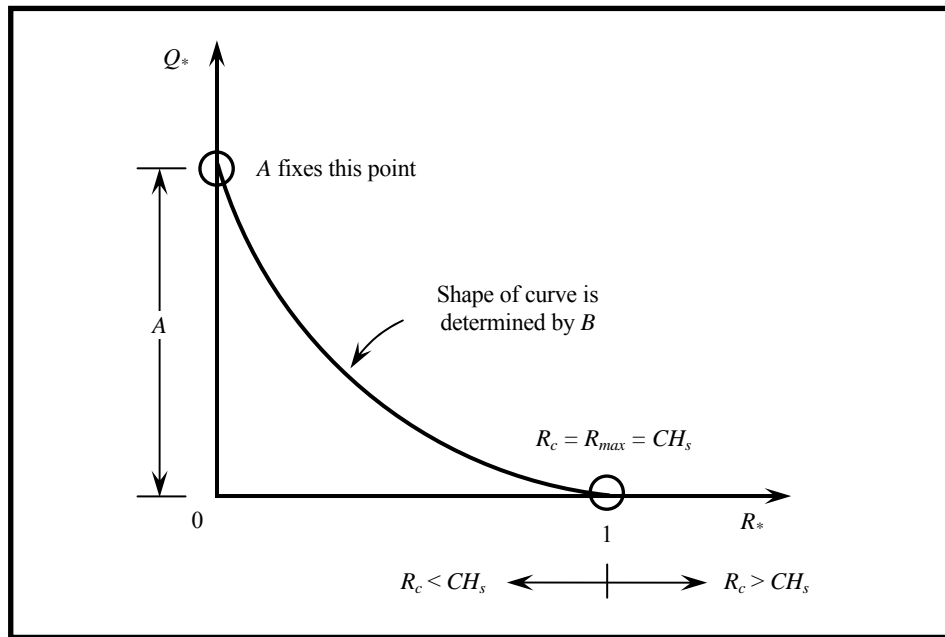


Figure 2-16 Influences of coefficients  $A$ ,  $B$  and  $C$  in the H&R model (Hedges & Reis, 1998)

Regression coefficient  $A$  in the H&R model depends on the shape of the structure and represents the dimensionless discharge when the dimensionless freeboard is zero. Coefficient  $B$  depends on the detailed behaviour of the water surface on the seaward face of the structure. Coefficient  $C$  relates the maximum run-up to the significant height of the incident waves. It incorporates the influences of the sea-wall slope, the surface roughness and porosity, and the incident wave steepness.

Values of  $C$  ( $= (R_{\max})_{p\%,N_R} / H_s$ ) have been determined using the run-up equations in the CIRIA/CUR (1991) manual to establish  $R_s$ , together with equation (2.13). The most probable maximum run-up for each run of

Owen’s tests employing 100 waves (the value not exceeded in 37% of all cases for a Rayleigh distribution of run-ups) was estimated (assuming  $N_R = N$ ) to be:

$$(R_{\max})_{37\%,100} = \sqrt{[(\ln 100)/2]} R_s = 1.52 R_s \quad (2.44)$$

Hence, using equations (2.8) and (2.44):

$$\frac{(R_{\max})_{37\%,100}}{H_s} = \begin{cases} 1.52(1.35\xi_p) & = 2.05\xi_p & \text{for } \xi_p < 2 \\ 1.52(3.00 - 0.15\xi_p) & = 4.56 - 0.23\xi_p & \text{for } \xi_p > 2 \end{cases} \quad (2.45)$$

Table 2-5 Regression coefficients in H&R model (Hedges & Reis, 1998)

Regression coefficients	C given by $(R_{\max})_{37\%,100}$		C given by $(R_{\max})_{99\%,100}$	
	LAD	LS	LAD	LS
<i>Slope 1:1</i>				
A	0.00703	0.00581	0.00515	0.00474
B	3.42	3.22	6.06	6.04
<i>Slope 1:2</i>				
A	0.00753	0.00790	0.00542	0.00614
B	4.17	4.55	7.16	7.98
<i>Slope 1:4</i>				
A	0.0104	0.00792	0.00922	0.00870
B	6.27	5.94	10.93	11.12

Hedges & Reis (1998) noted that the value of  $C$  to be adopted in the regression model depended on the level of confidence associated with the

prediction of  $R_{\max}$ . If  $C$  is changed, then there should be corresponding changes in the values of  $A$  and  $B$ . Based on Owen's data,  $A$  and  $B$  values are tabulated both for 37% and 99% non-exceedance estimates for  $R_{\max}$  in Table 2-5, using both LAD and LS regression methods.

### 2.6.6. Extension to H&R prediction method

Shareef (2005) revised the  $A$  and  $B$  coefficients for the H&R method by taking into consideration additional data from Kansai University. Shareef (2005) used the LAD regression technique and found a linear relationship between coefficient  $A$  and the slope. However, he noted that there was not a single linear relationship between coefficient  $B$  and the slope:  $B$  increased as the slope reduced from 1:1, before falling as the slope continued to flatten.

Suggested coefficients for  $(R_{\max})_{37\%,100}$  were given as:

$$\begin{aligned}
 A &= 0.0047 + 0.0018m & \text{for} & \quad 1.0 \leq m \leq 20.0 \\
 B &= \begin{cases} 3.42 + 0.30m & \text{for} \quad 1.0 \leq m \leq 4.0 \\ 10.21 - 0.27m & \text{for} \quad 4.1 < m \leq 20.0 \end{cases} & (2.46)
 \end{aligned}$$

and for  $(R_{\max})_{99\%,100}$ :

$$\begin{aligned}
 A &= 0.0034 + 0.0012m & \text{for} & \quad 1.0 \leq m \leq 20.0 \\
 B &= \begin{cases} 6.09 + 0.73m & \text{for} \quad 1.0 \leq m \leq 4.0 \\ 16.07 - 0.43m & \text{for} \quad 4.1 < m \leq 20.0 \end{cases} & (2.47)
 \end{aligned}$$

where  $m$  defines the slope through 1(vertical):  $m$ (horizontal).



Earlier, Mase *et al.* (2003) had combined Owen’s data with the Kansai University data and provided  $A$  and  $B$  coefficients for  $(R_{\max})_{37\%,100}$  as follows:

$$\begin{aligned}
 A &= 0.0047 + 0.0018m & \text{for} & \quad 1.0 \leq m \leq 20.0 \\
 B &= \begin{cases} 1.83 + 1.27m & \text{for} \quad 1.0 \leq m \leq 5.3 \\ 9.86 - 0.25m & \text{for} \quad 5.3 < m \leq 20.0 \end{cases} & (2.48)
 \end{aligned}$$

### 2.6.7. Comparison of existing models

Besley (1990) compared Van der Meer & Janssen’s and Owen’s methods. He suggested using Owen’s method to predict overtopping discharges for smooth, simply-sloping and bermed seawalls around the UK coastline, since Owen’s data contains more structure-specific data than the method proposed by Van der Meer & Janssen. However, Owen’s model generally suggests higher freeboards than Van der Meer & Janssen’s model to limit overtopping to specified values.

In the case of the H&R model, it should be noted that the value  $(R_{\max})_{37\%,100}$  simply provides an estimate of the actual maximum run-up during a storm. However, this estimate should guarantee, at the very least, that any overtopping which does occur remains negligible. In this connection, it is worth noting that equations (2.45) estimate the most probable maximum run-up as  $4.1H_s$ , regardless of the structure slope or incident wave steepness, and Van der Meer & Janssen (1995) record no overtopping discharges for cases in which  $R_c > 4.1H_s$ , even for tests of length considerably exceeding 100 waves. Furthermore, if the Rayleigh distribution applies to run-ups, then:

$$(R_{\max})_{37\%,100} = R_{1\%} \quad (2.49)$$

in which  $R_{n\%}$  denotes the value exceeded by  $n\%$  of all the individual run-ups. It is worth noting that sea defences in continental Europe are often planned with a freeboard equal to  $R_{2\%}$  under design wave conditions.  $(R_{\max})_{37\%,100}$  used in the H&R model is about 8.5% greater than  $R_{2\%}$ , according to the Rayleigh distribution.

Hedges & Reis (1998) noted that there is a reasonable agreement between the H&R model and Owen's model only for prototype overtopping discharges in the range from  $10^{-2}$  m<sup>3</sup>/s/m to  $2 \cdot 10^{-1}$  m<sup>3</sup>/s/m, although both models were derived from the same data.

Owen's model and the improvement by Besley incorporate  $T_m$ , whereas the Van der Meer & Janssen and H&R models use  $T_p$  for the characteristic wave period. Nevertheless,  $T_m$  values had been taken as the basis for the H&R predictions (because  $T_p$  was not recorded) and the expression  $T_m = 0.87 \cdot T_p$  (or  $T_p = 1.15 \cdot T_m$ ) has been used to relate  $T_p$  to  $T_m$ . Table 2-6 compares predicted mean overtopping volumes given by the various models for a 1:2 smooth model seawall with a freeboard of 0.4m, water depth of 0.6m and for a run of 1000 incident waves.

Note that  $(R_{\max})_{99\%,100}$  was employed in the original version of the H&R model to obtain the following values.

Table 2-6 Comparison table for predicted mean overtopping volumes

$H_s$ (m)	$T_m$ (s)	Theoretical values (litres/metre/1000 waves)			
		Owen (1980)	Van der Meer & Janssen (1995)	H&R (1998)	Besley (1999)
0.15	1.25	85	99	181	72
0.15	1.50	324	118	176	269
0.20	1.50	828	845	1354	679
0.10	1.75	231	4	0	193
0.15	1.75	882	138	163	723
0.20	1.75	2053	986	1391	1662
0.20	2.00	4205	1126	1392	3373
0.10	2.25	1184	5	0	966

Figure 2-17 compares the predicted overtopping discharges using Owen's (1980) model with data from Owen, Hawkes and the SHADOW project. As noted in Bay *et al.* (2005) and Hawkes (1999), Owen's model tends to overestimate overtopping for swell conditions. Figure 2-18 compares the same measured overtopping discharges with the values predicted by the H&R (1998) model using  $(R_{\max})_{37\%,100}$  and the values of  $A$  and  $B$  given by Mase *et al.* (2003).

In addition to these two figures, Owen's, Besley's (modified Owen's), Van der Meer & Janssen's and the H&R prediction methods are employed in Figures 2-19 and 2-20 to investigate the differences in predicted freeboards for slopes of 1:2 and 1:4, respectively, for specified permissible discharges and for a single given wave condition of  $H_s = 2.0m$  and  $T_m = 5.0s$ .

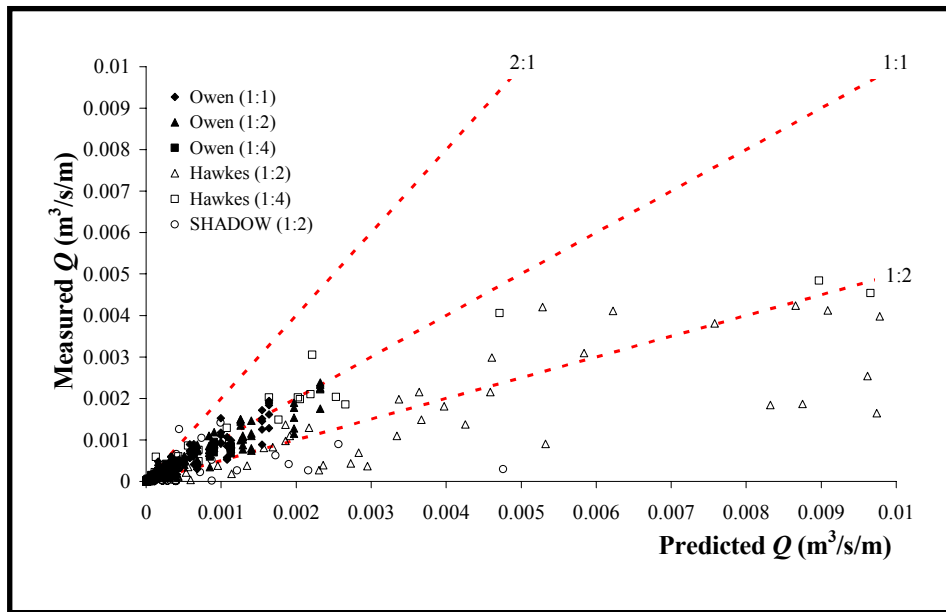


Figure 2-17 Comparison of measured and predicted overtopping discharges for 1:1, 1:2 and 1:4 slopes: Owen's (1980) model (Bay *et al.*, 2005)

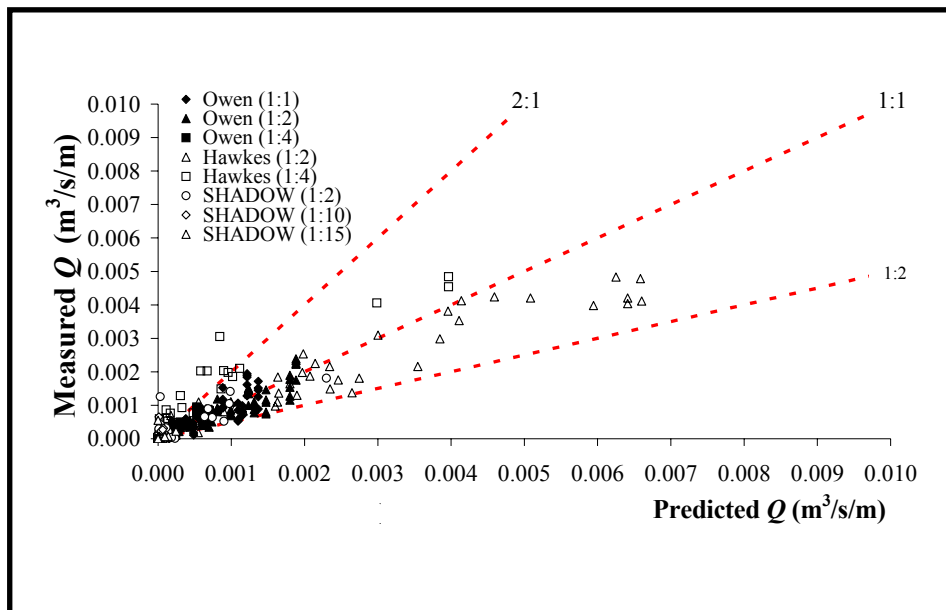


Figure 2-18 Comparison of measured and predicted overtopping discharges using Hedges & Reis (1998) model (Bay *et al.*, 2005)

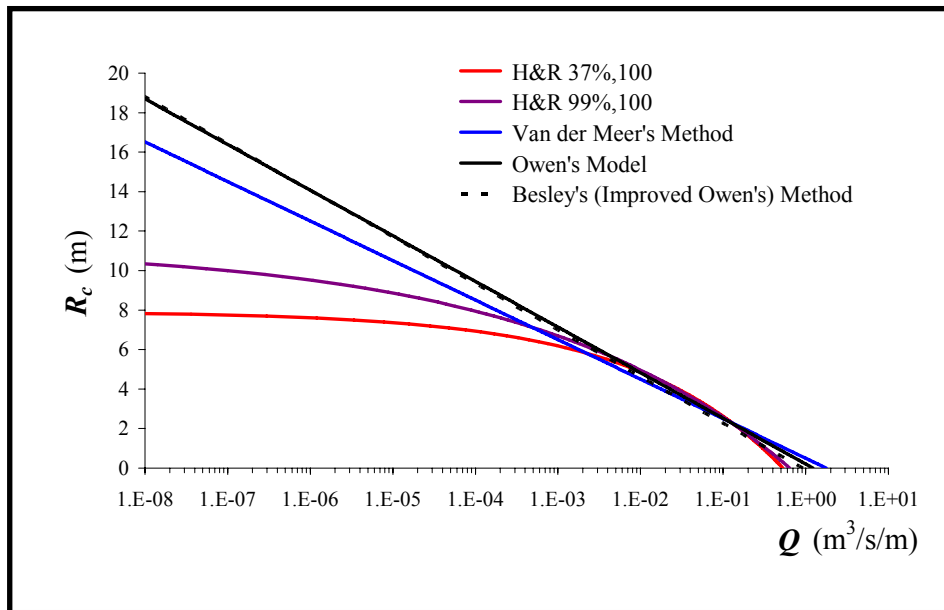


Figure 2-19 Predicted freeboards for 1:2 simply sloping smooth structures to limit overtopping to specified discharges for  $H_s = 2.0m$ ,  $T_m = 5.0s$

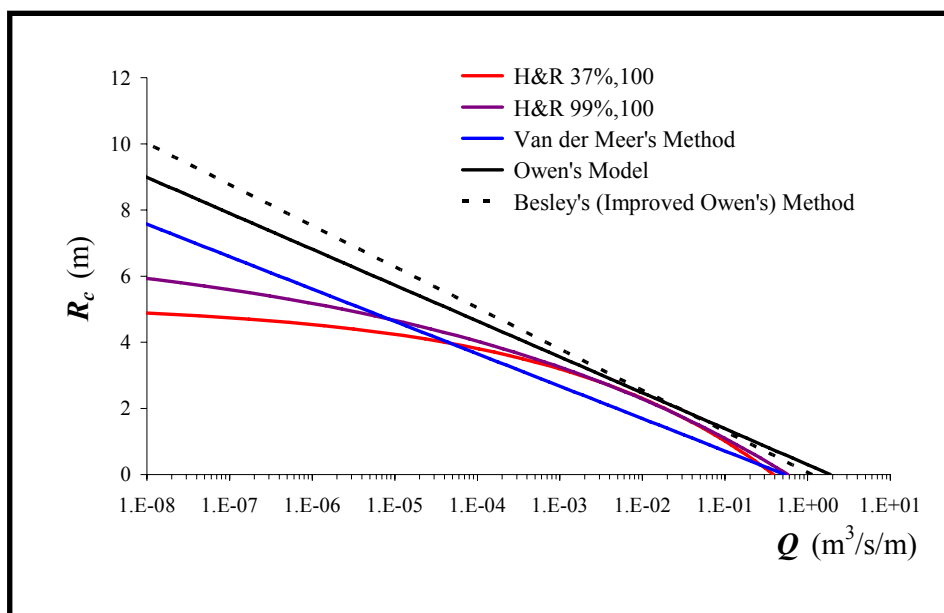


Figure 2-20 Predicted freeboards for 1:4 simply sloping smooth structures to limit overtopping to specified discharges for  $H_s = 2.0m$ ,  $T_m = 5.0s$

Figure 2-19, for a 1:2 slope, shows how well the prediction methods agree for relatively large mean overtopping discharges, but there is poor agreement for small discharges. Figure 2-20, for a 1:4 slope, shows poor agreement between some of the methods even for the larger discharges.

## 2.7. Other relevant studies

### 2.7.1. Use of Regular Waves

Regular waves rarely occur in the real world. Nevertheless, in early studies of wave run-up and overtopping, many tests were performed employing regular wave trains which provided some fundamental understanding of the phenomena. For example, Saville (1955) conducted small-scale laboratory tests on sloping structures with front faces of 1:3 and 1:1.5. Hudson (1959) conducted a series of experiments on rubble-mound structures using regular waves. Hunt (1959) also studied the run-up of regular waves on simply sloping and composite structures. The empirical equation provided by Hunt (1959) is still in use to estimate the run-up on simply sloping impermeable structures, having been modified to account for irregular waves (De Waal & Van der Meer, 1992; Burcharth & Hughes, 2002).

In most of the above investigations, it was assumed that the regular wave height,  $H$ , should be set equal to the significant height,  $H_s$ , of an irregular wave train, and that this substitution would yield conservative results (Raichlen, 1975). Unsurprisingly, Raichlen also reported that additional parameters were required to describe irregular waves when deriving equations for run-up calculations. Run-up data from regular waves were re-analysed by Stoa (1978) to estimate run-up and overtopping, the resulting formulae being published in SPM (1984).

### 2.7.2. Oblique wave attack

Not much research on wave run-up and overtopping has been conducted under oblique and multidirectional wave conditions. Franco & Franco (1999) ran laboratory experiments to test monolithic vertical breakwaters under oblique wave attack and concluded that the overtopping discharges reduced uniformly with an increasing wave approach angle. They also predicted a 30% decrease in the required freeboard level for multidirectional waves when compared with unidirectional wave attack.

A project called VOWS (Violent Overtopping of Waves at Seawalls) involved both physical and numerical modelling to investigate the overtopping performances of vertical and steep sloping seawalls. It showed (Allsop *et al.*, 2005) the difference between two distinctive overtopping regimes, for “impulsive” and “pulsating” waves, and concluded that existing tools may not correctly predict the overtopping rates.

### 2.7.3. Numerical Modelling

The previously described wave overtopping prediction models are based on experimental data. However, numerical modelling is an alternative way to estimate overtopping discharges.

ODIFLOCS is a computer program for one-dimensional flow (Troch *et al.*, 2002). The structure slope and the bottom friction coefficient have to be defined and the structure can be either permeable or impermeable. The program uses the non-linear shallow-water equations. Troch *et al.* (2002) consider the model to be a practical tool, whereas more advanced models still have to be regarded as research tools that require improvements in order to enhance their practical value.

AMAZON is second-order finite volume numerical model that is also based on the non-linear shallow-water equations (Hu *et al.*, 2000). It has been reported that the results of AMAZON compare well with some measured data. However, Hu *et al.* (2000) also reported that the model requires more verification with irregular waves.

Nichols & Hirt (1975) introduced two-dimensional numerical modelling called the volume-of-fluid (VOF) method which is a volume tracking method. Another method, called FAVOR (fractional area volume obstacle representation), treats curved boundaries. This technique deals with complex geometries by introducing effects of area fraction and volume fraction into the conservation equations (Wei, 2005). One definite advantage of the FAVOR method is that it can be combined with the VOF method for tracking the free surface in a straightforward manner (Troch *et al.*, 2002).

In their work, Dalrymple & Rogers (2006) employed a smoothed particle hydrodynamics (SPH) model to compute the trajectories of particles of fluid that interact according to the Navier-Stokes equations. Gomez-Gesteira *et al.*, (2005) have used a two-dimensional SPH model to investigate the overtopping of a flat plate.

Numerical models such as those based on the non-linear shallow-water equations are capable of simulating long sequences of incident waves, whilst the VOF and SPH models are still restricted in their application. Long sequences of at least 1000 waves may be required in order to achieve reliable estimates of mean overtopping discharges, both in numerical and physical models (Pullen & Allsop, 2003).



## **2.8. Conclusion**

Coastal structures are expensive to build and also difficult to maintain. Therefore, care needs to be taken in designing such structures to minimize the overall cost for an acceptable design.

Overtopping is the most important measure in fixing the crest of any type of coastal structure and a tolerable amount of wave overtopping should be accommodated. However, although they often provide close estimates for high discharges in storm conditions (not for swell), existing prediction methods yield widely different predictions for very small overtopping discharges. Douglass (1984) concluded that the calculated overtopping rates, using empirically-derived equations, should only be regarded as being within, at best, a factor of three of the actual overtopping rate. Of course, since the prediction methods herein are all based on experimental data, predictions should only ever be made within each model's own limits of validity.

# *Chapter 3*

## **PHYSICAL MODELLING**

Hydraulics Research Wallingford Ltd. was commissioned to perform physical model tests to investigate the overtopping performances of simply-sloping, smooth-surface coastal structures. The project was funded by the Department for Environment, Food and Rural Affairs under the project code FD2410. Model structures with three different front slopes were tested at two different water levels and for 219 wave conditions in total. This chapter gives detailed information about the physical modelling, summarizes initial results and draws conclusions about them.

### **3.1. Introduction**

The accuracy and applicability of the available methods for predicting overtopping volumes (both peak and mean) and discharges at coastal structures is a primary concern of coastal engineers. Existing prediction methods are derived from empirical data and their use is limited in the range and types of structures. Also, their reliability is yet to be confirmed.

The main aim of this research was to collect new data on the overtopping of model seawalls with impermeable front slopes of 1:2, 1:10 and 1:15, with particular emphasis on low overtopping rates. The reliability of the new data could be checked by comparing the 1:2 values with previous results. Furthermore, individual overtopping volumes could be

investigated. Therefore, structure configurations not previously tested were to be employed in a wide range of wave climates.

The UK Ministry for Agriculture Fisheries and Food, MAFF (later changed to the Department for Environment, Food and Rural Affairs, DEFRA) funded project FD2410, which was initially called “**Coastal Flooding Hazard by Wave Overtopping**” (CoFloHWO), in September 2000 and Hydraulics Research Wallingford Ltd (HRW) was commissioned to perform an extensive series of laboratory tests. Amongst the collaborators, the project was known as SHADOW, which stands for **Sea Hazard Defences against Overtopping by Waves**. As part of this PhD study, the University of Liverpool assisted HRW in designing, physically modelling and performing the tests, and in analysing the data.

Depending on the availability at the time of testing, the “Absorbing Flume” and the “Three-foot Flume” at HRW were employed in the project. Further details about the facilities and the model tests are given in the following sections.

*SHADOW Phase I* consisted of testing a 1:2 simply-sloping, smooth structure. These tests were conducted in the Absorbing Flume. A 1:2 slope is the most extensively tested structure for overtopping performance and most of the existing empirical prediction methods were derived using data obtained from similar configurations. Thus, there was nothing new about testing an impermeable 1:2 smooth slope, but the idea was to compare the results from these tests with existing data. The results for these tests could then act as a benchmark against which all other new data could be compared.

The Three-foot Flume was used in *SHADOW Phase II* where 1:10 and 1:15, smooth, impermeable slopes were tested: 1:10 is a general minimum for shingle slopes and 1:15 is a general maximum for sand slopes. Such beach slopes are common throughout the British Isles, and will often terminate with a vertical wall at the top of the beach.

At the start of this project, there were no data or methods available that were capable of predicting the overtopping discharges with accuracy for a structure with 1:10 or 1:15 front slopes. However, the application range and the accuracy of the Hedges and Reis method has been improved by using Japanese data on shallow-sloping structures (Shareef, 2005).

### **3.2. Facilities and measuring devices**

Both flumes were equipped to run two-dimensional waves. A control hut, one for each flume, housed ancillary equipment, i.e. computers (one for the wave generator and one to collect and store data in digital form), printer, amplifier, wave probe monitor, power supply control, etc (see Figure 3-1). Software called *HR WaveMaker*, which was compiled by the HRW Software Group, provided signals to the wave paddle. More detailed information about this software is given in Appendix A8.

The paddle could generate regular, random or solitary waves. However, some part of the wave energy would be reflected from each model and, therefore, the paddle was also capable of absorbing reflected wave energy. Two wave probes mounted on the front face of the paddle measured the water surface elevation continuously. This signal was then compared with that generated, with a feedback loop adjusting the signal to the paddle to ensure that only the required incident wave train was produced, and that reflections from the structure were absorbed.



Figure 3-1 Control hut for the Absorbing Flume

A 24-channel analogue to digital converter card (ADC), analogue input card (AIP) and digital pulse counter timer card (DPC) were installed in the second computer. The program *HR Waves* (later changed to *HR WaveData*) was installed on this computer to record wave data in digital files for further analysis (more detailed information about *HR WaveData* is given in Appendix A7).

Waves were measured using wave probes consisting of a pair of parallel stainless steel wires. They were mounted vertically, immersed in the water and wired for data collection. The current flowing between the probe wires was proportional to the depth of immersion. Typically 600mm probes were employed, which were sufficiently sensitive to measure water level changes of 0.2mm.

Another sensor, consisting of an isolated 300mm high pair of probes with open conductive ends (see Figure 3-2), was used to capture overtopping events. It was designed to detect green water overtopping only: water between the tips closed a circuit, sending a signal back to *HR WaveData*. The tips of the detector were placed very close to the crest of the model to catch even small overtopping events. A pulse was required for each overtopping event. Consequently, the gain was set to the maximum level for the channel dedicated to the overtopping detector.

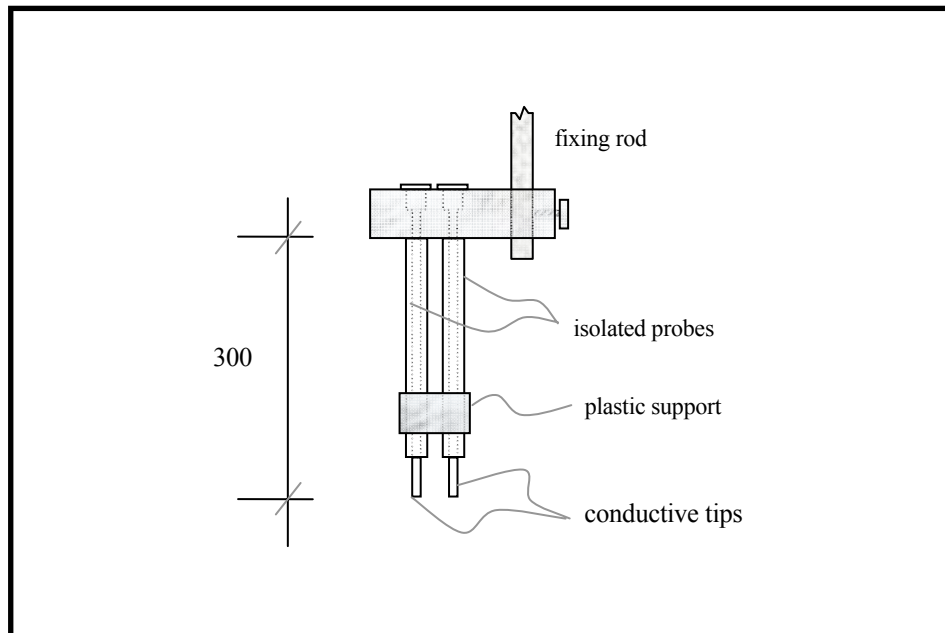


Figure 3-2 Overtopping detector

The overtopping depth detector was a small scale wave probe, shown in Figure 3-3. It consisted of a pair of probes, 300mm high, placed next to the overtopping counter at the crest of the structure. It was supported by a non-conductive plastic holder mounted at the crest of the model structure. The fixing rod contained holes with a centimetre interval to assist the calibration process. It was moved, calibrated, placed back into the holder and fixed on a daily basis. However, data recorded with the

overtopping depth detector have not been used in the present study owing to doubts about their quality.

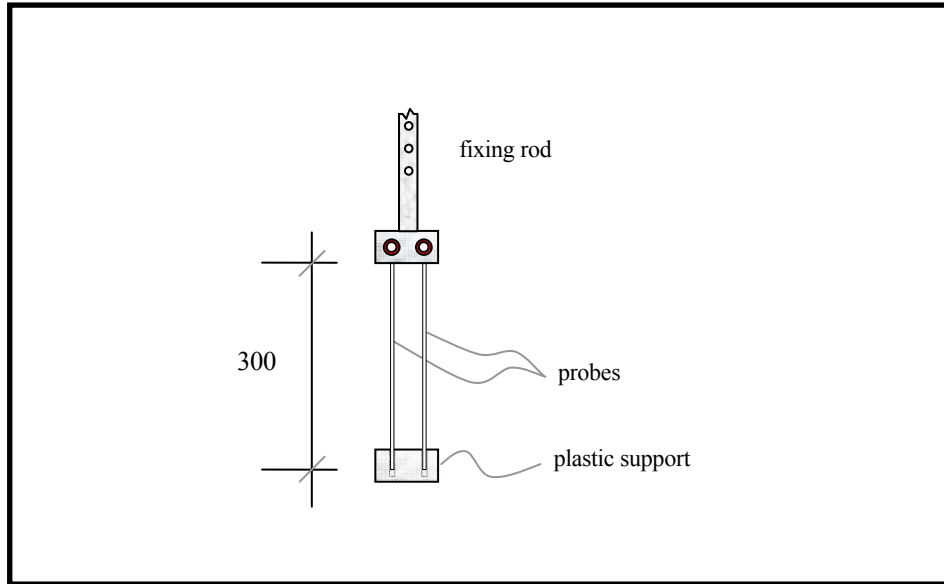


Figure 3-3 Overtopping depth detector

The wave probes needed to be calibrated daily to achieve high quality records. An overall calibration from wave height to output voltage was performed by noting the change in output voltage when the probe was raised or lowered by a known amount in still water. Wave probes were attached to a calibrated fixing rod which had a series of accurately spaced holes drilled along its length. When the wave probe was immersed and set to the required depth in still water, the datum control was used to bring the datum indicator to its central position. A linear least-squares fit to the data completed the calibration.

Overtopping volumes were collected in a plastic tank with 43 litres of water capacity. It was placed behind the structure and was protected by another larger, sealed metal box (see Figure 3-4) to prevent it floating.

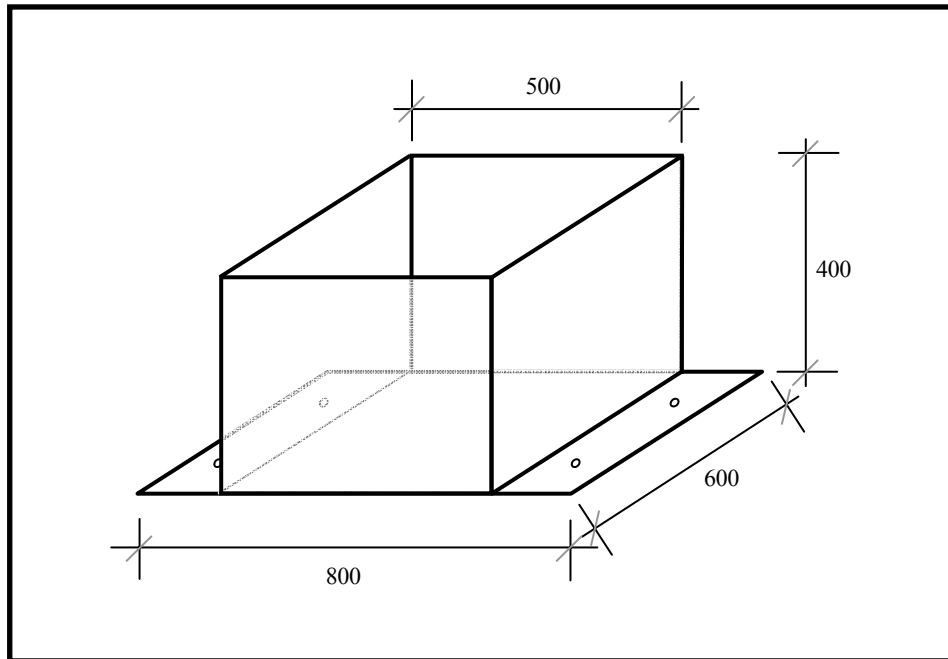


Figure 3-4 Metal box protecting the overtopping tank

A load cell (see Figure 3-5), which was capable of responding to up to 50kgf, was fixed at the bottom of the metal tank, together with a plate to support the overtopping tank. This system could record the difference in water mass throughout the test and, hence, the individual overtopping volumes of water could be determined once the system had been calibrated.

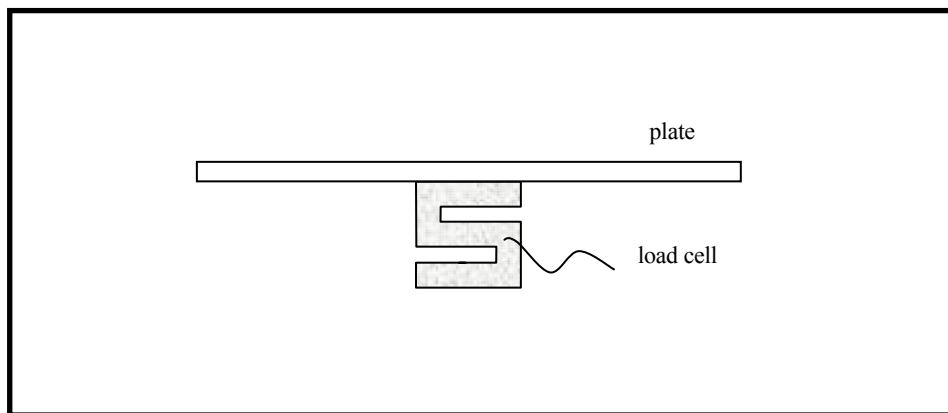


Figure 3-5 Load cell



Overtopping volumes were directed into the tank by means of chutes shown in Figures 3-6 and 3-7. Depending on the expected total volume, either 100mm or 500mm wide chutes were used. The wider chute was preferred for the sake of accuracy, but the narrow one was utilised for relatively larger overtopping conditions. The overtopping tank was protected by barriers against water overtopping the crest but falling outside the chute.

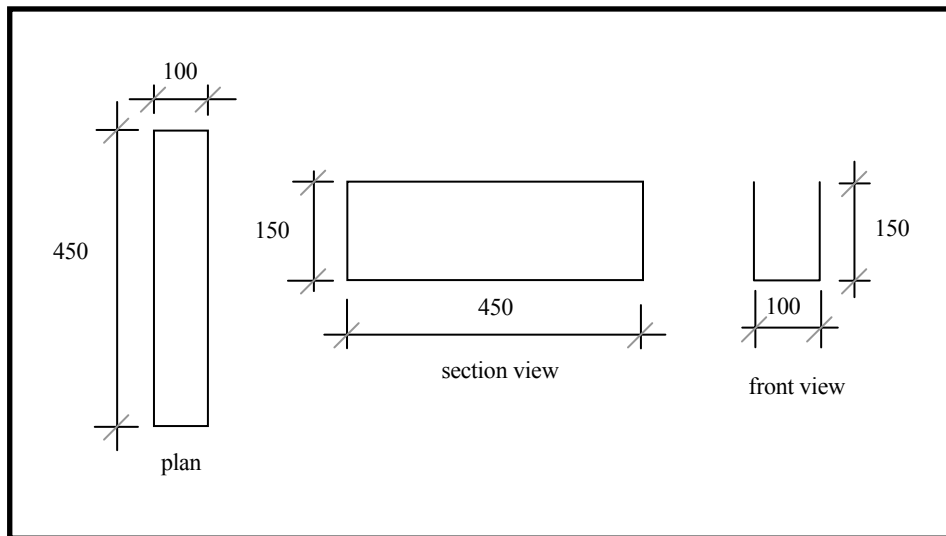


Figure 3-6 100mm-wide chute details

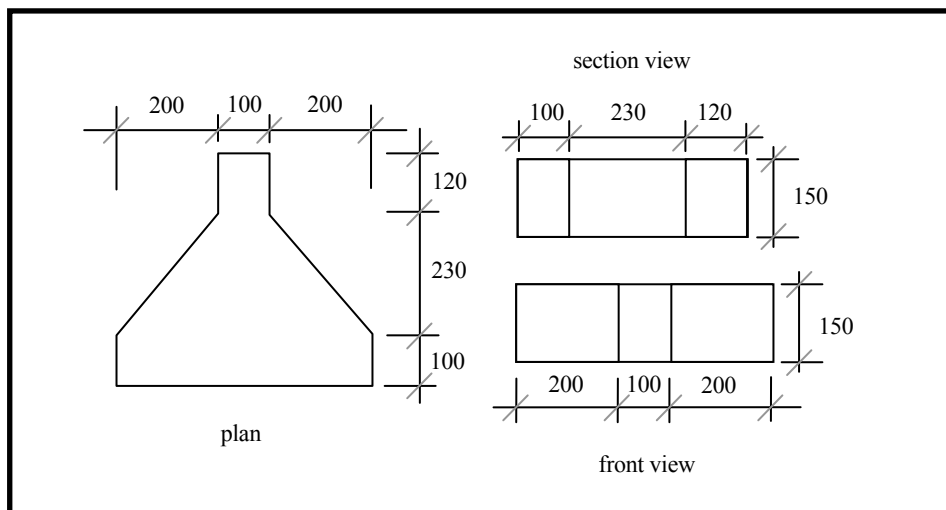


Figure 3-7 500mm-wide chute details

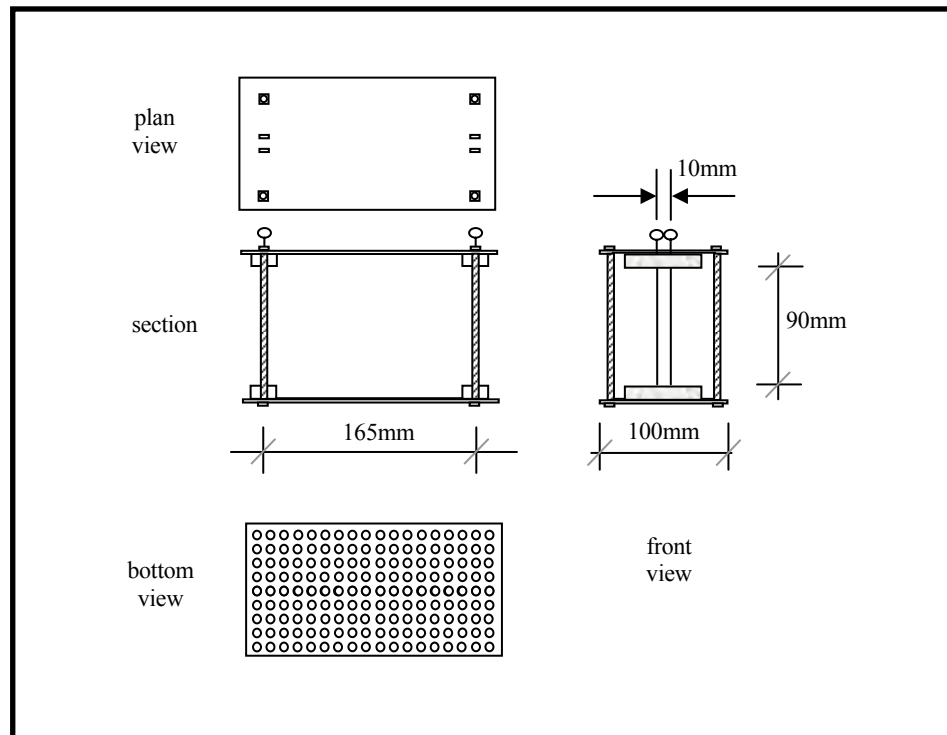


Figure 3-8 Velocity detector

The apparatus shown in Figure 3-8 was designed to determine overtopping velocities. It was mounted immediately behind the crest of the structure. A pair of probes was placed at the front of the crest with another pair 165mm behind the first pair. Overtopping velocities of the water passing through the probes could then be calculated. However, data recorded using this apparatus were found to be very low in quality. Therefore, the velocity detector data have not been used in this study.

### 3.2.1. Absorbing Flume

Model tests for SHADOW Phase I were performed in the Absorbing Flume. This flume is 40m long and 1.5m wide. It has a flat, smooth floor and an operating range of water depths at the wave paddle of 0.5-1.2m (see Figure 3-9). The flume was equipped with an absorbing piston paddle, wave probes, wave energy spending beach which was graded to a

1:4 slope for wave calibration purposes, pumps and sluice gates where any section of the flume needs to be drained. An electro-hydraulic piston paddle is controlled by means of a computer program, *HR WaveMaker*.

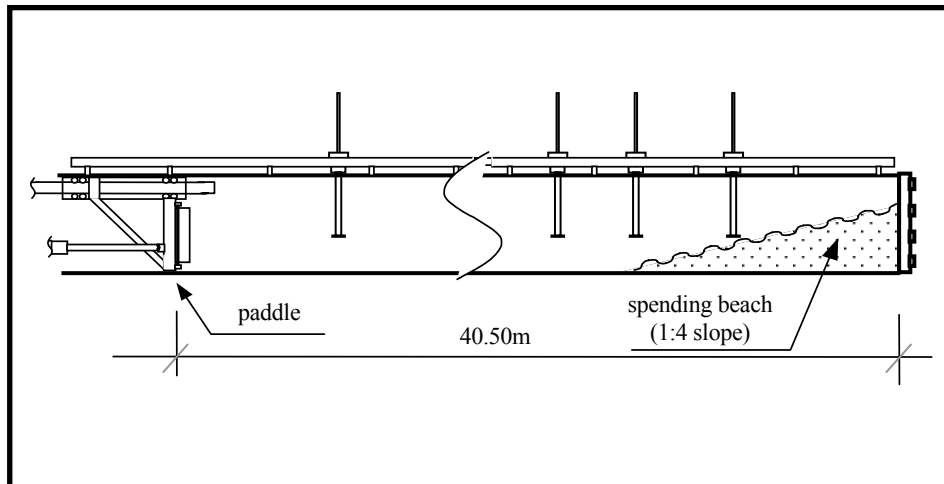


Figure 3-9 Absorbing Flume facility

### 3.2.2. Three-foot Flume

The Three-foot Flume at HRW (Figure 3-10) was employed for the SHADOW Phase II experiments. The total operational length (from the paddle, when it is at rest, to the end) of the flume is 50m. The inner width of the flume is 1m and the depth is 1.24m. There are three viewing panels in the side of the flume which are 1.85m wide and 0.96m high. The energy spending beach was graded to 1:12 for wave calibration purposes.

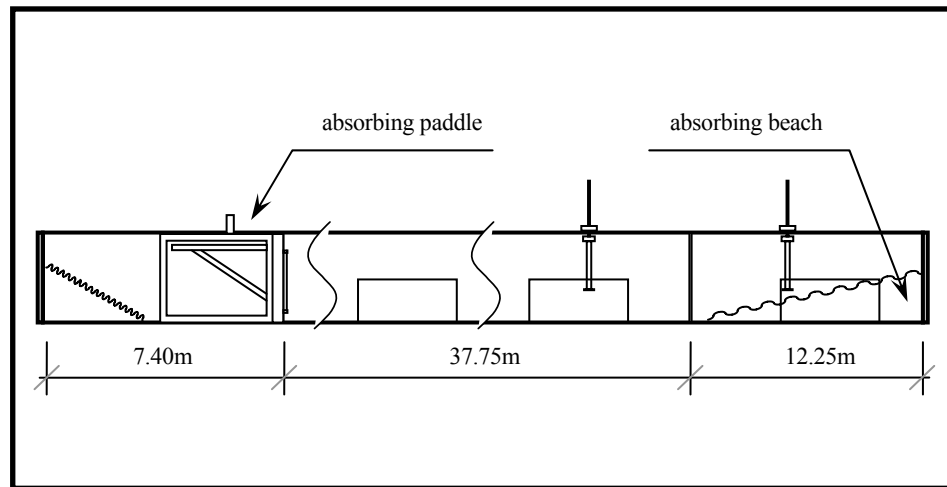


Figure 3-10 Three-foot Flume facility

### 3.3. Designing model tests

#### 3.3.1. Modelling the structures

Details of the model structure which was tested in the Absorbing Flume are given in Figure 3-11. The model was designed in such a way that structures with an impermeable smooth slope, or rock armoured layers on a dense fill material, could be tested. The crest of the structure was fixed at 1.00m above the floor level and the front face was set to a 1:2 slope. A plywood sheet was spray-painted to achieve as smooth a surface as possible. The sheet was bolted to the concrete toe at the front and to the concrete wall at the back to prevent floatation and it was supported with wooden struts along its body against flexing.

Two four-inch-pipes were placed underneath the model structure. They permitted water to flow past the model. Therefore, any water level change in the flume was kept small. The total overtopping volume collected in the tank was limited to a maximum of 43 litres and this amount was tiny compared to the size of the flume.

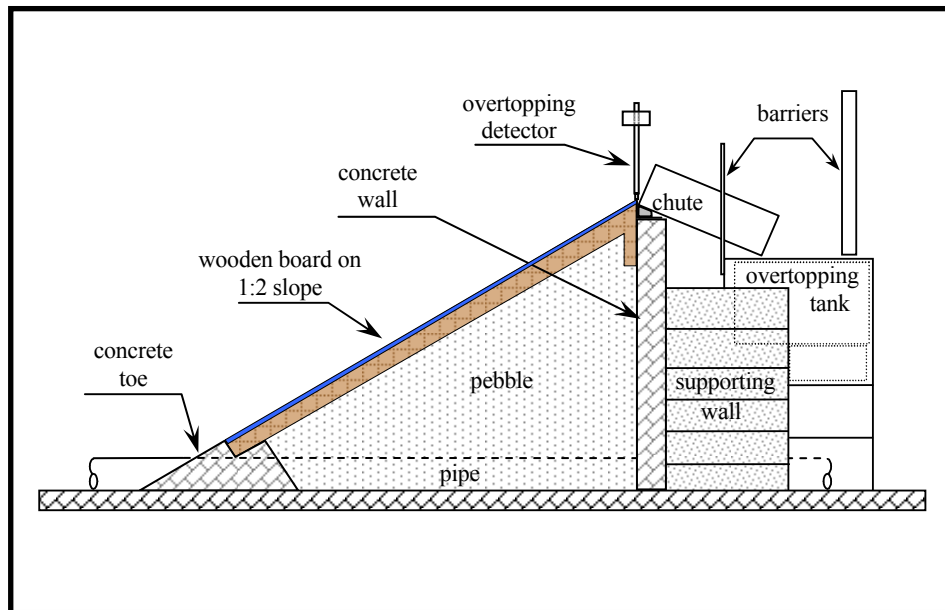


Figure 3-11 1:2 smooth slope structure (Absorbing Flume)

Figure 3-12 illustrates one of the model structures tested in the Three-foot Flume. Supporting struts were bolted to the side walls at a 1:10 slope and smooth, spray-painted plywood sheets placed onto the struts and screwed to them. The crest of the structure was fixed at 0.65m above the bed of the flume. Instead of using pipes, a 3cm gap was left under the toe of the structure to allow flow past it. A metal tank, to protect the overtopping tank, was supported on metal legs and was bolted to the floor against buoyancy. An overtopping detector, chutes, barriers and the overtopping tank were mounted and used in the same way as was described earlier.

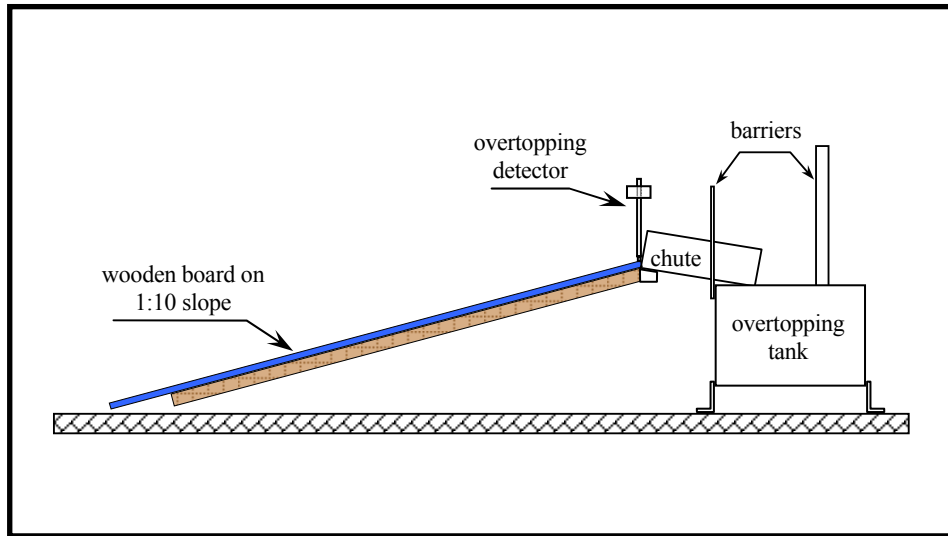


Figure 3-12 1:10 smooth slope structure (Three-foot Flume)

The 1:15 slope model structure was prepared in the way as the 1:10 slope structure (see Figure 3-13). In this case, the crest was set to 0.585m above the bed of the flume.

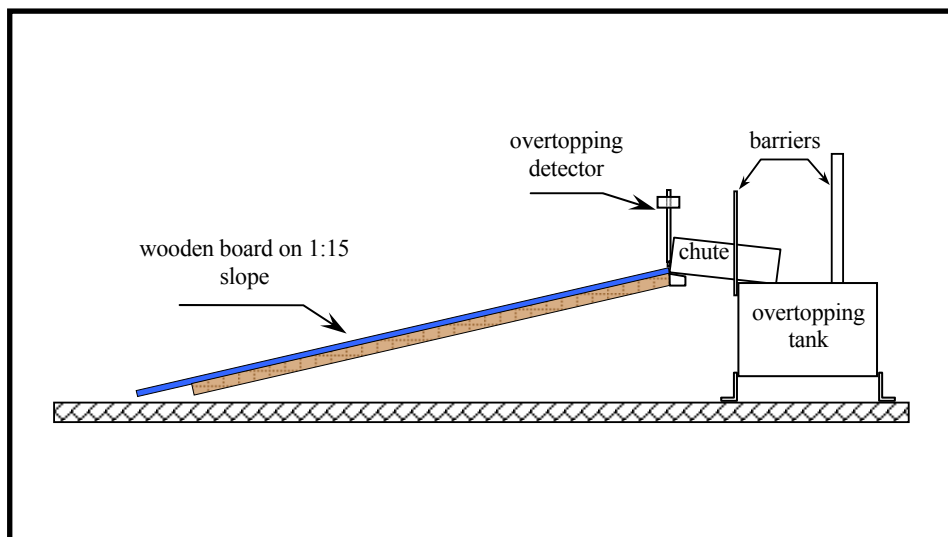


Figure 3-13 1:15 smooth slope structure (Three-foot Flume)

### 3.3.2. Modelling the waves

Knowing that overtopping data corresponding to low overtopping discharges are limited and that existing overtopping methods predict with wide variations in this range, wave conditions which would provide details of overtopping at the low/no overtopping threshold were planned. For this reason, it was decided to keep sequences reasonably long and to test structures for 1000 irregular waves conforming to the JONSWAP spectrum.

Wave conditions were designed by defining a range of offshore wave steepnesses and examining the predicted overtopping volumes by using the prediction methods described in Chapter 2. Owen's prediction method (see section 2.6.1) was used to estimate the expected overtopping volumes for the 1:2 model tests and a wave matrix prepared accordingly. Wave matrices for the 1:10 and 1:15 tests were prepared according to the estimated volumes provided by Van der Meer & Janssen's prediction method (see section 2.6.4) since, at the design stage, Owen's method was not capable of providing values for such mild-sloping structures.

The Absorbing Flume tests were designed for two different water levels. Water levels were set to 0.600m and 0.750m above the bed for the low-water and the high-water tests, respectively. The designed wave conditions, together with the paddle limit, steepness limit and depth limit curves are given in Figures 3-14 and 3-15 for low and high-water wave conditions, respectively. The initial test matrices provided more overtopping than originally anticipated and lower wave conditions to provide low overtopping volumes were added later.

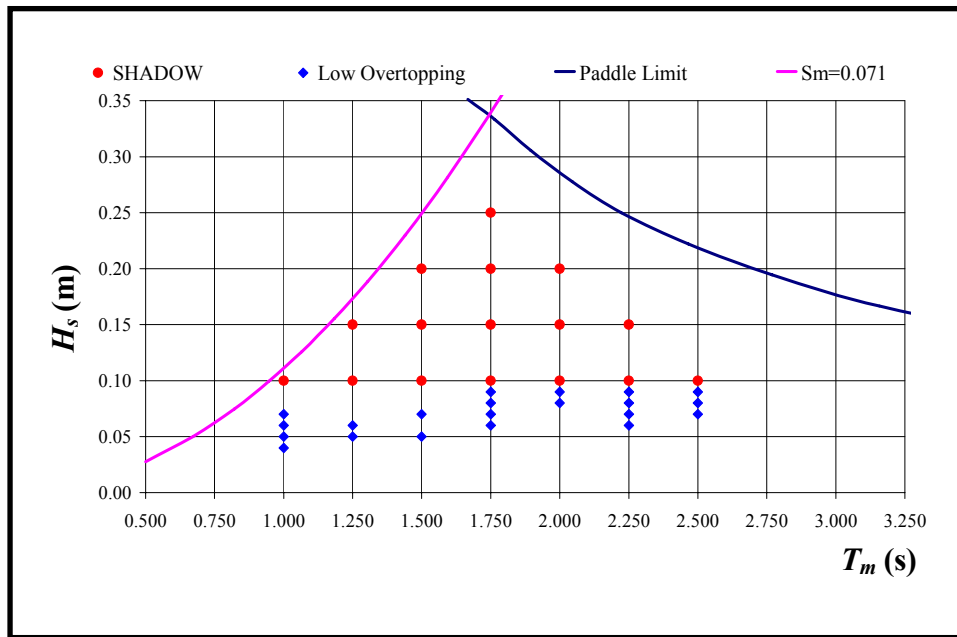


Figure 3-14 SHADOW Phase I - Wave conditions for 0.600m water depth

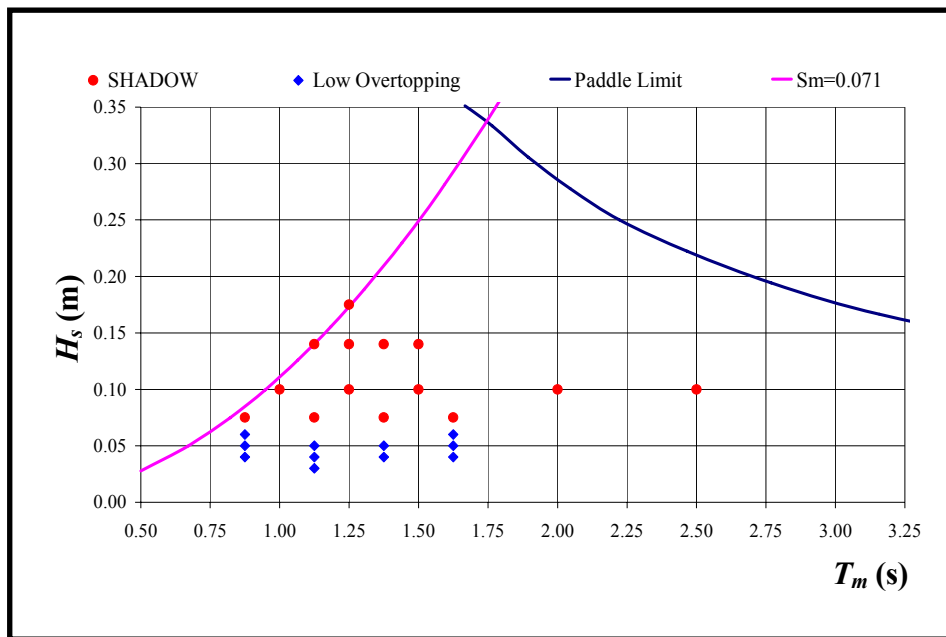


Figure 3-15 SHADOW Phase I - Wave conditions for 0.750m water depth

While performing the second stage tests, HRW was commissioned by WSP Development Ltd. (WSP) to undertake a case study of a site at



Haybridge, Maldon, Essex and perform tests to investigate functionality of the existing embankment against overtopping and flooding. Data belonging to that project were included in this study in order to widen the data range even further. Test conditions for the WSP files are shown in the following figure. The WSP wave matrix contains nine wave conditions at three different water levels (0.650m, 0.750m and 0.850m). They were small but comparatively steeper waves than in the SHADOW tests.

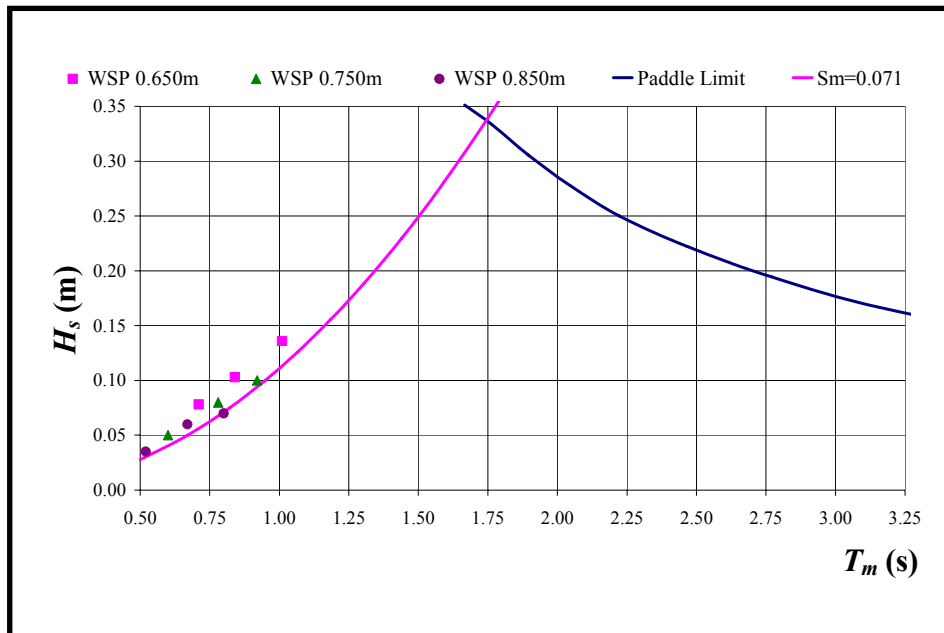


Figure 3-16 WSP wave conditions (Absorbing Flume)

The names of the wave conditions, and their characteristic heights ( $H_s$ ), mean periods ( $T_m$ ) and peak periods ( $T_p$ ) for the Absorbing Flume tests are given in the following tables.  $T_m$  was related to  $T_p$  using  $T_m = 0.87 * T_p$ . Letters at the beginning of each file name were selected randomly. The next two digits represent the test numbers and the last two digits indicate the water depth.

Table 3-1 SHADOW Phase I - 600mm water depth wave matrix

File Name	$H_s$ (m)	$T_m$ (s)	$T_p$ (s)
TAP0160	0.100	1.000	1.149
TAP0260	0.100	1.250	1.437
TAP0360	0.150	1.250	1.437
TAP0460	0.100	1.500	1.724
TAP0560	0.150	1.500	1.724
TAP0660	0.200	1.500	1.724
TAP0760	0.100	1.750	2.011
TAP0860	0.150	1.750	2.011
TAP0960	0.200	1.750	2.011
TAP1060	0.250	1.750	2.011
TAP1160	0.100	2.000	2.299
TAP1260	0.150	2.000	2.299
TAP1360	0.200	2.000	2.299
TAP1460	0.100	2.250	2.586
TAP1560	0.150	2.250	2.586
TAP1660	0.100	2.500	2.874

Table 3-2 SHADOW Phase I - 600mm water depth wave matrix (low overtopping)

File Name	$H_s$ (m)	$T_m$ (s)	$T_p$ (s)
KJO0160	0.040	1.000	1.149
KJO0260	0.050	1.000	1.149
KJO0360	0.060	1.000	1.149
KJO0460	0.070	1.000	1.149
KJO0560	0.060	1.250	1.437
KJO0660	0.050	1.250	1.437
KJO0760	0.050	1.500	1.724
KJO0860	0.070	1.500	1.724
KJO0960	0.060	1.750	2.011
KJO1060	0.070	1.750	2.011
KJO1160	0.090	1.750	2.011

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KJO1260	0.080	1.750	2.011
KJO1360	0.080	2.000	2.299
KJO1460	0.090	2.000	2.299
KJO1560	0.090	2.250	2.586
KJO1660	0.080	2.250	2.586
KJO1760	0.070	2.250	2.586
KJO1860	0.060	2.250	2.586
KJO1960	0.070	2.500	2.874
KJO2060	0.090	2.500	2.874
KJO2160	0.080	2.500	2.874

Table 3-3 SHADOW Phase I - 750mm water depth wave matrix

<b>File Name</b>	<b><math>H_s</math> (m)</b>	<b><math>T_m</math> (s)</b>	<b><math>T_p</math> (s)</b>
TAP0175	0.075	0.875	1.006
TAP0275	0.075	1.125	1.293
TAP0375	0.075	1.375	1.580
TAP0475	0.075	1.625	1.868
TAP0575	0.100	1.000	1.149
TAP0675	0.100	1.250	1.437
TAP0775	0.140	1.125	1.293
TAP0875	0.140	1.250	1.437
TAP0975	0.140	1.375	1.580
TAP1075	0.175	1.250	1.437
TAP1175	0.100	1.500	1.724
TAP1275	0.100	2.000	2.299
TAP1375	0.100	2.500	2.874
TAP1475	0.140	1.500	1.724

Table 3-4 SHADOW Phase I - 750mm water depth wave matrix (low overtopping)

File Name	$H_s$ (m)	$T_m$ (s)	$T_p$ (s)
KJO0175	0.060	0.875	1.006
KJO0275	0.050	0.875	1.006
KJO0375	0.040	0.875	1.006
KJO0475	0.050	1.125	1.293
KJO0575	0.040	1.125	1.293
KJO0675	0.030	1.125	1.293
KJO0775	0.040	1.375	1.580
KJO0875	0.050	1.375	1.580
KJO0975	0.040	1.625	1.868
KJO1075	0.050	1.625	1.868
KJO1175	0.060	1.625	1.868

Table 3-5 SHADOW Phase I - WSP wave matrix

File Name	$H_s$ (m)	$T_m$ (s)	$T_p$ (s)
WSP01	0.850	0.035	0.520
WSP02	0.850	0.070	0.800
WSP03	0.750	0.050	0.600
WSP04	0.750	0.100	0.920
WSP05	0.650	0.080	0.710
WSP06	0.650	0.130	1.010
WSP07	0.650	0.100	0.840
WSP08	0.750	0.080	0.780
WSP09	0.850	0.060	0.670

It was decided to run the SHADOW Phase II tests in the Three-foot Flume. Van der Meer & Janssen's prediction method was applied to estimate the overtopping volumes and the wave matrix was formed accordingly. Again the  $T_m = 0.87 * T_p$  relationship was used to relate mean

wave periods to peak wave periods. The wave matrices for the two different water levels are given in Tables 3-6 and 3-7. Figures 3-17 and 3-18 are graphical representations of these test conditions. Paddle limit and steepness limit curves are also included in these figures. As water levels for the second stage tests were lower than for the first ones, the depth-limiting lines associated with wave breaking are also included.

Table 3-6 SHADOW Phase II - 425mm water depth wave matrix

File Name	H <sub>s</sub> (m)	T <sub>m</sub> (s)	T <sub>p</sub> (s)
IB0104	0.035	0.750	0.862
IB0204	0.035	1.250	1.437
IB0304	0.070	1.250	1.437
IB0404	0.105	1.250	1.437
IB0504	0.035	1.750	2.011
IB0604	0.070	1.750	2.011
IB0704	0.105	1.750	2.011
IB0804	0.140	1.750	2.011
IB0904	0.035	2.250	2.586
IB1004	0.070	2.250	2.586
IB1104	0.105	2.250	2.586
IB1204	0.140	2.250	2.586
IB1304	0.035	2.750	3.161
IB1404	0.070	2.750	3.161
IB1504	0.105	2.750	3.161
IB1604	0.140	2.750	3.161
IB1704	0.035	3.250	3.736
IB1804	0.123	1.750	2.011
IB1904	0.123	2.250	2.586
IB2004	0.070	3.250	3.736

Table 3-7 SHADOW Phase II - 525mm water depth wave matrix

<b>File Name</b>	<b>H<sub>s</sub> (m)</b>	<b>T<sub>m</sub> (s)</b>	<b>T<sub>p</sub> (s)</b>
IB0105	0.035	0.75	0.862
IB0205	0.035	1.25	1.437
IB0305	0.07	1.25	1.437
IB0405	0.105	1.25	1.437
IB0505	0.035	1.75	2.011
IB0605	0.07	1.75	2.011
IB0705	0.105	1.75	2.011
IB0805	0.14	1.75	2.011
IB0905	0.175	1.75	2.011
IB1005	0.035	2.25	2.586
IB1105	0.07	2.25	2.586
IB1205	0.105	2.25	2.586
IB1305	0.14	2.25	2.586
IB1405	0.175	2.25	2.586
IB1505	0.035	2.75	3.161
IB1605	0.07	2.75	3.161
IB1705	0.105	2.75	3.161
IB1805	0.14	2.75	3.161
IB1905	0.175	2.75	3.161
IB2005	0.035	3.25	3.736
IB2105	0.055	1.75	2.011
IB2205	0.055	2.25	2.586
IB2305	0.055	2.75	3.161

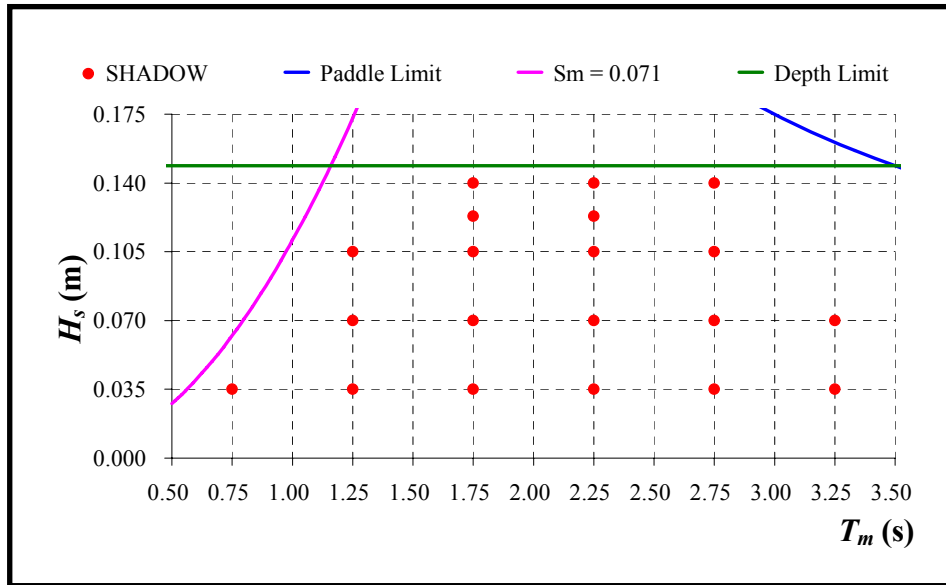


Figure 3-17 SHADOW Phase II - Wave conditions for 0.425m water depth

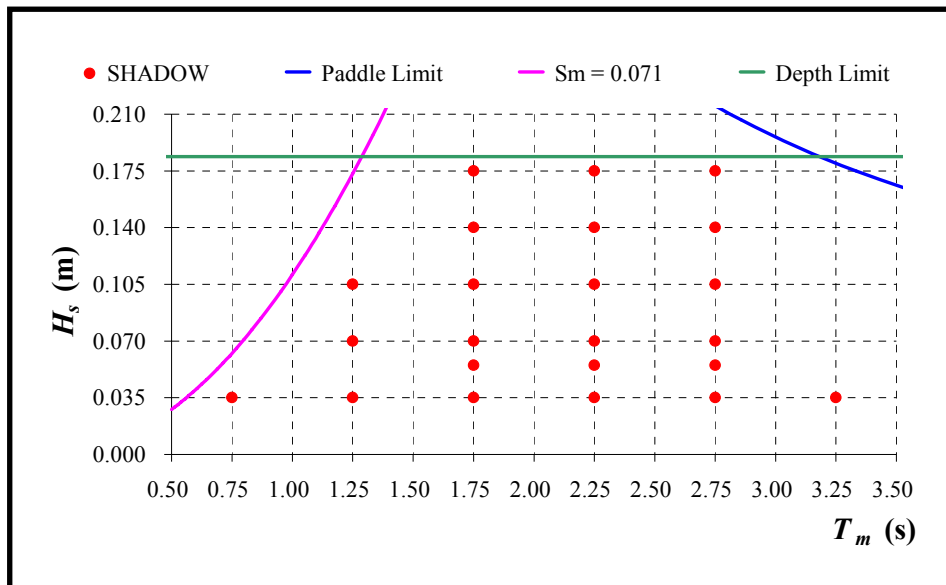


Figure 3-18 SHADOW Phase II - Wave conditions for 0.525m water depth

### 3.4. Model tests

A channel was dedicated to each of the wave probes, one for the overtopping detector, one for the load cell, two for the velocity detector and one for the overtopping depth detector, and all were connected to the computer. Software called *HR WaveData v2.2* was installed to collect and store data from each channel in separate files. Depending on the wave period, the data were recorded at frequencies in the 20~90Hz range.

#### 3.4.1. Wave calibrations

After setting the water to the required level, the wave probes were calibrated when the water was absolutely still. *CAL* is an analysis routine for *HR WaveData* and allows simple calibration of the wave probes. Calibration curves and the goodness-of-fit value for each channel were monitored and accepted if accurate enough. *CAL* assumes linear scaling and makes the best use of the available digital range of the input cards by allowing the user the choice of three selectable voltage ranges for each data channel. Calibration data, the calibration factor, the zero level (in digits), the goodness-of-fit value and the description for each channel number were saved as a text file with the extension “.*CAL*”.

After calibrating the wave probes, the system was ready to start the testing. *SPEC* is another routine in the *HR WaveData* program. It records data up to the user-defined number of data points. This number has to be a power of two and *SPEC* does the analysis when data collection stops. The scanning interval is a parameter in *SPEC* which defines the total test length together with the set number of data points. If the output wave statistics do not match the required wave conditions, the gain factor for the *HR Wavemaker* signal is set to a new level and the *SPEC* test is repeated. This process continues until the required  $H_s$  and  $T_m$  values are obtained.



When the target wave conditions had been achieved in the *SPEC* runs, longer sequence *WARP* runs were employed and the results of the *WARP* runs were considered as the actual wave conditions. *WARP* is another routine in the *HR WaveData* program. It records and analyses analogue signals in real time. *WARP* was set to record for  $1000 * T_m$  at a 20Hz scanning interval and the sequence length of each test was set to a suitable value so that the generated waves did not repeat. As soon as the data collection stopped, values of  $H_s$ ,  $H_{1/10}$ ,  $H_{max}$  and  $T_m$  were displayed on the monitor and saved in a named file. These values were then assigned to the calibrated wave conditions.

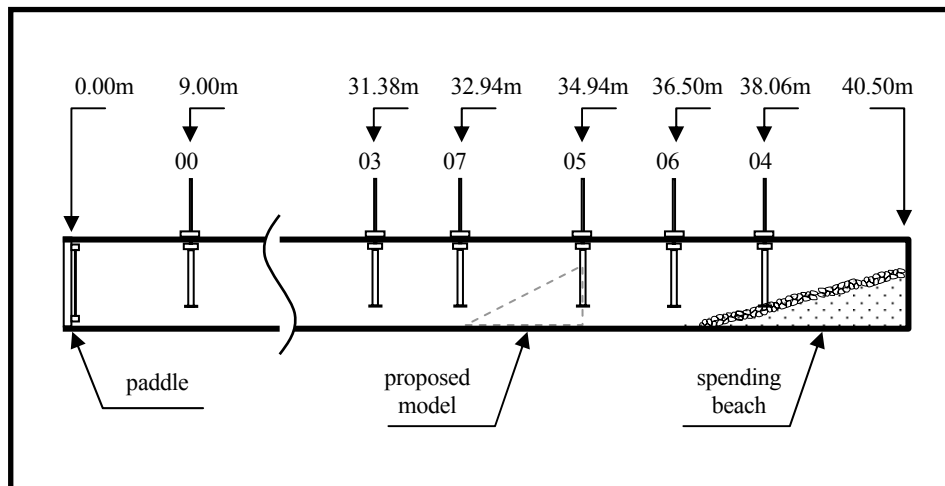


Figure 3-19 SHADOW Phase I – Wave gauge positions for wave calibration purposes

Wave conditions were calibrated according to the wave probe placed at the “Proposed Toe of the structure” (channel no: 07 in Figure 3-19). Positions for the other wave probes and their channel numbers are also shown in this figure and their descriptions are listed in Table 3-8. Although channel numbers 04, 05 and 06 were recorded during the experiments, the information was not used during the present study.

Table 3-8 SHADOW Phase I - Wave gauge definitions for the calibration files

Channel No	Definition
00	Deep water
03	1.56m from toe of structure
04	1.56m up spending beach
05	1.56m from toe of spending beach
06	Spending beach toe
07	Structure toe

Only one wave probe was employed for the Three-foot Flume wave calibrations (see Figure 3-20). The probe was defined as “Deep Water” and placed 7.50m from the paddle (when the paddle was at rest).

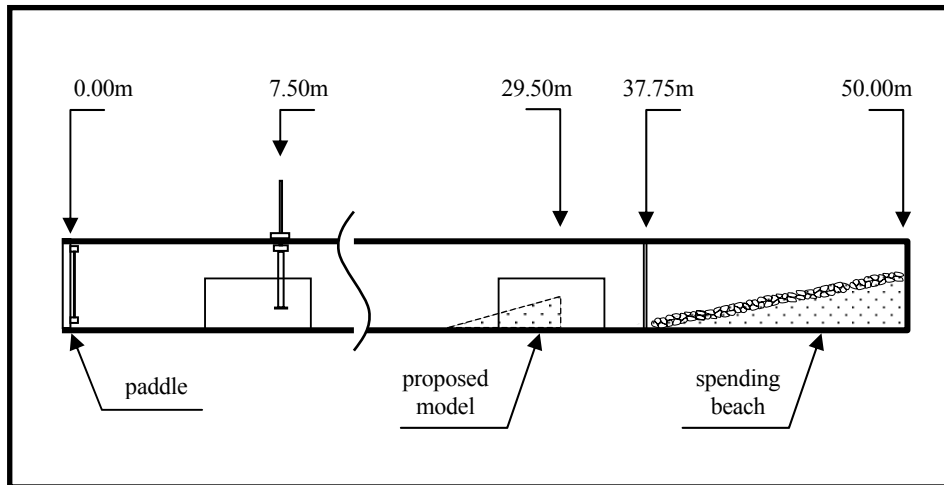


Figure 3-20 SHADOW Phase II - Wave gauge positions for wave calibration purposes

The first plot in Figure 3-21 shows the complete wave series for TAP0160 and the plot at the bottom clearly illustrates the irregularity of the wave train.

After completing wave calibrations, the spectra of the calibrated wave conditions were investigated. Actual spectra were plotted and compared with the theoretical JONSWAP form (see Appendix B4). Figure 3-22 is an example and figures for all other test conditions are given in Appendix B5. The basis of the spectral analysis was the Fast Fourier Transform algorithm.

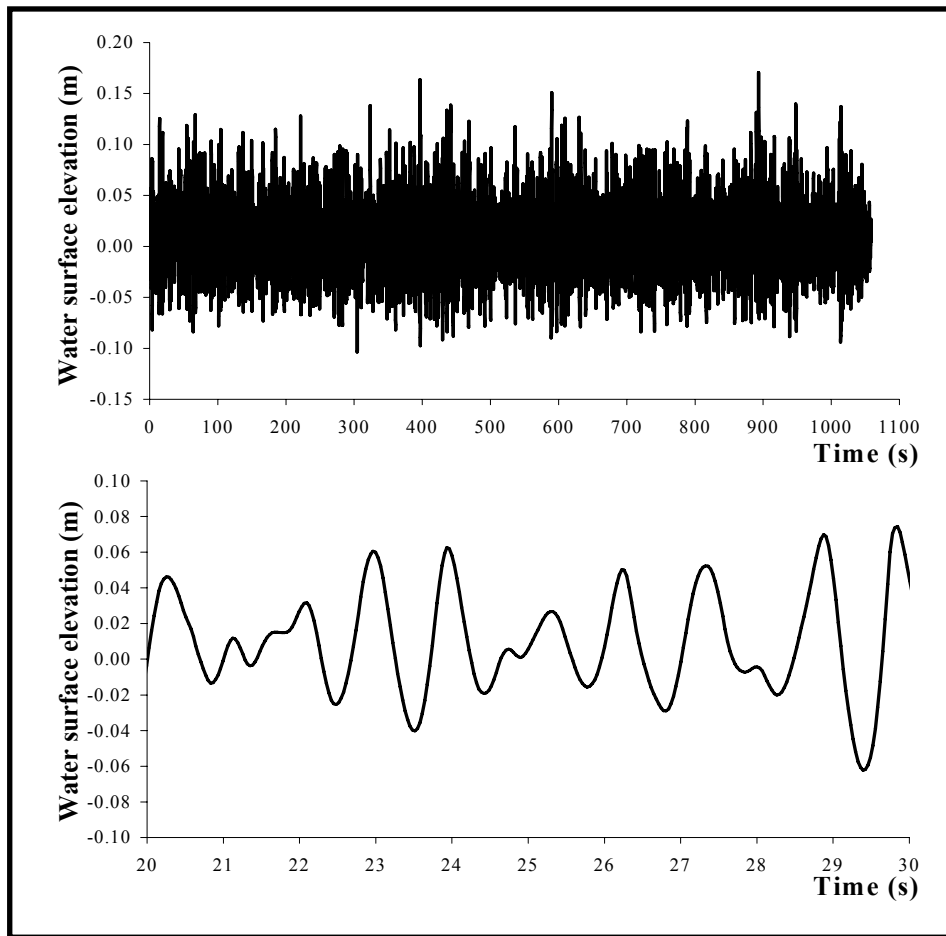


Figure 3-21 Wave series for TAP0160

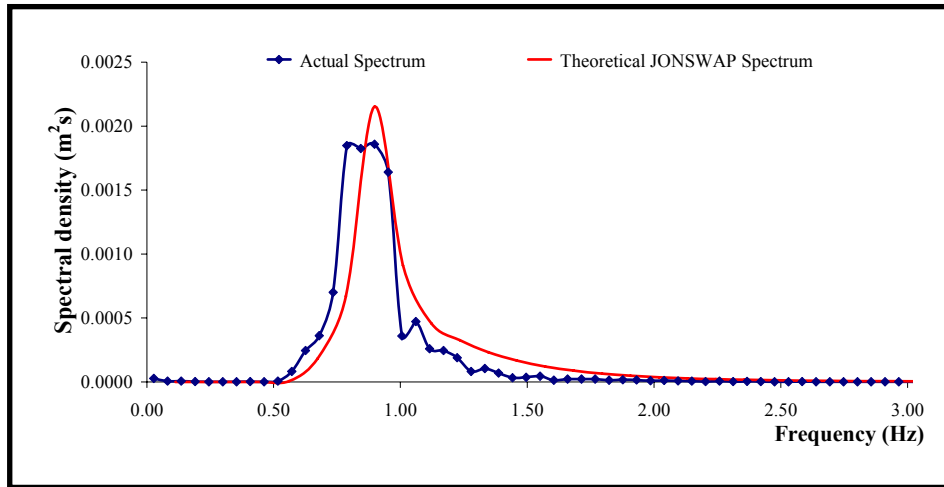


Figure 3-22 Wave spectrum for TAP0160

### 3.4.2. Overtopping tests

When all wave conditions had been calibrated, the flume was drained to construct the model seawall. Afterwards, the measuring equipment was replaced in the flume. The load cell was then calibrated before the tests started. Details of the load cell calibration for the Absorbing Flume tests are given in Table 3-9 and Figure 3-23. Table 3-10 and Figure 3-24 present information about the load cell calibration in the Three-foot Flume. Both load cell calibrations were highly accurate.

Table 3-9 SHADOW Phase I - Load cell calibration details

Load (ml of water)	Readings	Millivolts
0	3845	9387
1000	3762	9285
2000	3682	8989
3000	3595	8777
5000	3431	8376
10000	3016	7363
20000	2189	5344
30000	1359	3318

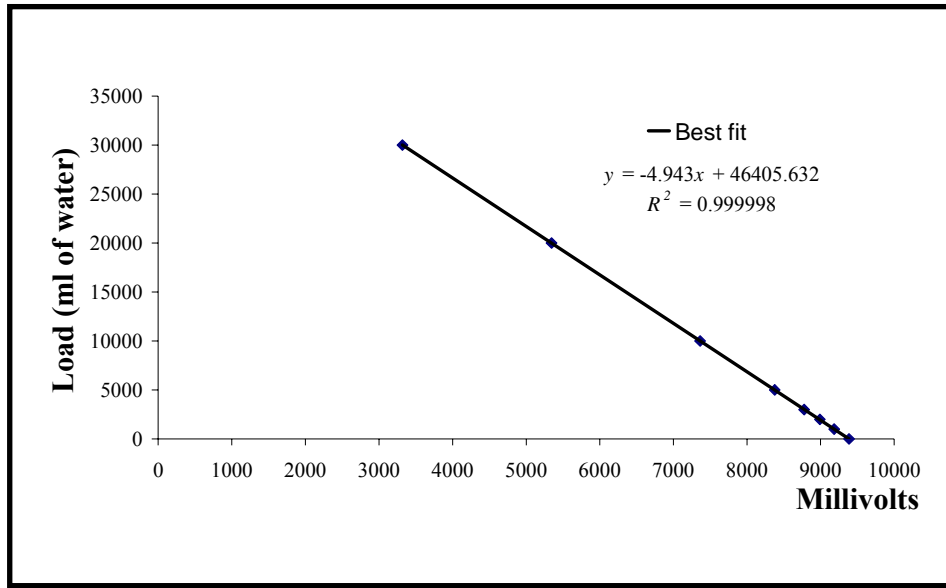


Figure 3-23 SHADOW Phase I - Load cell calibration

Table 3-10 SHADOW Phase II - Load cell calibration details

Load (ml of water)	Readings	Millivolts
0	419	1023
500	479	1169
1000	538	1313
2000	655	1599
3000	773	1887
5000	1010	2466
10000	1598	3901
12000	1834	4478
20000	2785	6799

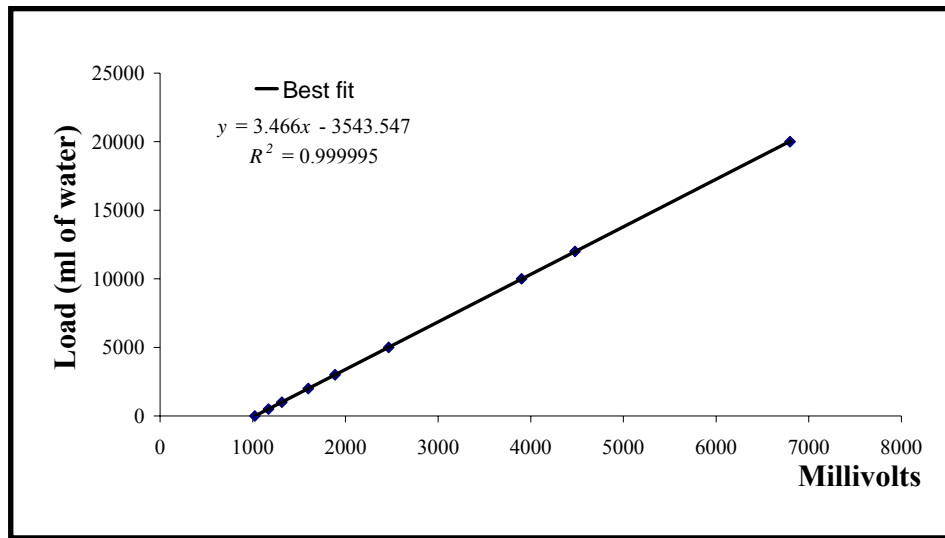


Figure 3-24 SHADOW Phase II - Load cell calibration

A schedule was prepared for running the experiments. According to this schedule, the overtopping tank was to be checked first to make sure that it was drained. After that, the input details for the *HR WaveMaker* and the *HR WaveData* programs had to be provided so that the computers were ready to start generating waves and recording the related data. Then, buttons to start the wave generation and a stopwatch were pressed together. *HR WaveMaker* was then left to generate waves for ninety seconds before *HR WaveData* started to record data. Another thirty seconds was left between the sampling start time and placing the chute to collect water in the tank. In other words, the real tests started when the stopwatch read one hundred and twenty seconds. As the total test length was  $1000 * T_m$ , the chute was removed when the stopwatch read  $120 + 1000 * T_m$  (seconds). However, *HR WaveData* continued recording for another thirty seconds. As soon as data collection was completed, *HR WaveMaker* was stopped too. The total overtopping volume in the tank was then measured by means of a calibrated plastic cylinder and recorded. The overtopping tank was emptied and left ready for the next test.

3.4.2.1. SHADOW Phase I – Absorbing Flume Tests

After building the model structure, the measuring equipment was replaced in the flume as shown in Figure 3-25. Table 3-11 provides definitions of the channels. A wave probe was placed at the structure toe, with another one located 0.75m away from the toe, towards the crest of the structure.

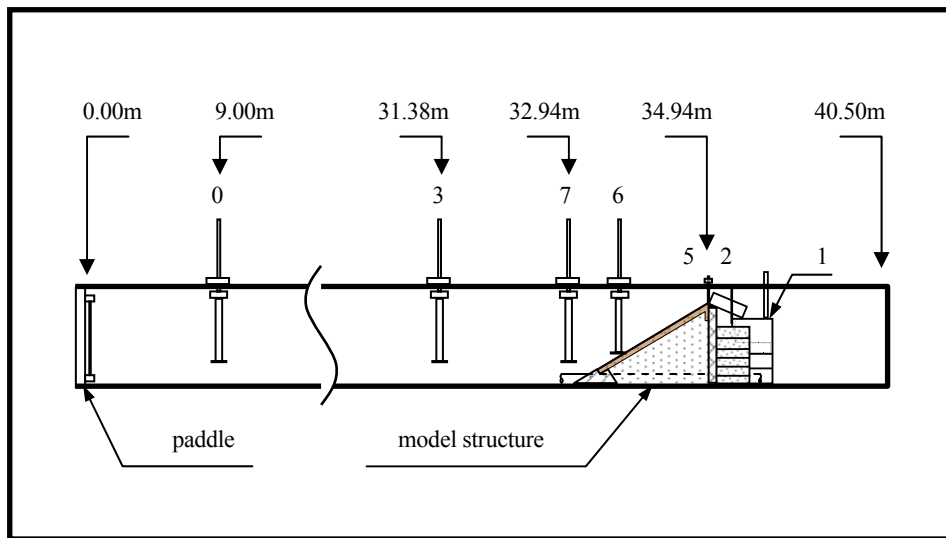


Figure 3-25 SHADOW Phase I - Channel numbers and their positions

Table 3-11 SHADOW Phase I - Definitions for channel numbers

Channel No	Definition
0	Deep water
1	Load cell
2	Overtopping detector
3	1.56m from toe of structure
5	Overtopping height
6	Slope (0.75m from toe)
7	Structure toe

After a few tests, the velocity detector was available for installation in the flume to measure the overtopping velocities. Two channels (6 and 7) were dedicated to it. Therefore, the wave probes and channel numbers were re-arranged as shown in Figure 3-26 and Table 3-12.

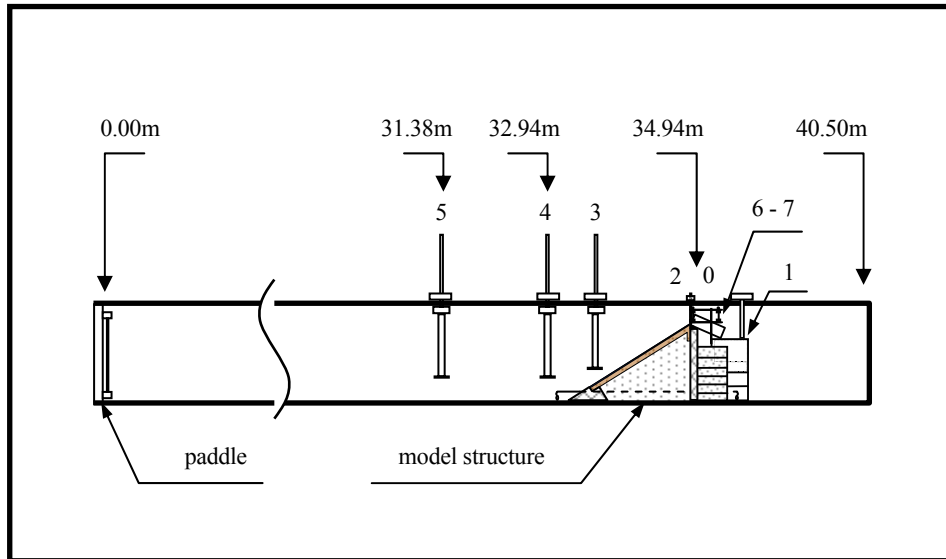


Figure 3-26 SHADOW Phase I - Channel numbers and their positions after installing the velocity detector

Table 3-12 SHADOW Phase I - Definitions for channel numbers after installing the velocity detector

Channel No	Definition
0	Overtopping detector
1	Load cell
2	Overtopping height
3	Slope (0.75m from toe)
4	Structure toe
5	1.56m from toe of structure
6	Overtopping velocity detector (first)
7	Overtopping velocity detector (second)



Details of the wave probes and other equipment for the low overtopping tests are shown in Figure 3-27 and details of the channels are given in Table 3-13.

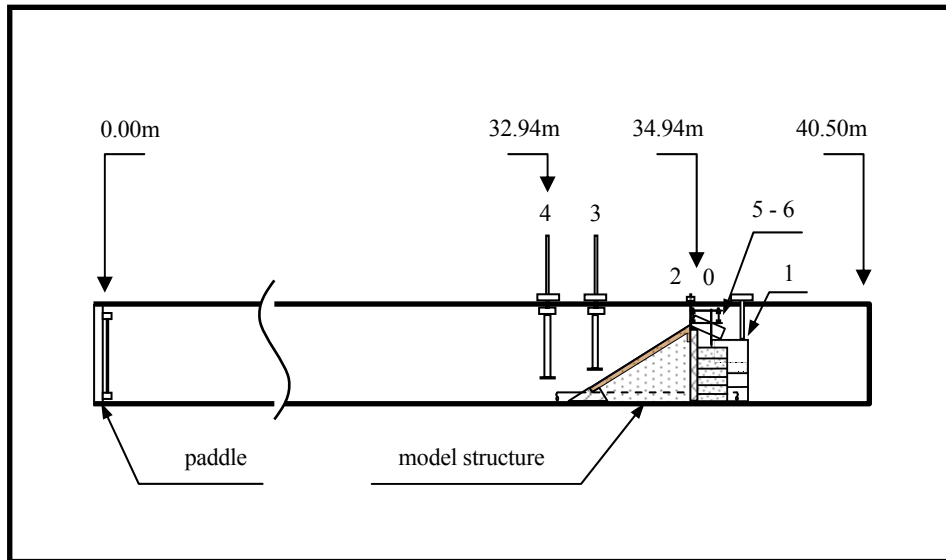


Figure 3-27 SHADOW Phase I - Channel numbers and their positions for low overtopping tests

Table 3-13 SHADOW Phase I - Definitions for channel numbers for low overtopping tests

Channel No	Definition
0	Overtopping height
1	Load cell
2	Overtopping detector
3	Wave gauge 1 – Shallow
4	Wave gauge 2 – Deep
5	Overtopping velocity detector (first)
6	Overtopping velocity detector (second)

3.4.2.2. SHADOW Phase II – Three-foot Flume Tests

The Three-foot Flume was employed to run the second phase SHADOW tests. 1:10 and 1:15 smooth structures were tested at this stage, with two different water levels. Figures 3-28 and 3-29 show probe positions at 0.425m and 0.525m water depths, respectively, together with additional details.

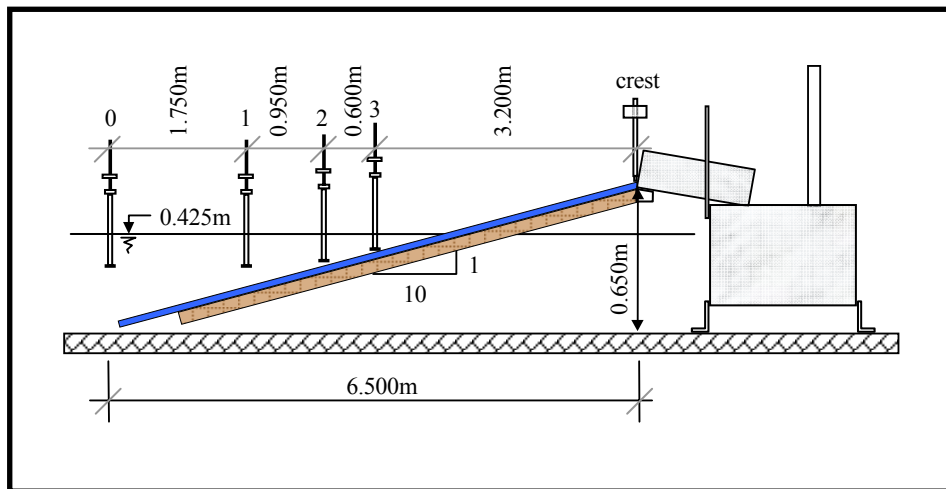


Figure 3-28 SHADOW Phase II - Channel numbers and their positions for 1:10 slope at 0.425m water depth

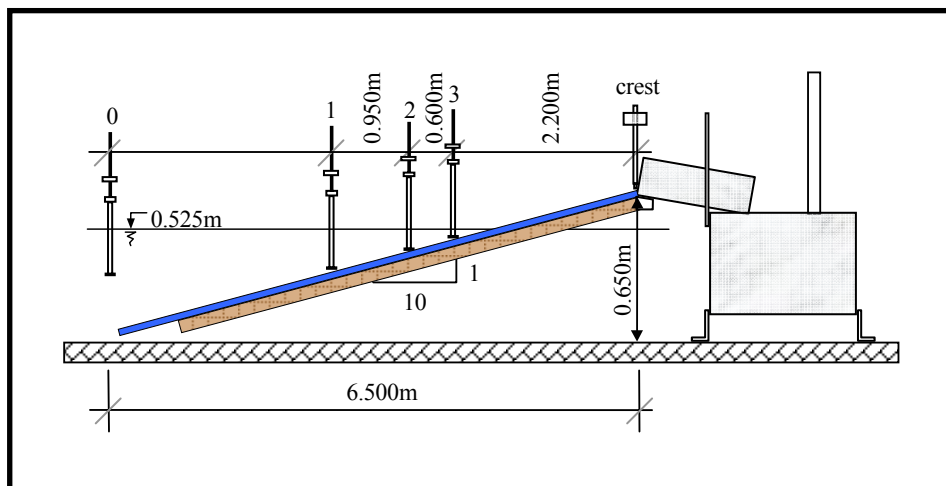


Figure 3-29 SHADOW Phase II - Channel numbers and their positions for 1:10 slope at 0.525m water depth

Channel numbers and their definitions for both structures are listed in Table 3-14.

Table 3-14 SHADOW Phase II - Channel numbers and their definitions

Channel No	Definition
0	Structure toe
1	Lower slope gauge
2	Mid-slope gauge
3	Upper slope gauge
4	Overtopping velocity detector (first)
5	Overtopping velocity detector (second)
6	Overtopping detector
7	Load cell

Details of the 1:15 sloping structure tests are shown in Figures 3-30 and 3-31 for water depths of 0.425m and 0.525m, respectively.

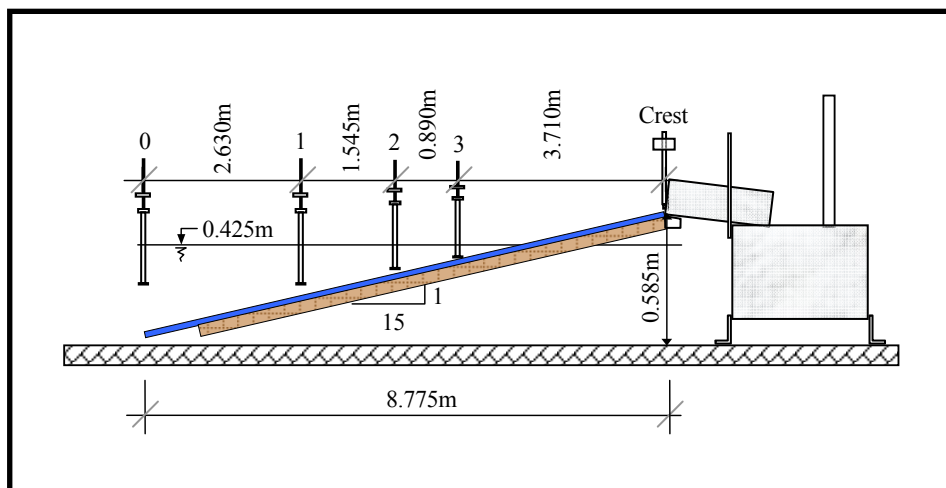


Figure 3-30 SHADOW Phase II - Channel numbers and their positions for 1:15 slope at 0.425m water depth

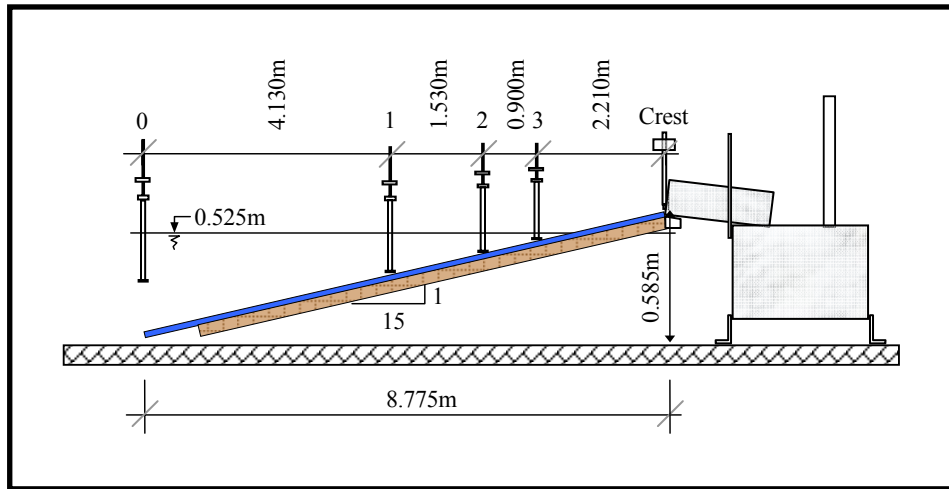


Figure 3-31 SHADOW Phase II - Channel numbers and their positions for 1:15 slope at 0.525m water depth

Typical examples of digitally-recorded overtopping detector and load cell signals for the TAP0160 wave condition are given in Figures 3-32 and 3-33. The level of the noise is also shown in both figures. Figure 3-34 is a good example of an overtopping event recorded during the TAP0160 test condition.

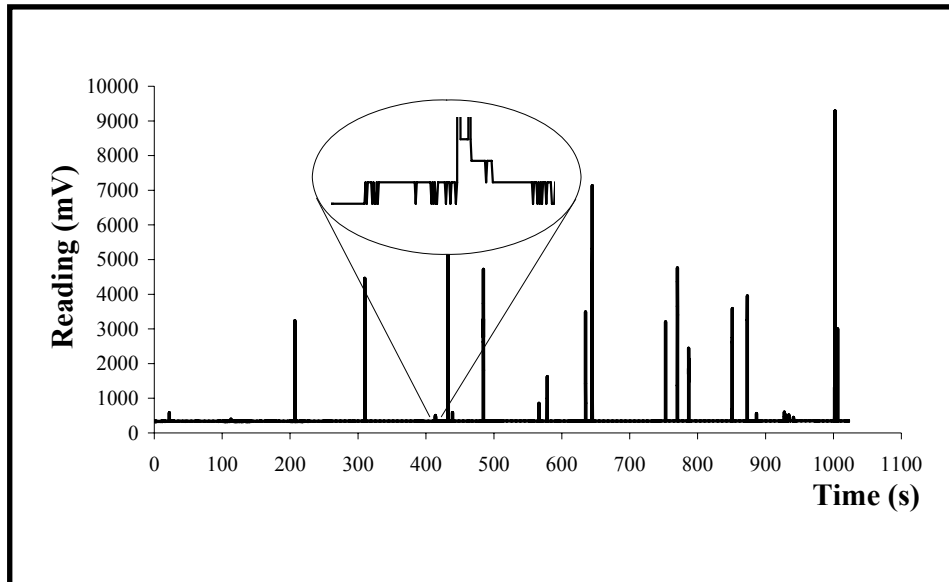


Figure 3-32 Example of an overtopping detector signal

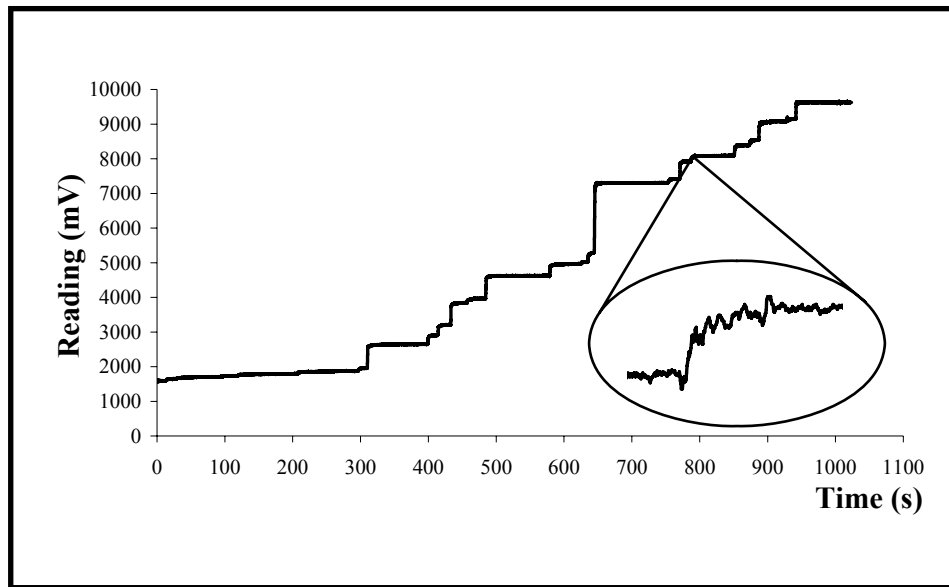


Figure 3-33 Example of a load cell signal



Figure 3-34 Snapshot of an overtopping event

### 3.5. Verification of the “repeatability”

As noted in the previous chapter, existing prediction methods give a poor estimate of the overtopping volumes, and their validity and applicability are restricted. This was proven once again, as soon as the physical model tests were commenced. After testing a few wave conditions, it was realised that the model waves were delivering more overtopping than predicted. Consequently, the collection tank was not always sufficiently large to contain the total overtopping volume for 1000 waves. For this reason, some tests were repeated using shorter wave sequences to check if conditions were sufficiently similar to allow tests to be divided into smaller numbers of waves.

TAP0160 was chosen for the repeatability test. A portion of the recorded signal from the wave gauges (at the structure toe), the overtopping detector and the load cell for two runs were plotted together for comparison. Figure 3-35 shows the good repeatability.

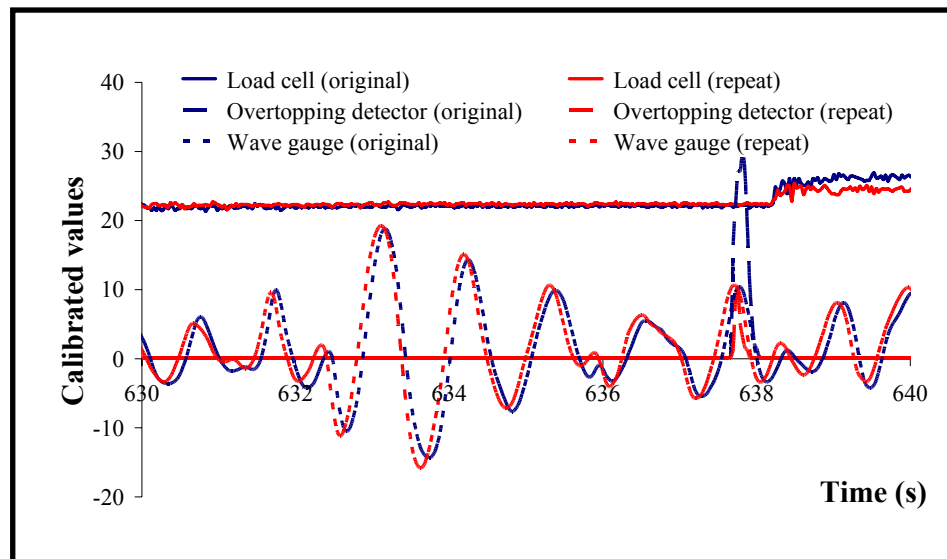


Figure 3-35 Repeatability of a test

Once it had been verified that repeatability was good, test conditions delivering higher overtopping volumes than the capacity of the overtopping tank were divided into smaller runs. Figure 3-36 illustrates the time schedule for TAP0660 and more detailed information about the application of the divided tests is given in Appendix B5.

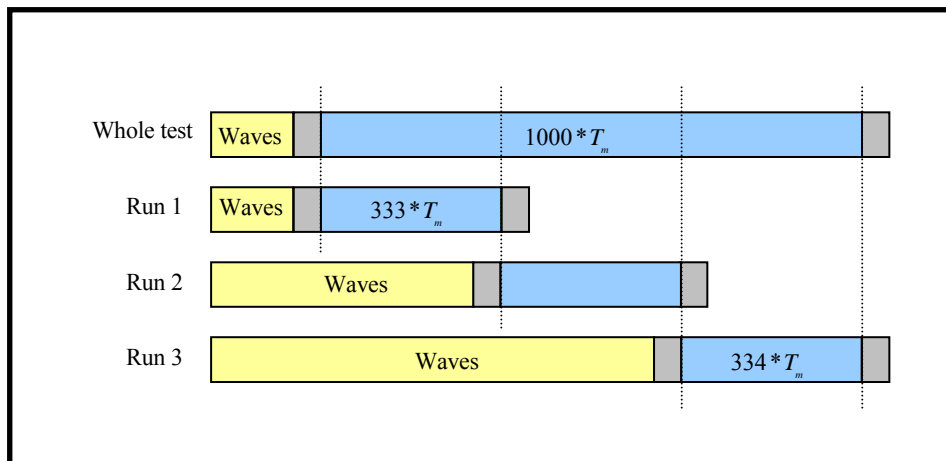


Figure 3-36 Time schedule for divided test condition, TAP0660

### 3.6. Primary results

Although the test results were recorded and saved digitally for future analysis, overtopping volumes were measured manually at the end of each test. The main reason was to check the accuracy of the digital recordings and the analysis software. A 2-litre calibrated cylinder was used for this purpose and the total overtopping volumes were found accordingly. Measured overtopping volumes for the 600mm water depth tests are listed in Table 3-15 and the 750mm water depth values are given in Table 3-16.

Table 3-15 SHADOW Phase I - Initial results for 1:2 slope, 600mm water depth tests

File Name	$H_s$ (m)	$T_m$ (s)	Water Depth (m)	Chute Used (m)	Number of Waves	Total Volume (lt)
TAP0160	0.096	1.092	0.6006	0.5	1000	3.32
TAP0260	0.108	1.288	0.6006	0.5	1000	14.56
TAP0360	0.153	1.360	0.6006	0.1	1000	28.48
TAP0460	0.101	1.568	0.6006	0.1	1000	3.39
TAP0460A	0.101	1.568	0.6006	0.5	1000	16.50
TAP0560	0.148	1.593	0.6006	0.1	1000	31.50
TAP0660	0.199	1.648	0.6002	0.1	1000	overflow
TAP0660X	0.199	1.648	0.6004	0.1	333	23.66
TAP0660Y	0.199	1.648	0.6004	0.1	333	28.96
TAP0660Z	0.199	1.648	0.6004	0.1	334	29.17
TAP0760	0.104	1.866	0.6002	0.1	1000	2.73
TAP0760A	0.104	1.866	0.6002	0.5	1000	16.40
TAP0860	0.149	1.885	0.6002	0.1	1000	39.31
TAP0960	0.199	1.913	0.6003	0.1	1000	overflow
TAP0960A	0.199	1.913	0.6000	0.1	1000	overflow
TAP0960B	0.199	1.913	0.6002	0.1	250	23.58
TAP0960W	0.199	1.913	0.6003	0.1	250	23.82
TAP0960X	0.199	1.913	0.6003	0.1	250	33.20
TAP0960Y	0.199	1.913	0.6003	0.1	250	30.44
TAP0960Z	0.199	1.913	0.6003	0.1	250	29.23
TAP1060	-	-				
TAP1160	0.103	2.090	0.6000	0.1	1000	1.98
TAP1160A	0.103	2.090	0.6000	0.5	1000	7.56
TAP1160B	0.103	2.090	0.6000	0.5	1000	7.84
TAP1260	0.149	2.108	0.6000	0.1	1000	overflow
TAP1260Y	0.149	2.108	0.6003	0.1	500	29.21
TAP1260Z	0.149	2.108	0.6003	0.1	500	25.03
TAP1360	0.199	2.105	0.6002	0.1	1000	overflow
TAP1360U	0.199	2.105	0.6004	0.1	166	31.34
TAP1360V	0.199	2.105	0.6004	0.1	166	24.70
TAP1360W	0.199	2.105	0.6004	0.1	166	34.90
TAP1360X	0.199	2.105	0.6004	0.1	166	30.04
TAP1360Y	0.199	2.105	0.6004	0.1	166	34.96
TAP1360Z	0.199	2.105	0.6004	0.1	170	35.64
TAP1460	0.101	2.488	0.6002	0.1	1000	3.36



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TAP1460A	0.101	2.488	0.6002	0.5	1000	18.25
TAP1560	0.149	2.417	0.6002	0.1	1000	overflow
TAP1560Y	0.149	2.417	0.6004	0.1	500	29.20
TAP1560Z	0.149	2.417	0.6004	0.1	500	31.17
TAP1660	0.101	2.749	0.6004	0.5	1000	7.18
TAP1660A	0.101	2.749	0.6004	0.5	1000	6.82

Table 3-16 SHADOW Phase I - Initial results for 1:2 slope, 750mm water depth tests

File Name	$H_s$ (m)	$T_m$ (s)	Water Depth (m)	Chute Used (m)	Number of Waves	Total Volume (lt)
TAP0175	0.075	0.965	0.7503	0.5	1000	6.84
TAP0175R	0.075	0.965	0.7499	0.5	1000	8.72
TAP0275	0.075	1.129	0.7503	0.5	1000	26.82
TAP0275R	0.075	1.129	0.7499	0.5	1000	24.04
TAP0375	0.075	1.399	0.7503	0.5	1000	35.22
TAP0375R	0.075	1.399	0.7500	0.5	1000	43.48
TAP0375S	0.075	1.399	0.7500	0.5	1000	43.78
TAP0475	0.077	1.755	0.7496	0.1	1000	12.52
TAP0575	0.094	1.089	0.7496	0.5	1000	overflow
TAP0575A	0.094	1.089	0.7496	0.1	1000	9.60
TAP0575R	0.094	1.089	0.7500	0.1	1000	8.96
TAP0675	0.104	1.277	0.7496	0.1	1000	42.13
TAP0775	0.136	1.219	0.7496	0.1	1000	overflow
TAP0775L	0.136	1.219	0.7496	0.1	333	22.16
TAP0775M	0.136	1.219	0.7496	0.1	333	32.40
TAP0775N	0.136	1.219	0.7496	0.1	334	24.95
TAP0875	0.145	1.333	0.7502	0.1	1000	overflow
TAP0875K	0.145	1.333	0.7502	0.1	250	31.34
TAP0875L	0.145	1.333	0.7502	0.1	250	40.40
TAP0875M	0.145	1.333	0.7502	0.1	250	38.20
TAP0875N	0.145	1.333	0.7502	0.1	250	32.60
TAP0975	0.146	1.420	0.7502	0.1	1000	overflow
TAP0975J	0.146	1.420	0.7502	0.1	200	32.06
TAP0975K	0.146	1.420	0.7502	0.1	200	43.04
TAP0975L	0.146	1.420	0.7502	0.1	200	overflow
TAP0975M	0.146	1.420	0.7502	0.1	200	41.98

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TAP0975N	0.146	1.420	0.7502	0.1	200	42.44
TAP1075	0.175	1.384	0.7499	0.1	1000	overflow
TAP1075I	0.175	1.384	0.7499	0.1	166	32.15
TAP1075J	0.175	1.384	0.7499	0.1	166	40.61
TAP1075K	0.175	1.384	0.7499	0.1	166	overflow
TAP1175	0.095	1.541	0.7499	0.1	1000	overflow
TAP1175M	0.095	1.541	0.7499	0.1	500	26.72
TAP1175N	0.095	1.541	0.7499	0.1	500	24.96
TAP1275	0.102	2.100	0.7499	0.1	1000	overflow
TAP1275L	0.102	2.100	0.7499	0.1	333	19.68
TAP1275M	0.102	2.100	0.7499	0.1	333	39.35
TAP1275N	0.102	2.100	0.7499	0.1	334	27.22
TAP1375	0.103	2.757	0.7499	0.1	1000	overflow
TAP1375M	0.103	2.757	0.7500	0.1	500	29.68
TAP1375N	0.103	2.757	0.7500	0.1	500	overflow
TAP1475	0.095	1.541	0.7499	0.1	1000	overflow
TAP1475J	0.095	1.541	0.7499	0.1	200	32.21
TAP1475K	0.095	1.541	0.7499	0.1	200	42.64
TAP1475L	0.095	1.541	0.7499	0.1	200	overflow

It is clear from Tables 3-15 and 3-16 that the tests for some wave conditions were split into shorter runs. Overtopping volumes were added together to find the total overtopping volume corresponding to 1000 waves. Note that the different sizes of chutes used during testing must be considered when analysing the results to obtain the total overtopping volumes corresponding to a metre length of the wall.

Testing started with medium size waves in SHADOW Phase II. This decision saved time by avoiding testing with smaller waves if no overtopping was recorded for the medium size waves. Also, there was a chance to avoid testing with bigger waves if any wave condition provided more overtopping than some reasonable threshold. The same measuring equipment was used as in Phase I and, again, results were recorded both

manually and digitally. Tables 3-17 and 3-18 give measured overtopping volumes for the 1:10 structure with 425mm and 525mm water depths, respectively.

A few exceptional tests were performed. For example, zero overtopping might occur during a test period. However, an overtopping event might still be observed immediately after the completion of the test, before the waves were stopped. In such cases, the test was repeated using 2000 waves. Similarly, tests with very low overtopping volumes were repeated with longer wave sequences.

Table 3-17 SHADOW Phase II - Initial results for 1:10 slope, 425mm water depth tests

File Name	$H_s$ (m)	$T_m$ (s)	Water Depth (m)	Chute Used (m)	Number of Waves	Total Volume (lt)
ESI0104	0.039	0.756	-	-	-	-
ESI0204	0.037	1.235	-	-	-	-
ESI0304	0.076	1.241	-	-	-	-
ESI0404	0.112	1.254	-	-	-	-
ESI0504	0.035	1.721	-	-	-	-
ESI0604	0.074	1.735	-	-	-	-
ESI0704	0.111	1.751	-	-	-	-
ESI0804	0.145	1.759	0.425	0.5	1000	0.350
ESI0904	0.035	2.205	-	-	-	-
ESI1004	0.072	2.150	-	-	-	-
ESI1104	0.108	2.080	0.423	0.5	1000	0.000
ESI1204	0.139	2.035	0.422	0.5	1000	1.620
ESI1304	0.035	2.723	-	-	-	-
ESI1404	0.072	2.637	0.424	0.5	1000	0.000
ESI1504	0.105	2.538	0.423	0.5	1000	15.350
ESI1604	0.133	2.470	0.423	0.5	1000	45.800
ESI1704	0.036	3.247	0.424	0.5	1000	0.000
ESI1804	0.128	1.760	0.425	0.5	1000	0.000
ESI1904	0.128	2.043	0.422	0.5	1000	0.240
ESI2004	0.072	3.291	0.425	0.5	1000	0.925

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ESS0804	0.145	1.759	0.425	0.5	2000	2.200
ESS1104	0.108	2.080	0.425	0.5	5000	0.280
ESS1204	0.139	2.035	0.425	0.5	5000	21.530
ESS1904	0.128	2.043	0.425	0.5	2000	1.150

Table 3-18 SHADOW Phase II - Initial results for 1:10 slope, 525mm water depth tests

File Name	$H_s$ (m)	$T_m$ (s)	Water Depth (m)	Chute Used (m)	Number of Waves	Total Volume (lt)
ESI0105	0.037	0.774	0.525	0.5	1000	0.000
ESI0205	0.040	1.239	0.525	0.5	1000	0.000
ESI0305	0.079	1.242	0.524	0.5	1000	0.000
ESI0405	0.113	1.254	0.524	0.5	1000	0.865
ESI0505	0.036	1.741	0.524	0.5	1000	0.000
ESI0605	0.076	1.732	0.523	0.5	1000	0.990
ESI0705	0.117	1.743	0.522	0.5	1000	15.320
ESI0805	0.155	1.753	0.522	0.5	1000	85.650
ESI0905	0.186	1.758	0.521	0.1	1000	41.910
ESI1005	0.035	2.219	0.521	0.5	1000	0.000
ESI1105	0.075	2.189	0.520	0.5	1000	3.620
ESI1205	0.115	2.140	0.523	0.5	1000	79.360
ESI1305	0.154	2.090	0.522	0.1	1000	68.090
ESI1405	0.184	2.058	-	-	-	-
ESI1505	0.036	2.723	0.523	0.5	1000	0.000
ESI1605	0.073	2.758	0.524	0.5	1000	43.010
ESI1705	0.113	2.585	0.523	0.1	1000	70.910
ESI1805	0.147	2.521	-	-	-	-
ESI1905	0.175	2.479	-	-	-	-
ESI2005	0.036	3.289	0.525	0.5	1000	1.080
ESI2105	0.060	1.766	0.521	0.5	1000	0.000
ESI2205	0.059	2.221	0.521	0.5	1000	0.110
ESI2305	0.060	2.713	0.520	0.5	1000	2.910
ESS0405	0.113	1.254	0.525	0.5	5000	0.920
ESS0605	0.076	1.732	0.525	0.5	5000	0.520
ESS1105	0.075	2.189	0.525	0.5	2000	6.090

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Tables 3-19 and 3-20 provide the results for the 1:15 structure with 425mm and 525mm water depths, respectively.

Table 3-19 SHADOW Phase II - Initial results for 1:15 slope, 425mm water depth tests

File Name	$H_s$ (m)	$T_m$ (s)	Water Depth (m)	Chute Used (m)	Number of Waves	Total Volume (lt)
ESB0104	0.039	0.756	0.4240	0.5	1000	0.000
ESB0204	0.037	1.235	0.4239	0.5	1000	0.000
ESB0304	0.076	1.241	0.4238	0.5	1000	0.000
ESB0404	0.112	1.254	0.4236	0.5	1000	0.000
ESB0504	0.035	1.721	0.4234	0.5	1000	0.000
ESB0604	0.074	1.735	0.4250	0.5	1000	0.000
ESB0704	0.111	1.751	0.4230	0.5	1000	1.730
ESB0804	0.145	1.759	0.4232	0.5	1000	18.300
ESB0904	0.035	2.205	0.4248	0.5	1000	0.000
ESB1004	0.072	2.150	0.4245	0.5	1000	0.000
ESB1104	0.108	2.080	0.4225	0.5	1000	3.160
ESB1204	0.139	2.035	0.4228	0.5	1000	56.930
ESB1304	0.035	2.723	0.4237	0.5	1000	0.000
ESB1404	0.072	2.637	0.4234	0.5	1000	0.000
ESB1504	0.105	2.538	0.4222	0.5	1000	22.570
ESB1604	0.133	2.470	0.4219	0.5	1000	161.100
ESB1704	0.036	3.247	0.4242	0.5	1000	0.000
ESB1804	0.128	1.760	0.4250	0.5	1000	10.420
ESB1904	0.128	2.043	0.4250	0.5	1000	25.640
ESB2004	0.072	3.291	0.4249	0.5	1000	0.145

Table 3-20 SHADOW Phase II - Initial results for 1:15 slope, 525mm water depth tests

File Name	$H_s$ (m)	$T_m$ (s)	Water Depth (m)	Chute Used (m)	Number of Waves	Total Volume (lt)
ESB0105	0.037	0.774	0.5250	0.5	1000	0.000
ESB0205	0.040	1.239	0.5248	0.5	1000	0.000
ESB0305	0.079	1.242	0.5243	0.5	1000	3.750
ESB0405	0.113	1.254	0.5239	0.5	1000	16.140

ESB0505	0.036	1.741	0.5250	0.5	1000	0.000
ESB0605	0.076	1.732	0.5246	0.5	1000	35.880
ESB0705	0.117	1.743	0.5244	0.1	1000	54.500
ESB0805	0.155	1.753	-	-	-	-
ESB0905	0.186	1.758	-	-	-	-
ESB1005	0.035	2.219	0.5244	0.5	1000	0.170
ESB1105	0.075	2.189	0.5241	0.1	1000	18.610
ESB1205	0.115	2.140	-	-	-	-
ESB1305	0.154	2.090	-	-	-	-
ESB1405	0.184	2.058	-	-	-	-
ESB1505	0.036	2.723	0.5240	0.5	1000	5.020
ESB1605	0.073	2.758	0.5239	0.1	1000	52.900
ESB1705	0.113	2.585	-	-	-	-
ESB1805	0.147	2.521	-	-	-	-
ESB1905	0.175	2.479	-	-	-	-
ESB2005	0.036	3.289	0.5250	0.5	1000	24.570
ESB2105	0.060	1.766	0.5250	0.5	1000	6.995
ESB2205	0.059	2.221	0.5250	0.5	1000	19.800
ESB2305	0.060	2.713	0.5249	0.5	1000	90.580

### 3.7. Some sources of error

The purpose of this project was to test the overtopping performance of model structures against two-dimensional waves. However, for several reasons, some three-dimensional (3D) effects were observed while testing. To reduce their impact, the widest chute size (500mm) was employed whenever possible.

It was also found that data from the overtopping depth detector and from the velocity detector were of poor quality, partly owing to the 3D effects, but also because of high gain settings on the recordings which introduced a high level of noise. Furthermore, after completing the experiments, an error became apparent in the load cell calibration for the Three-foot Flume tests. The calibration did not extend to water volumes greater than

20,000ml (see Table 3-10). Even though the overtopping volumes were measured manually, because of the faulty calibration, serious errors were found in the digitally recorded files for those wave conditions providing large overtopping volumes (see Figure 3-37). Therefore, data files for those wave conditions providing high total overtopping volumes were not reliable and needed special treatment (see section 4.8). However, the results from wave conditions providing smaller total overtopping volumes were still useful.

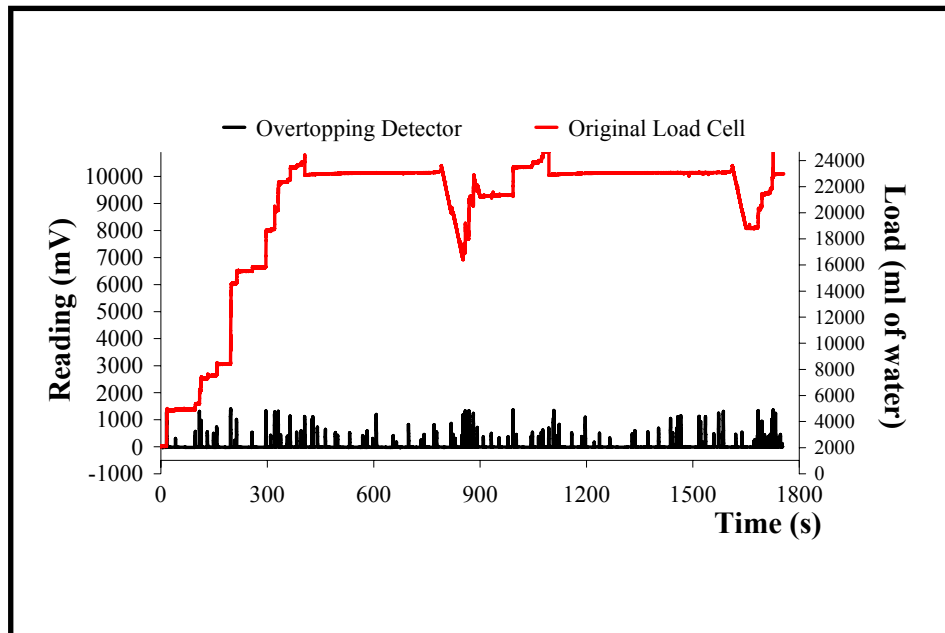


Figure 3-37 Example of problematic test conditions

### 3.8. Conclusion

Model structures with 1:2, 1:10 and 1:15 front slopes with smooth surfaces were tested. Initially, it was thought that there was nothing new in testing a 1:2 slope structure and these tests were to be taken as a benchmark against which to compare results for the other slopes. However, the initially

selected wave conditions provided more overtopping than expected and the test wave conditions were subsequently modified. In addition, the tests provided information on low overtopping conditions for which existing prediction methods are in poor agreement.

The various model structures have been tested against 219 wave conditions in total. The tests have been performed at two different water levels with irregular waves. Initially, test lengths were planned to be 1000 waves but, under some circumstances, the test lengths were changed to range from 166 to 5000 waves. Total overtopping volumes were measured and recorded manually. Therefore, mean discharges could easily be calculated. In addition, data were recorded in digital files and these files provided the opportunity to investigate wave-by-wave overtopping volumes.



# *Chapter 4*

## **DATA PROCESSING USING *proBAY***

The SHADOW project model tests were recorded digitally and these files have been analysed by means of a computer program. This chapter gives detailed information about the software called *proBAY* which was compiled in FORTRAN and used to analyse data files recorded during the physical modelling. In addition, Microsoft Excel files, containing macros, were created to assist *proBAY* for further analysis. A description of the *proBAY* software and how it has been used, together with detailed information about the parameter list and the output files, is followed by a description of the Microsoft Office based programs.

### **4.1. Introduction**

After completing the physical model tests (both Phase I and Phase II), the recorded data files needed processing before further analysis. Software called *proBAY* was developed for this purpose. It was written in FORTRAN and compiled using the FTN95 compiler. Therefore, it should run without any problem on personal computers in which FORTRAN 95 has been installed. Alternatively, the FORTRAN library file “*salflibc.dll*” is required in the same folder where *proBAY* is run.

The present version of *proBAY* was compiled to analyse SHADOW data files only. Since *HR Waves* has a unique output form, this version of *proBAY* can only read data files created by *HR Waves*. However, with some simple modifications, data files could be analysed from other sources.

## 4.2. *proBAY* Software

Besides finding the total overtopping volumes, mean discharges, etc., *proBAY* permits enquiries about individual overtopping volumes. After acquiring user-defined parameters, *proBAY* first deals with the overtopping detector signal. Once the number of overtopping events from this source has been computed, the load cell signal is included and both signals are used concurrently in further operations.

### 4.2.1. Parameters

*proBAY* needs to read 17 user-defined parameters from a file called “*parabay.txt*”. This file must be located in the same folder as the program files. Table 4-1 gives the list of parameters and their definitions. Further descriptions and their uses are explained in the following sections.

Table 4-1 Parameters used in *proBAY* and their definitions

Parameter	Definition
CNDET	Channel number for overtopping detector
CNLOAD	Channel number for load cell
LOADCAL	Load cell calibration factor
RUNAVF	$T_m$ multiplication factor to define the number of data points required for the running average
FILMF	Multiplication factor for the filter calculations
SDMF	Standard deviation multiplication factor for the filter calculations

DELA	$T_m$ multiplication factor to synchronize the delay between the two channels
SPAR	$T_m$ multiplication factor to provide time to skip overtopping noise
CHUTE	Overtopping collector chute size (in mm)
CHOBE	Time (in seconds) between the start of data collection and placing the overtopping chute
NOWA	Number of waves to be analysed
SUBS	$T_m$ multiplication factor to define the number of data points required for the subsequent events
AVPSD	A multiplication factor for the mean plus/minus standard deviation
PERC	Percent of the data between two events which are continuously below/above the threshold
LIMOV	Limit for the minimum acceptable overtopping volume
SPANB	Percent of total data points between two detected events for a possible event immediately before detection
SPANB	Percent of total data points between two detected events for a possible event immediately after detection

Required values in the parameter list may change from one test to another. Default values are saved in “*parabaysafe.txt*” as a read only file. A simple batch file, “*parabay reset.bat*”, which works in the DOS environment as an executable file, is placed in the same folder where all *proBAY* files are, and it needs to be executed before each *proBAY* run to reset the parameters. It simply copies the content of the *parabaysafe.txt* and replaces the content of the “*parabay.txt*” file.

### 4.3. Application of *proBAY*

*proBAY* reads a list of parameters from “*parabay.txt*” and then asks the user to type in the “Overtopping Detector File Name”, the “Load Cell File Name” and the “Mean Wave Period,  $T_m$  (in seconds)” (see Figure 4-1). The “total number of data points” (*N**DATA*) and the “clock ticks” (*TICS*) are gathered from the header of the source files. Apart from the channel numbers, the header rows are identical in both files.

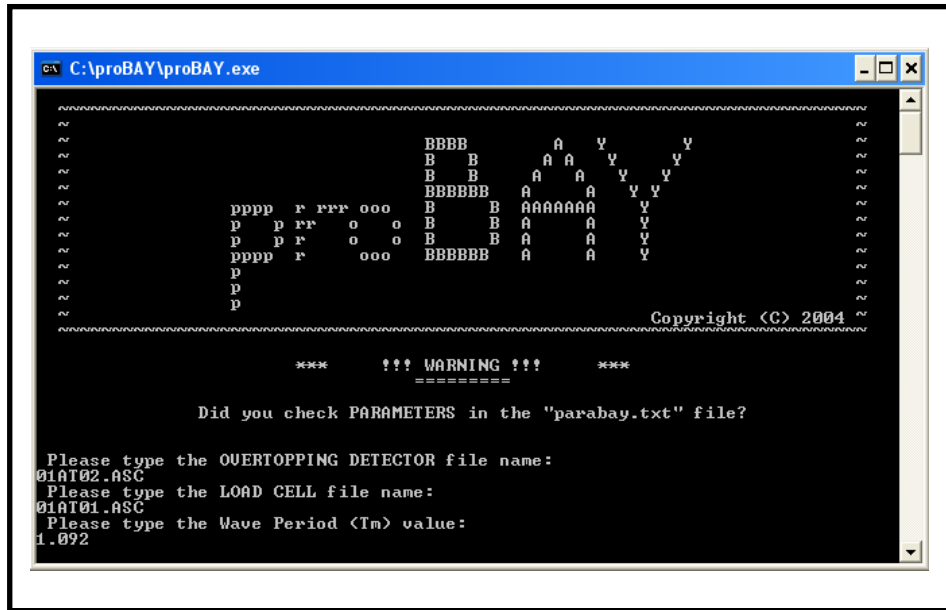


Figure 4-1 The *proBAY* front page

The data scanning interval is converted to seconds by dividing *TICS* by 10000. The frequency of the recorded data, *FREQ*, is the inverse of this value.

$$FREQ = \frac{1}{TICS/10000} \quad (4.1)$$

*FREQ* is used to identify the times of the overtopping occurrences.

The subsequent event time limit (*SETL*) is a constraint that does not allow the program to record two consecutive events within a certain time interval. This is controlled by *SUBS* in the parameter list and the number of data points corresponding to that limit is calculated by:

$$SETL = SUBS * \frac{T_m}{TICS} + 1 \quad (4.2)$$

Water overtopping the crest of the structure required some time to arrive in the tank. Therefore, there was a lag in the load cell signal when compared to the overtopping detector. This delay has been calculated by *DELAY*:

$$DELAY = \frac{DELA}{TICS} + 1 \quad (4.3)$$

where *DELA* is a parameter in the list and the two channels were synchronised accordingly.

*LOADCAL* was utilized in the parameter list for the load cell calibrations. It was adjusted according to the required units for the results.

Remembering the 30-seconds time gap between the start of data collection and the overtopping measurements (explained in Chapter 3), data corresponding to the first 30 seconds were excluded from the analysis. Parameter *CHOBE* was utilized for this purpose to find the number of data points to be ignored:

$$CHDATA = \frac{CHOBE}{TICS} + 1 \quad (4.4)$$

The extracted overtopping detector data and load cell data were then stored in new arrays called *CHOPDET* and *CHOPLOAD*, respectively. In addition, they were written and saved as “*CONDITIONED.CSV*” in a comma separated value file.

Although the tests were planned to last about 1000 waves, some wave conditions were run for shorter and some for longer sequences. *NOWA*

defines how many waves are to be analysed. Also, the time required for *NOWA* waves is calculated by:

$$TIREQ = T_m * NOWA \quad (4.5)$$

Knowing the scanning interval, the number of data points required to analyse *NOWA* waves is then found using:

$$NDREQ = \frac{TIREQ}{TICS} \quad (4.6)$$

Water coming into the overtopping tank produced an impact and this caused oscillations in the load cell data. When analysing the load cell signal, these data points needed to be skipped.

$$SPARE = SPAR * \frac{T_m}{TICS} + 1 \quad (4.7)$$

Equation (4.7) was used to find out how many data points should be skipped. Additionally, data points corresponding to five waves were subtracted (*SECURE*) to prevent the program reading data from the very end of the record.

$$SECURE = 5 * \frac{T_m}{TICS} \quad (4.8)$$

Finally, the total number of data points available was found as:

$$NDAVA = NDATA - CHDATA - SPARE - SECURE \quad (4.9)$$

In the next stage, *proBAY* relates *NDAVA* to *NDREQ*. If *NDAVA* is less than *NDREQ* to analyse *NOWA* waves, it gives the user a “Caution!” message together with the maximum possible number of waves (*POWA*) that can be analysed under these conditions. Here, *POWA* is calculated by:

$$POWA = NDAVA * \frac{TICS}{T_m} \quad (4.10)$$

In this case, the program needs to be run after revising the *NOWA* parameter.

#### 4.3.1. Using the overtopping detector signal

*proBAY* starts by accounting for the noise on the overtopping detector signal. An iterative technique is used to set a threshold value and a signal exceeding that threshold is counted as an overtopping event.

After backing up the original data, the mean (*DETAV*) and the standard deviation (*STDEV*) are found. Using the standard deviation multiplication factor (*SDMF* in the parameters list), *MPXSD* is found as:

$$MPXSD = DETAV + SDMF * STDEV \quad (4.11)$$

Data higher than this value are then equated to *MPXSD*. The above operations are repeated once again for the new mean and standard deviation and the difference between two consecutive *MPXSD* values is found and assigned to *DIFF1*.

$$DIFF1 = MPXSD1 - MPXSD2 \quad (4.12)$$

$DIFF2$  is found after the next iteration by finding the difference between the second  $MPXSD$  value and the third one.

$$DIFF2 = MPXSD2 - MPXSD3 \quad (4.13)$$

$DIFF1$  is then divided by the filter multiplication factor ( $FILMF$ ). If this value is higher than  $DIFF2$ , the iteration process stops and the last  $MPXSD$  value is assigned to  $FILTER$ . Otherwise, the new  $MPXSD$  and the new  $DIFF$  values are calculated by iterating until the condition has been satisfied. Filtered data are then saved in the “ $CONDITIONED2.CSV$ ” file separately. Noise filtering iterations are illustrated in Figure 4-2.

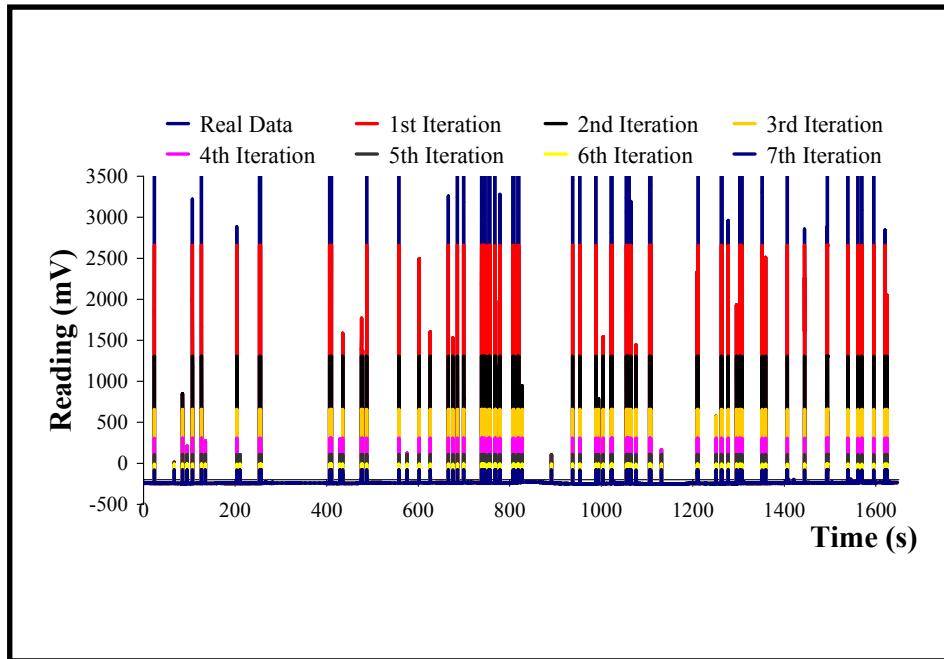


Figure 4-2 Threshold setting for the overtopping detector signal

#### 4.3.2. Overtopping Event Counter

Following the noise filtering process, the number of overtopping events ( $NEVENT$ ) is found in the next stage. The overtopping detector signal is



examined and an overtopping event is counted every time the threshold line is exceeded (see Figure 4-3). Each overtopping event is recorded, together with its occurrence time (in seconds from the beginning of the analysis).

The main purpose of recording data through the overtopping event counter was to work out the number of overtopping events. However, using the overtopping detector signal alone did not provide accurate results. Due to 3D effects in the flume, there were some overtopping volumes reaching the overtopping tank without being recorded by the overtopping detector. Therefore, to increase the sensitivity of the analysis, the load cell signal was also used with the overtopping detector data.

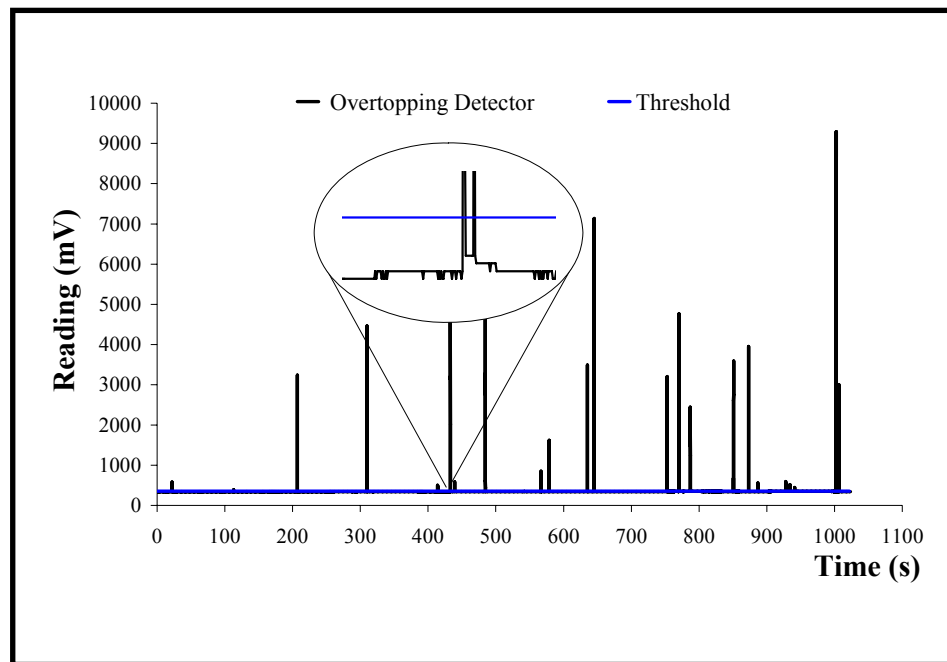


Figure 4-3 Investigating the overtopping detector signal

### 4.3.3. Using the load cell signal

There was noise in the overtopping detector data. Likewise, the load cell data were contaminated with noise. Therefore, before further analysis, the noise had to be filtered out. A running average technique was used for this purpose. *RUNAV* is the number of data points required for smoothing the signal and is found using:

$$RUNAV = RUNAVF * \frac{T_m}{TICS} + 1 \quad (4.15)$$

where *RUNAVF* is a parameter. The average of *RUNAV* data points was found and stored for each run. Results were then converted into an array (*SMOLC*) for further calculations. They were also backed-up onto a file “*CHOPSMOLC.CSV*”. The smoothed load cell signal, together with the original data and the *proBAY* steps, are shown in Figure 4-4.

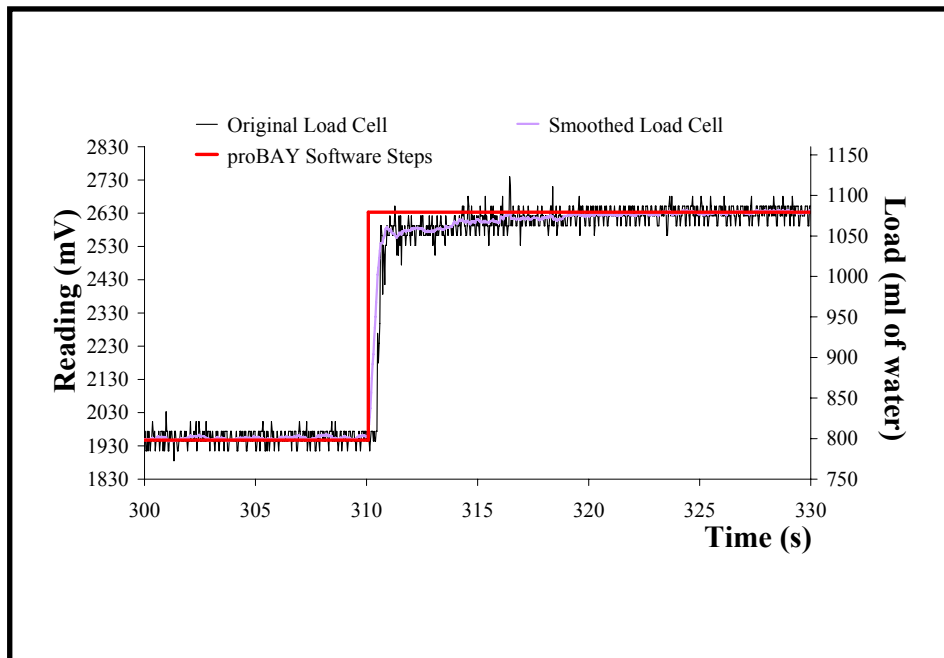


Figure 4-4 Step from a smoothed load cell signal

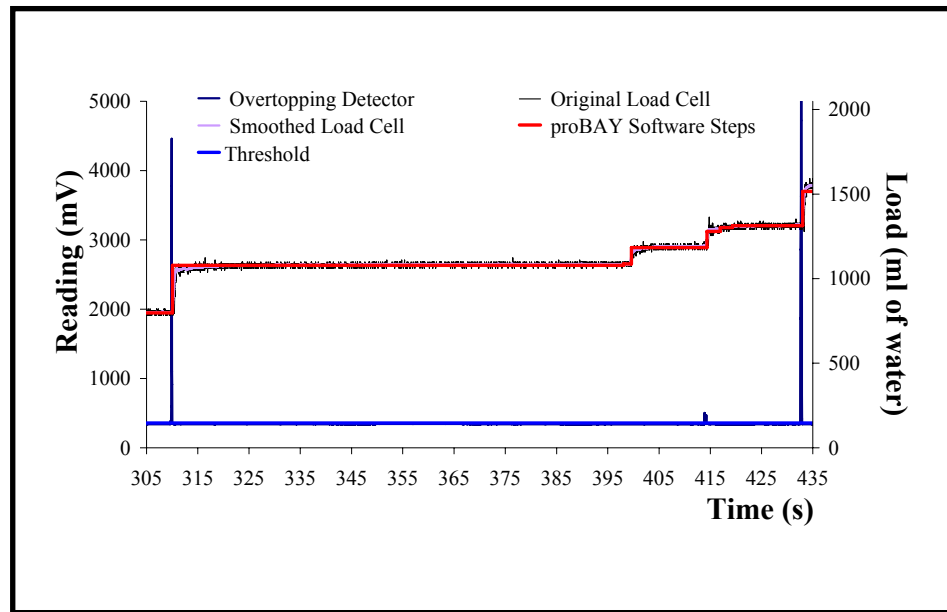


Figure 4-5 Scrutinized overtopping detection

The magnified area in Figure 4-3 shows a recorded overtopping event between two high spikes. However, if the area is scrutinized carefully, Figure 4-5 shows that the recorded overtopping event is not the only one between these two high spikes. Utilising the load cell signal was necessary to find the number of overtopping events more accurately.

Details of the initially detected overtopping events assisted in analysis of the load cell signal. Data falling between two recorded overtopping events were investigated at this stage and the total number of data points, *SPAN*, within that range was found as the first step. A *SPARE* number of data points were excluded from both ends and, if *SPAN* did not have more data points than  $2*SPARE$ , then there was no further action. Otherwise, the average and the standard deviation of *SPAN* data points were calculated and the first data point where the average of *SPAN* was exceeded was found. Then, depending on the position of that point, one of the following conditions applied:

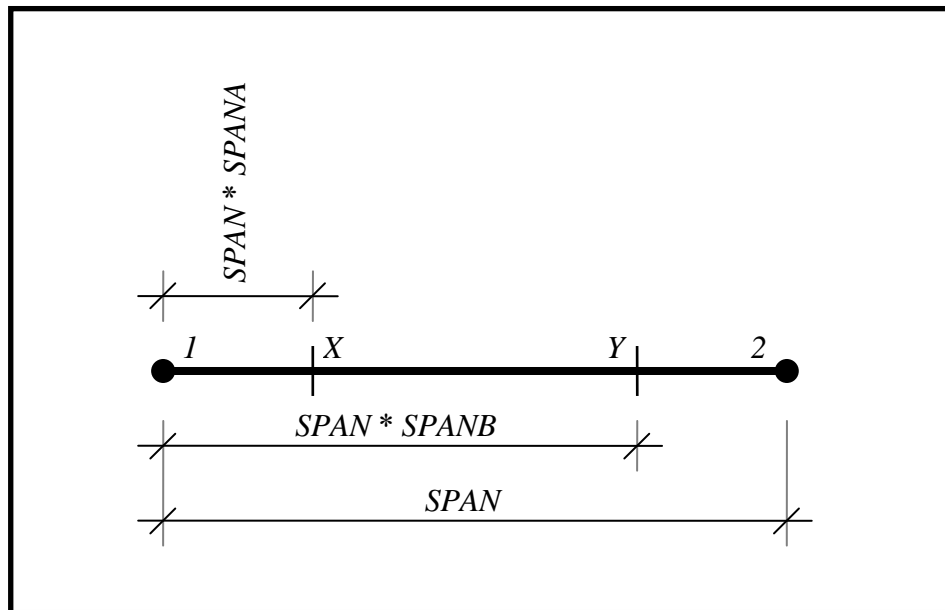


Figure 4-6 Overtopping detection between two recorded events

- If the point where the average was exceeded was within the first  $SPAN_A$  percent of the  $SPAN$  (between 1 and X), the mean minus  $AVPSD$  times the standard deviation was set as a threshold; or
- If the average was exceeded after  $SPAN_A$  percent of the  $SPAN$  and before  $SPAN_B$  percent of the  $SPAN$ , therefore between X and Y, the mean of the  $SPAN$  was set as the threshold;
- If the average was exceeded after  $SPAN_B$  percent of the  $SPAN$  (between Y and 2), then the mean plus  $AVPSD$  times the standard deviation was set as a threshold.

Figure 4-6 illustrates the above detection procedure.

Finally, if  $PERC$  percent of the data fell below the threshold and  $PERC$  percent of the data were higher than the threshold, the point where the threshold was exceeded was counted as another overtopping event.

The whole process is iterative. If an overtopping event is identified in this way, then the routine starts from the beginning to check for the next possible event. Figure 4-7 is an example in which an overtopping event was missed by the overtopping detector but found using the above procedure.

Figure 4-7 illustrates overtopping event detection by chasing the load cell signal. The longest red line is the mean of the whole range and the purple signal is the smoothed load cell signal. The point where the smoothed load cell signal exceeded the mean was counted as an overtopping event. The lower red line shows the average of the data points from the beginning to the point where the signal exceeded the average. The upper red line represents the mean of the load cell signal from the newly identified overtopping event to the event recorded by the overtopping detector.

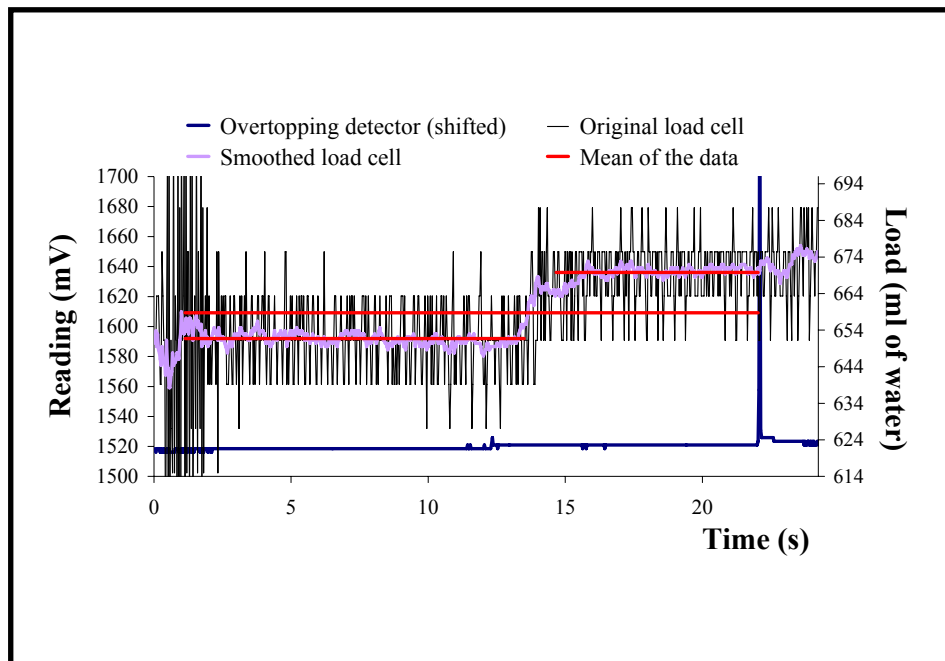


Figure 4-7 Overtopping event detection using the load cell signal

The time series of confirmed overtopping events was recorded with the average load cell values between events. The differences between two consecutive averages were stored to determine individual overtopping volumes.

#### 4.3.4. Precision checks

Details of the overtopping detector and the plastic block used to hold it were given in the previous chapter. After a large volume of water overtopped the crest, it was observed that a small drop was often trapped on the plastic unit. When this drop was released, a bogus spike was recorded as an overtopping event. A subsequent event time limit (*SETL*), described earlier, was used to surmount this problem. If any two consecutive events are recorded within a certain time, *proBAY* simply ignores the second one.

There is a potential limit to the minimum recordable overtopping volume and a parameter, *LIMOV*, is employed for this purpose. The program considers this limit and can eliminate any overtopping volume smaller than that value. However, in practice, *LIMOV* was set to zero when analysing the data and all identified overtopping volumes were considered in the analysis.

#### 4.4. Output and storage

When the program finishes, the results of the analysis are displayed and stored in files. Events and their corresponding times, together with the average values of the load signal before and after each overtopping event are saved in “*AVERAGES.CSV*”. Individual overtopping volumes and their occurrence times are held in “*TIME.CSV*”. Individual overtopping volumes are ranked in “*RANKED.CSV*”. Then, the “*ISSUE.CSV*” file is

created to store: “Detector file name”, “Load cell file name”, “Chute width (mm)”, “Total data sampling time (s)”, “Analysis start time (s)”, “Analysis finish time (s)”, “Total analysis time (s)”, “Number of waves analysed”, “Noise filter threshold”, “Number of overtoppings”, “Total overtopping volume (lt)”, “Maximum overtopping volume (lt)”, “Mean overtopping volume (lt)” and “Mean overtopping rate (lt/s.m)”. Finally, the results of the analysis are displayed and a “Process Completed!” message appears (see Figure 4-8). The program asks the operator to confirm the termination.



```

C:\proBAY\proBAY.exe
-----
proBAY ANALYSIS OUTPUT
-----
Ovtp Detector file name = 01A102.ASC
Load Cell file name = 01A101.ASC
Chute size = 500 (mm)
Total data sampling time = 1058.41 (s)
Analysis start time = 30.0067 (s)
Analysis finish time = 1052.11 (s)
Total analysis time = 1022.10 (s)
Number of waves analysed = 936
Noise filter threshold = 148.443
Number of Ovtp Waves = 42
Total Ovtp Volume = 3.29227 (lt)
Max Individual Ovtp Volume = 0.824892 (lt)
Mean Ovtp Volume = 7.838742E-02 (lt)
Mean Ovtp Rate = 6.442164E-03 (lt/s.m)

TIME.CSU, RANKED.CSU and ISSUE.CSU files have been updated
-----
PROCESS COMPLETED !
Press ANY KEY to terminate

```

Figure 4-8 *proBAY* results

#### 4.5. VBA packages to assist *proBAY*

Small scale macro programs were created using Visual Basic Applications (VBA) for use in Microsoft Excel. They were prepared to assist *proBAY* in further analysis, to keep track of the results and to store results in the required format.

#### 4.5.1. “*proBAY Full List.xls*”

The introductory page to “*proBAY Full List.xls*” (see Figure 4-9) gives brief information about applications. It has some command buttons for simple operations. The “*Start*” button opens the main process page (Figure 4-10). Here, there are buttons for simple operations and the “*View Summary*” button is a link to the summary page for the processed data. The “*Transfer*” button copies all the necessary information from the *proBAY* output files. “*Close proBAY Files*” makes source files ready for the next *proBAY* run. Apart from individual overtopping details, results are copied and pasted into a summary sheet using the “*Summarize*” button. The “*Save*” button simply saves the file and takes the user to the start page. The “*Save and Exit*” button on the start page saves and closes the file whilst the “*Exit*” button only closes the file without saving any changes. The main purpose of the summary page (Figure 4-11) is to bring data into a form that simplifies further analysis.

Codes for the macros are given in the Appendices.



## CHAPTER 4 – proBAY and its Applications

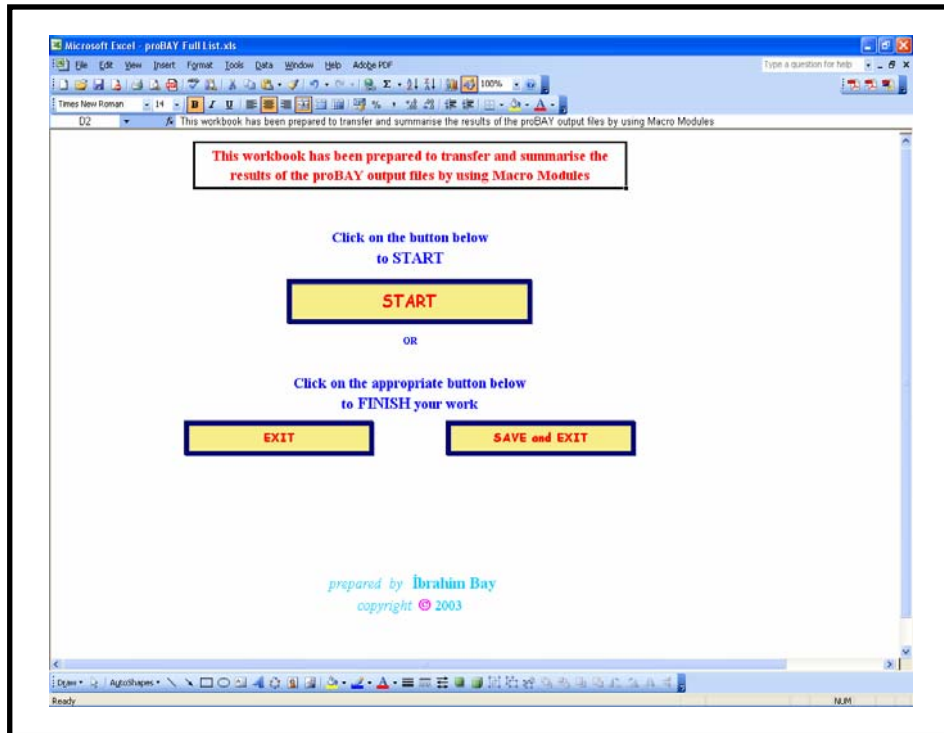


Figure 4-9 “proBAY Full List.xls” start page

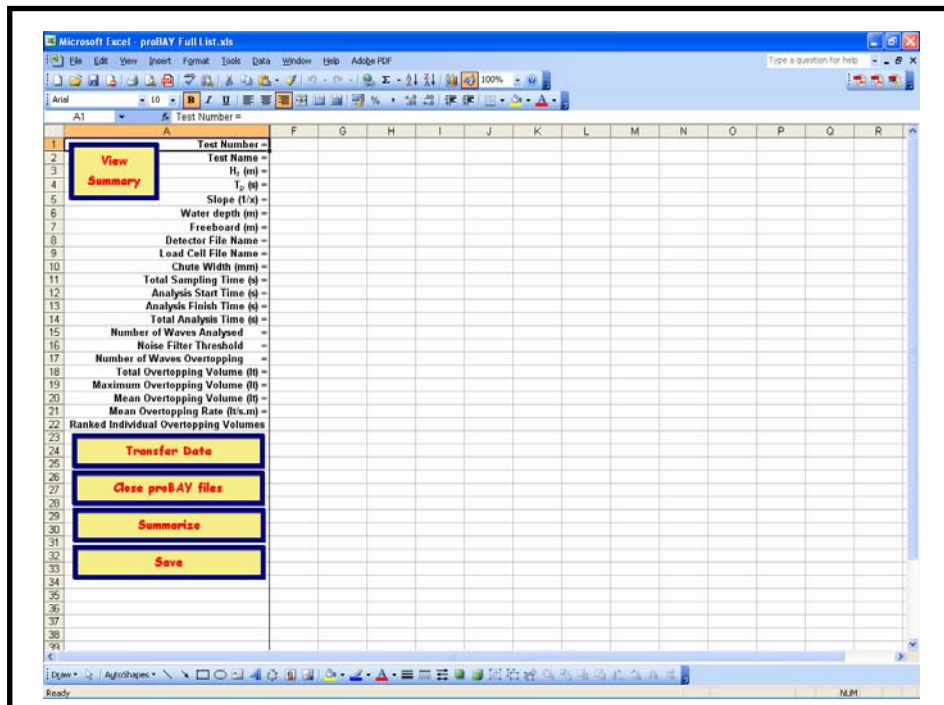


Figure 4-10 The process page of the “proBAY Full List.xls” file

Test Number	Test Name	H <sub>t</sub> (m)	T <sub>m</sub> (s)	T <sub>s</sub> (s)	Slope (1/x)	Water Depth (m)	Free-board (m)	Detector File Name	Load Cell File Name	Chute Width (mm)	Total Sampling Time (s)	Analysis Start Time (s)	Analysis Finish Time (s)	Total Air Thr (k)
<b>600mm Water Depth Tests for 1 on 2 smooth slopes.</b>														
11	TAP0160	0.096	1.092	1.114	2	0.601	0.399	01a02.asc	01a01.asc	500	1058.41	30.0067	1052.110	1022.
12	TAP0260	0.108	1.208	1.393	2	0.601	0.399	02a02.asc	02a01.asc	500	1310.72	30.04	1302.550	1272.
13	TAP0360	0.153	1.360	1.393	2	0.601	0.399	03a02.asc	03a01.asc	100	1310.72	30.04	1302.960	1272.
14	TAP0460	0.101	1.568	1.672	2	0.601	0.399	04a02.asc	04a01.asc	100	1559.76	30.0366	1550.950	1520.
15	TAP0560	0.148	1.593	1.672	2	0.601	0.399	05a02.asc	05a01.asc	100	1559.76	30.0356	1549.710	1519.
16	TAP0660	0.199	1.648	1.672	2	0.600	0.400	06a02.asc	06a01.asc	100	560.33	30.0105	550.774	520.
17	TAP0760	0.199	1.648	1.672	2	0.600	0.400	07a02.asc	07a01.asc	100	560.33	30.0105	550.774	520.
18	TAP0860	0.199	1.648	1.672	2	0.600	0.400	08a02.asc	08a01.asc	100	560.33	30.0105	550.774	520.
19	TAP0960	0.199	1.648	1.672	2	0.600	0.400	09a02.asc	09a01.asc	100	560.33	30.0105	550.774	520.
20	TAP1060	0.199	1.648	1.672	2	0.600	0.400	10a02.asc	10a01.asc	100	560.33	30.0105	550.774	520.
21	TAP0660ALL	0.199	1.648	1.672	2	0.600	0.400			100	1681.90			1562.
22	TAP0760	0.104	1.866	2.076	2	0.600	0.400	07a02.asc	07a01.asc	100	1808.79	30.0288	1797.090	1767.
23	TAP0760A	0.104	1.866	2.076	2	0.600	0.400	07c02.asc	07c01.asc	500	1808.79	30.0288	1797.090	1767.
24	TAP0960	0.149	1.895	2.076	2	0.600	0.400	09a02.asc	09a01.asc	100	1808.79	30.0288	1798.140	1768.
25	TAP0960W	0.199	1.913	2.076	2	0.600	0.400	09b02.asc	09b01.asc	100	498.07	30.0048	487.206	457.
26	TAP0960X	0.199	1.913	2.076	2	0.600	0.400	09c02.asc	09c01.asc	100	498.07	30.0048	487.206	457.
27	TAP0960Y	0.199	1.913	2.076	2	0.600	0.400	09d02.asc	09d01.asc	100	498.07	30.0048	487.206	457.
28	TAP0960Z	0.199	1.913	2.076	2	0.600	0.400	09e02.asc	09e01.asc	100	498.07	30.0048	487.206	457.
29	TAP0960ALL	0.199	1.913	2.076	2	0.600	0.400			100	1992.30			1928.
30	TAP1160	0.103	2.090	2.230	2	0.600	0.400	11a02.asc	11a01.asc	100	2057.83	30.0184	2044.770	2014.
31	TAP1160A	0.103	2.090	2.230	2	0.600	0.400	11b02.asc	11b01.asc	500	2057.83	30.0184	2044.770	2014.
32	TAP1160B	0.103	2.090	2.230	2	0.600	0.400	11c02.asc	11c01.asc	500	2057.83	30.0184	2044.770	2014.
33	TAP1260	0.149	2.108	2.230	2	0.600	0.400	12a02.asc	12a01.asc	100	1061.68	30.0024	1048.160	1018.
34	TAP1260Z	0.149	2.108	2.230	2	0.600	0.400	12b02.asc	12b01.asc	100	1061.68	30.0024	1048.160	1018.
35	TAP1260ALL	0.149	2.108	2.230	2	0.600	0.400			100	2123.36			2036.
36	TAP1360U	0.199	2.105	2.230	2	0.600	0.400	13u02.asc	13u01.asc	100	393.22	30	379.428	349.
37	TAP1360V	0.199	2.105	2.230	2	0.600	0.400	13v02.asc	13v01.asc	100	393.22	30	379.428	349.
38	TAP1360W	0.199	2.105	2.230	2	0.600	0.400	13w02.asc	13w01.asc	100	393.22	30	379.428	349.
39	TAP1360X	0.199	2.105	2.230	2	0.600	0.400	13x02.asc	13x01.asc	100	393.22	30	379.428	349.
40	TAP1360Y	0.199	2.105	2.230	2	0.600	0.400	13y02.asc	13y01.asc	100	393.22	30	379.428	349.

Figure 4-11 The summary page of the “*proBAY Full List.xls*” file

#### 4.5.2. “*proBAY Results – Graphical Expression.xls*”

This is the second application for further analysis of the *proBAY* results. It contains two operation sheets and two chart sheets. Macros in the first worksheet are used to prepare the data for plotting results and to store the processed information (Figure 4-12).

The test name has to be typed into the dedicated cell as a first step. This name will be used for other processes, i.e. renaming the plots, saving the file, etc. The button at the top copies the “*Average.CSV*” information over and closes the source file. The next button counts the number of overtopping events and writes the value into a cell. It also transforms the copied information so that Microsoft Excel can plot the overtopping volume steps. The next two buttons copy the information from the “*CONDITIONED.CSV*” and the “*CHOPSMOLC.CSV*” files, respectively,

and closes them afterwards. The plot on the “Chart1” tab is now completed and the next button renames the tab and the title of the plot (see Figure 4-13).

The “Preview” button may be used to view the plot and the “Go back” button on the graph tab will divert the user back to the data sheet. The “Go to next page” button brings the next data sheet to the screen.

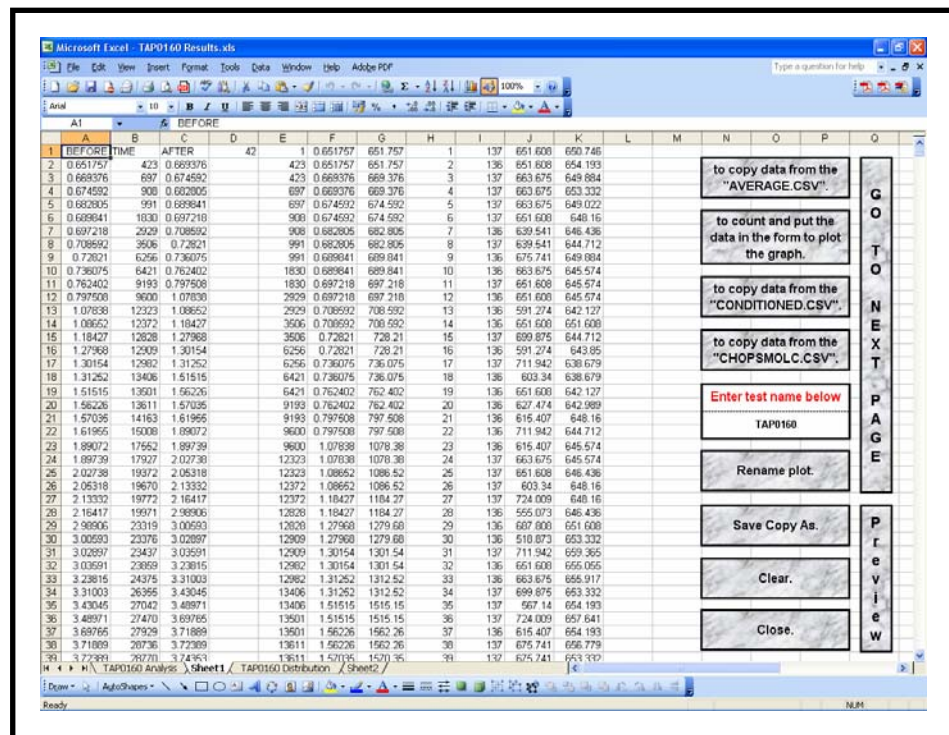


Figure 4-12 “Sheet1” of the “*proBAY Results – Graphical Expression.xls*” file

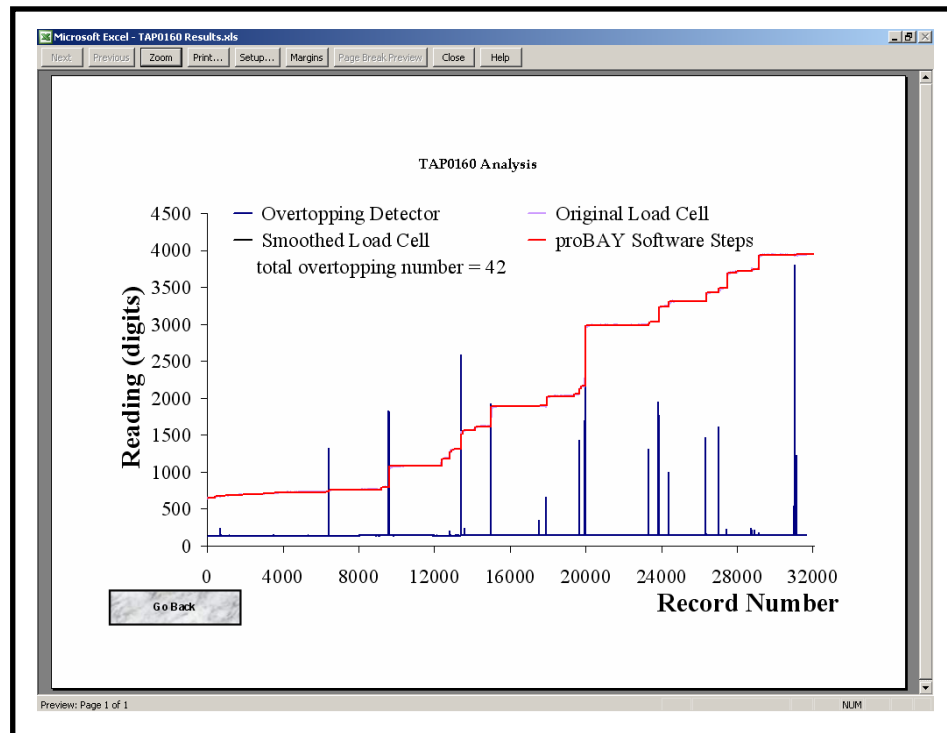


Figure 4-13 “Chart1” in “*proBAY Results – Graphical Expression.xls*”

Besides simple copy-paste operations, the macros in the second worksheet (see Figure 4-14) produce some basic probability calculations. The first button copies the file name from the previous data sheet onto this one and asks for confirmation. Then it goes to the “*proBAY Full List.xls*” file to retrieve the relevant detailed information about this test. Once the data have been transferred onto this page, then the “*Calculations for the probability curves*” button simply calculates  $\text{Prob}[V \geq V_{\#}]$  in which  $V_{\#}$  is a specified volume and writes them down. Also, it calculates  $\ln[V_{\#}]$  and  $\ln\left\{\ln\left(\text{Prob}[V \geq V_{\#}]\right)^{-1}\right\}$ . The plot on the “*Chart2*” tab has now been completed (see Figure 4-15). The button below renames the “*Chart2*” tab and also the title of the plot. The “*Preview*” button can now be used to view the graph and, to come back to the same page again, the “*Go Back*” button needs to be used. The “*Clear this sheet ONLY*” button is there to

delete all the information copied and calculated and can be used if there is any mistake. Finally, the “*Previous Page*” button navigates back to “*Sheet1*”.

The “*Save copy as*” button adds the word “*Results*” to the file name and a copy of the workbook is saved with this name (e.g. “*TAP0160 Results.xls*”). Since all the information about the test condition has now been processed, the original file can now be cleared using the “*Clear*” button.

Codes for the macros are given in the Appendices.

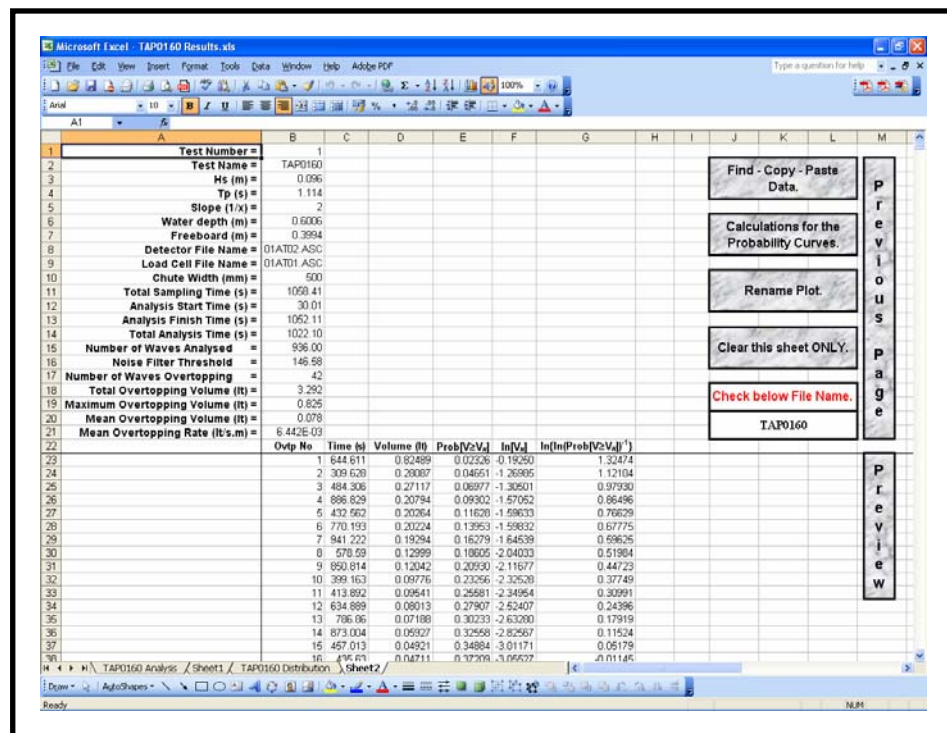


Figure 4-14 “*Sheet2*” of the “*proBAY Results – Graphical Expression.xls*” file

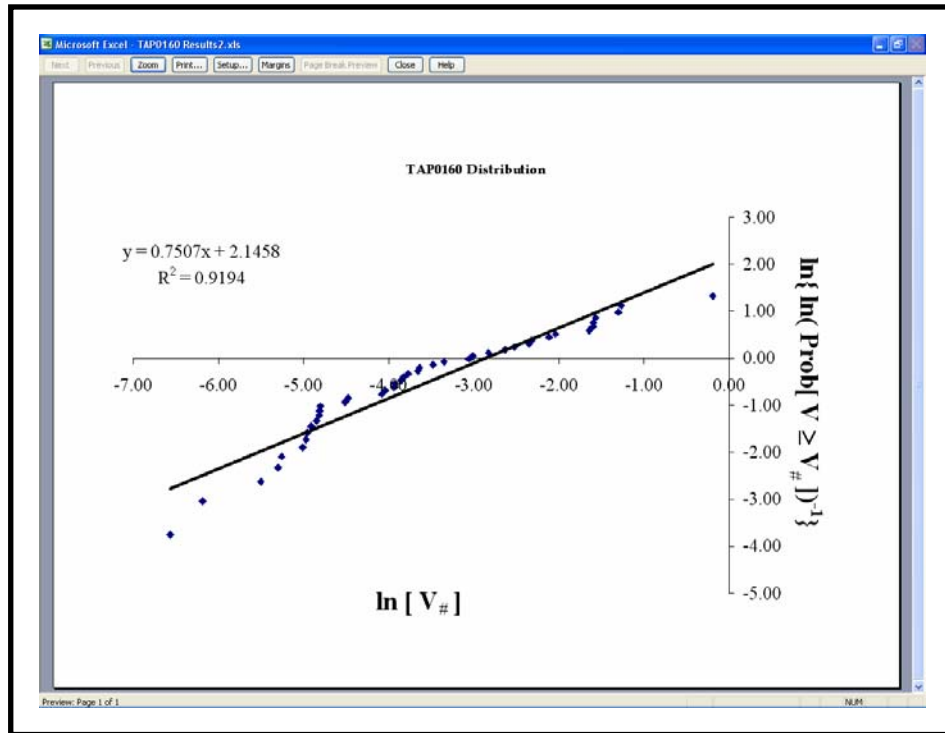


Figure 4-15 “Chart2” in the “*proBAY Results – Graphical Expression.xls*” file

#### 4.5.3. “*LS-LAD comparison.xls*”

This template is also prepared using macros in Microsoft Excel. The first worksheet contains data and command buttons (see Figure 4-16), the second worksheet contains data to prepare the plots and there are eight other sheets for the graphs. Macros have been written so that the graphs and the regression lines will be automatically updated when the process is completed.

A statistical program called SYSTAT (version 10.2; 2002) is employed for processing the data (Figure 4-17). Data columns are copied from the source file and the LAD fitting constants (both for the slope and for the intercept) and the R-squared values are found by SYSTAT (see Figure 4-18). Results are copied back to the spreadsheet for the rest of the calculations and the plots.

CHAPTER 4 – probAY and its Applications

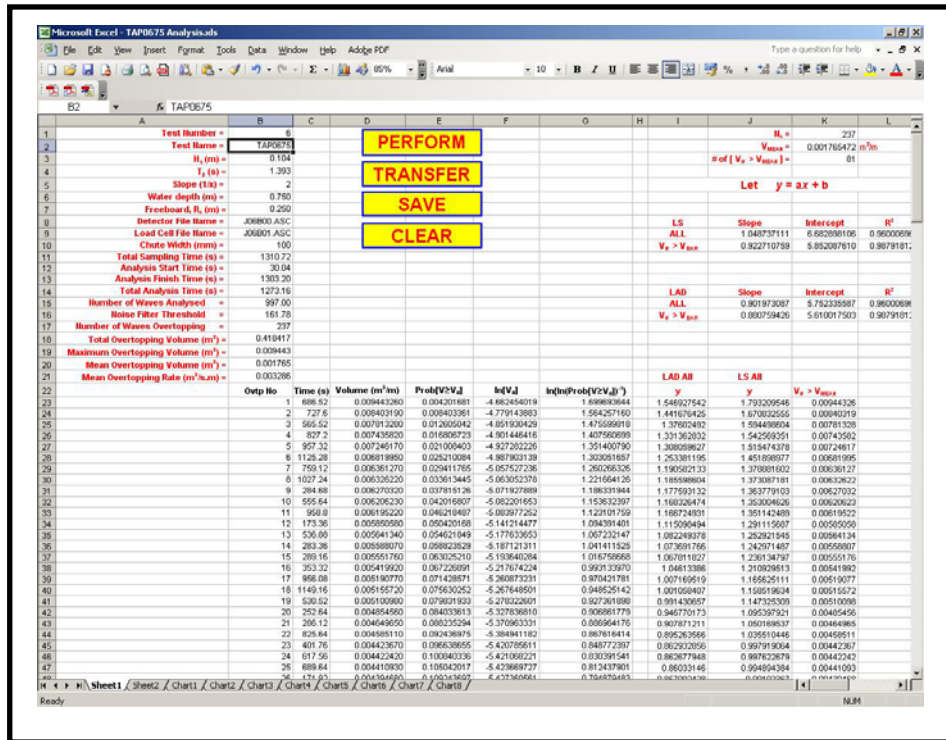


Figure 4-16 "Sheet1" in "LS-LAD comparison.xls" file

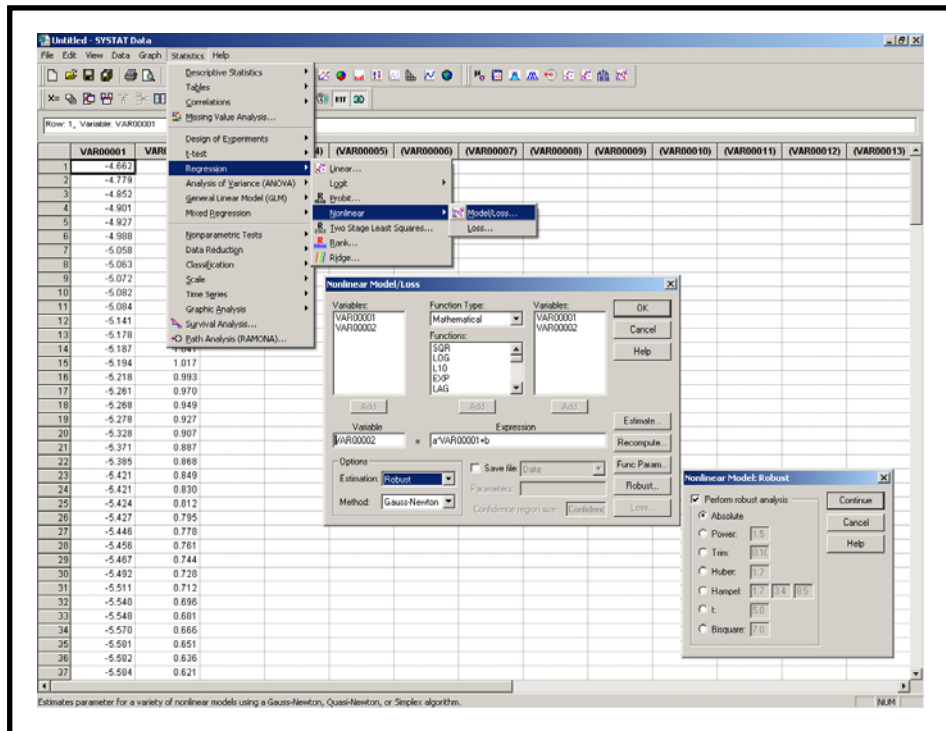


Figure 4-17 SYSTAT program to perform regression analysis for LAD fits.

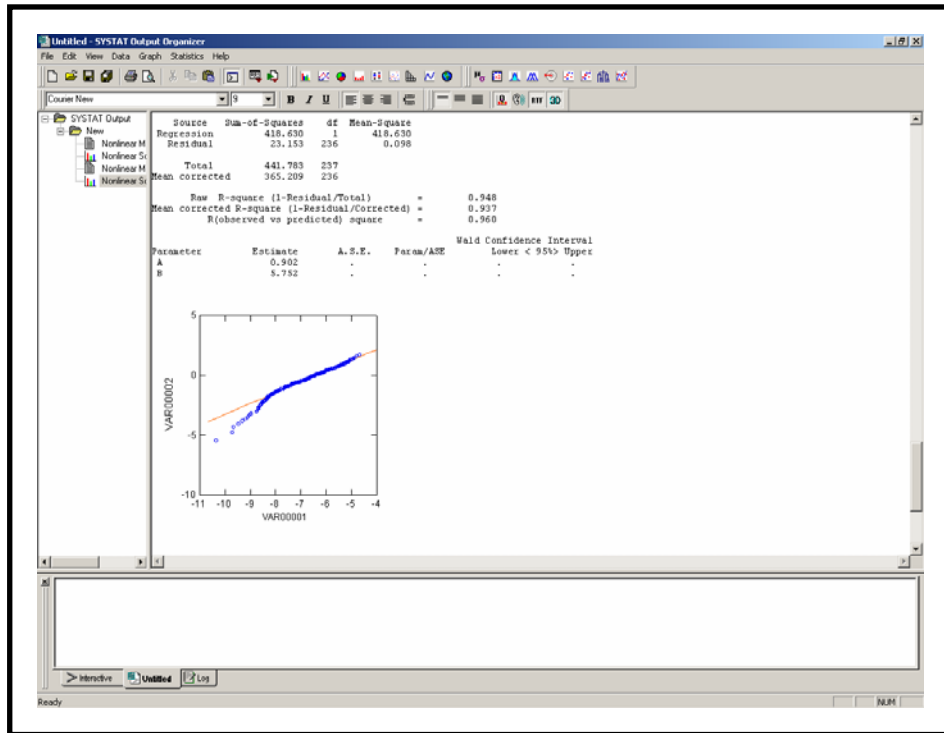


Figure 4-18 SYSTAT output organizer for regression analysis

This process is repeated for cases where  $V_{\#} > V_{mean}$  in which  $V_{mean}$  is the mean overtopping volume (see details in Chapter 5). Relevant data are automatically copied to the second worksheet to prepare the data for graphs. There are four different graphs, two of which are for curve fitting and two for different conditions (one for using all the data and one for using data where  $V_{\#} > V_{mean}$ ). These graphs are plotted and placed on the next four sheets and are enhanced versions of those plotted in the second part of “*proBAY Results – Graphical Expression.xls*”.

The distributions of the individual overtopping volumes are plotted on the last four sheets. Details of the calculations are given in Chapter 5.



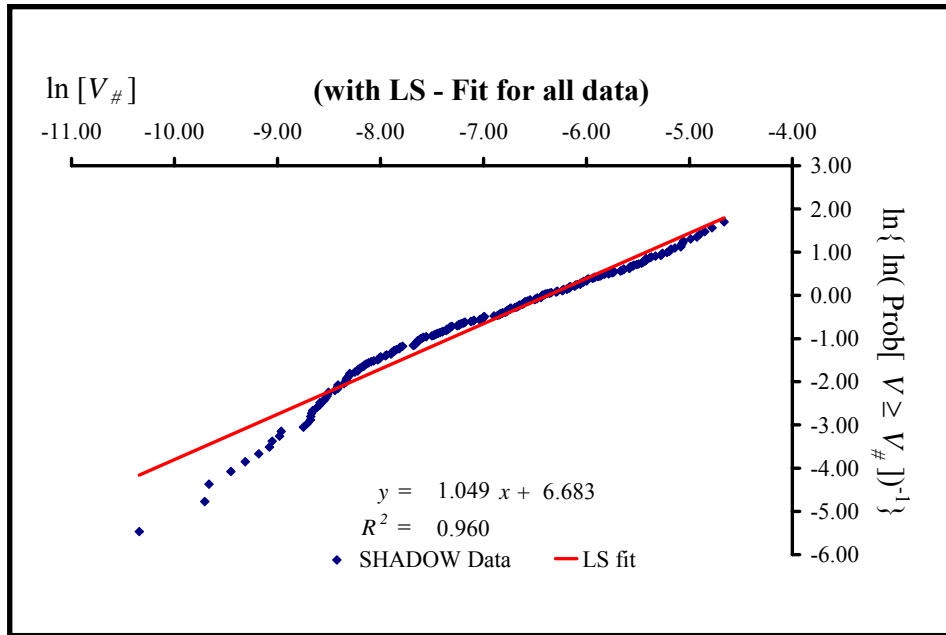


Figure 4-19 Regression analysis

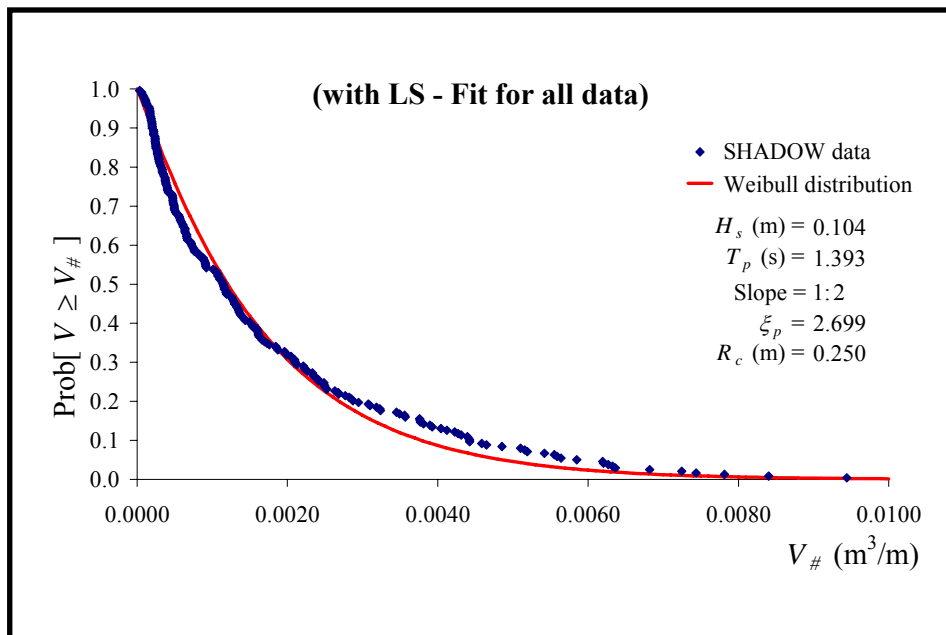


Figure 4-20 Distribution of individual overtopping volumes

Figures 4-19 and 4-20 are examples of the graphs and are plotted using LS regression analysis. The advantages and disadvantages of LS and LAD fitting techniques have been described by Hedges (2001).

Codes for the macros are given in the Appendices.

#### 4.5.4. “Gamma Function - Interpolation.xls”

Another Microsoft Excel workbook was prepared to return the value of the Gamma function and to find  $V_{bar}$  (an estimate of  $V_{mean}$ ; see Chapter 5) for the given conditions. The first worksheet contains some general information, relevant data for the Gamma function and a graph to show the determined values (see Figure 4-21). Figure 4-22 shows the second sheet, which holds further information and a command button. The result for  $V_{bar}$  is also printed on the second worksheet.

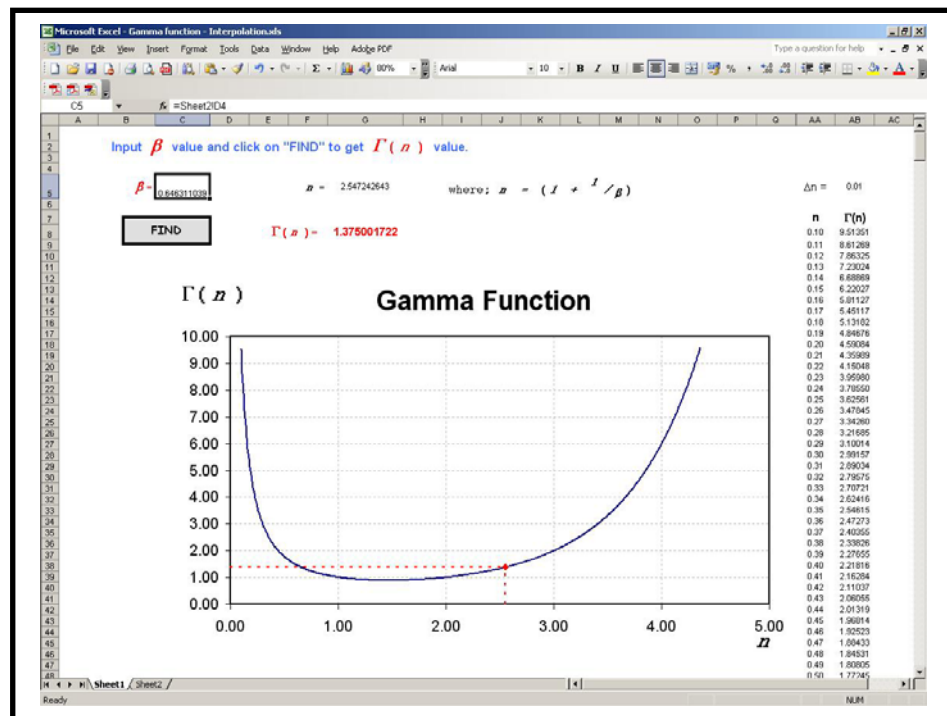


Figure 4-21 Excel worksheet for the Gamma function and  $V_{bar}$  calculations

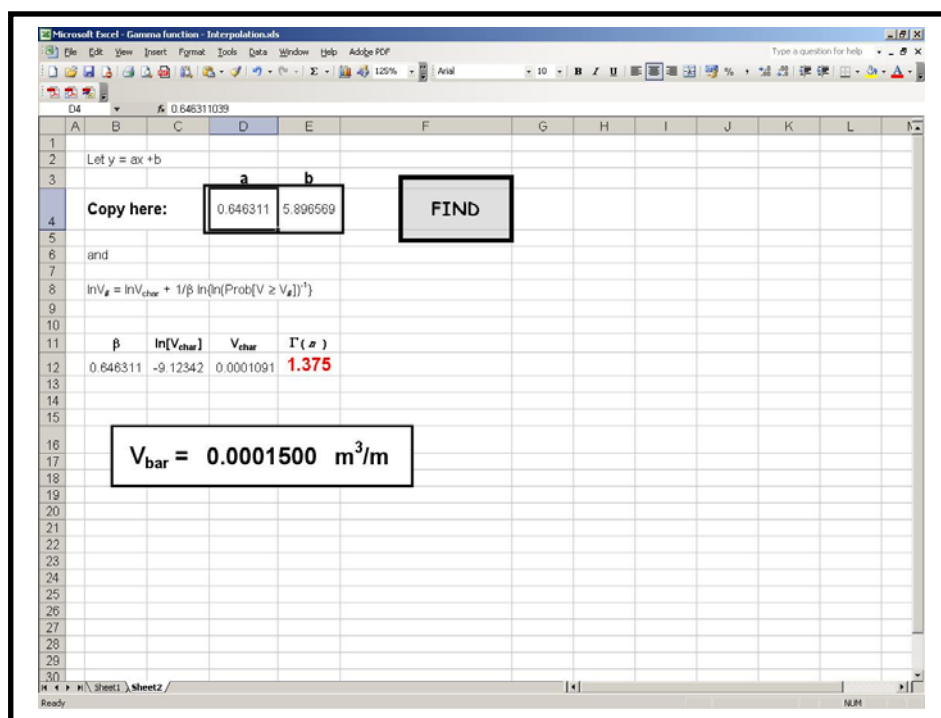


Figure 4-22 Excel worksheet for the Gamma function and  $V_{\bar{}}$  calculations

$a$  and  $b$  values, corresponding to the slope and the intercept of the regression line fitted to the distribution of individual overtopping volumes (see Figure 4.18) need to be entered in the dedicated cells in the second worksheet. The command button then runs a macro to evaluate the Gamma function which, in turn, is used to find the estimated mean overtopping volume,  $V_{\bar{}}$ . More detailed information about these calculations is given in Chapter 5.

Codes for the macros in this workbook are also given in the Appendices.

#### 4.6. Effects of parameters

There are seventeen parameters employed in the *proBAY* software. Four of them (*RUNAVF*, *DELA*, *SPAR* and *SUBS*) are  $T_m$  dependent and play

important roles in determining the accuracy of the output. The parameters can always be set to obtain better results for individual test conditions, whereas default values have been set for efficiency.

The same applies to the filtering parameters, in particular in identifying overtopping events not detected by the overtopping counter. The values of *FILMF*, *SDMF*, *AVPSD*, *PERC*, *SPAN A* and *SPAN B* can always be adjusted to change the accuracy of the results.

#### **4.7. Visual checks**

Before running the program for all test conditions, the accuracy of the *proBAY* results was checked visually (see Appendix B1) for a limited number of cases. Individual *proBAY* results were then saved using “*proBAY Full List.xls*”. Results were saved for each water depth in separate files and all together in another file. Detailed test results are given in Appendix B2 (see Tables B2-1 to B2-9).

#### **4.8. Data handling for special cases**

A faulty load cell calibration caused some test output in SHADOW Phase II to be partly damaged. Data files, in particular for test conditions providing large overtopping volumes, were corrupted. The calibrated range of the load cell was exceeded and this caused a plateau in the load cell signal (see Figure 3.37 for ESI0805). Data files belonging to these test conditions were handled separately. *proBAY* was run twice in these circumstances. Using “*proBAY Results – Graphical Expression.xls*”, the place of the failure was found visually after the first run (see Figure 4-23). From the available number of data points, the number of waves that could be analysed was calculated. Then *proBAY* was run once again for a shorter

sequence with an updated parameter list. The result of the next *proBAY* run is illustrated in Figure 4-24.

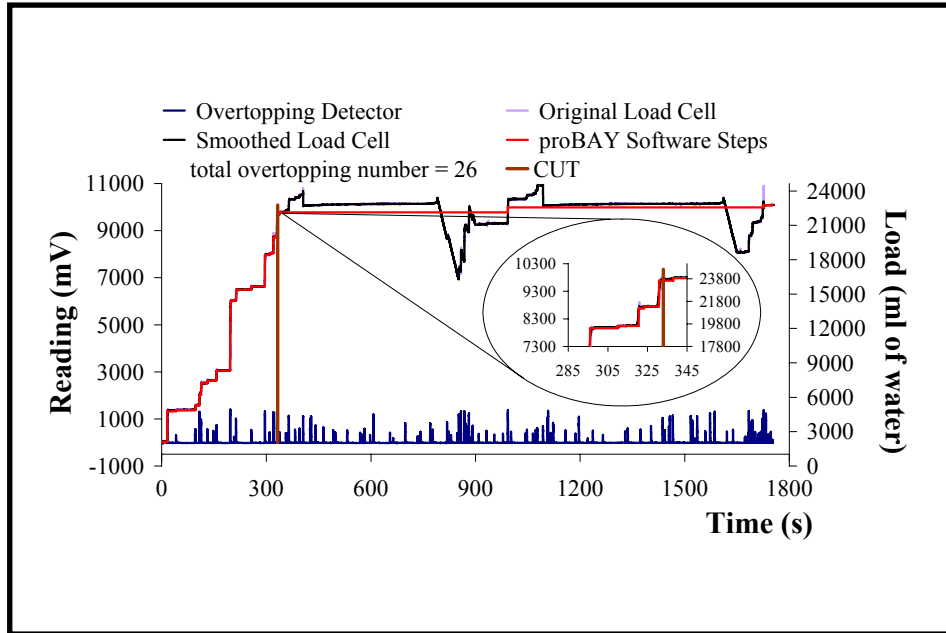


Figure 4-23 Handling the damaged data files

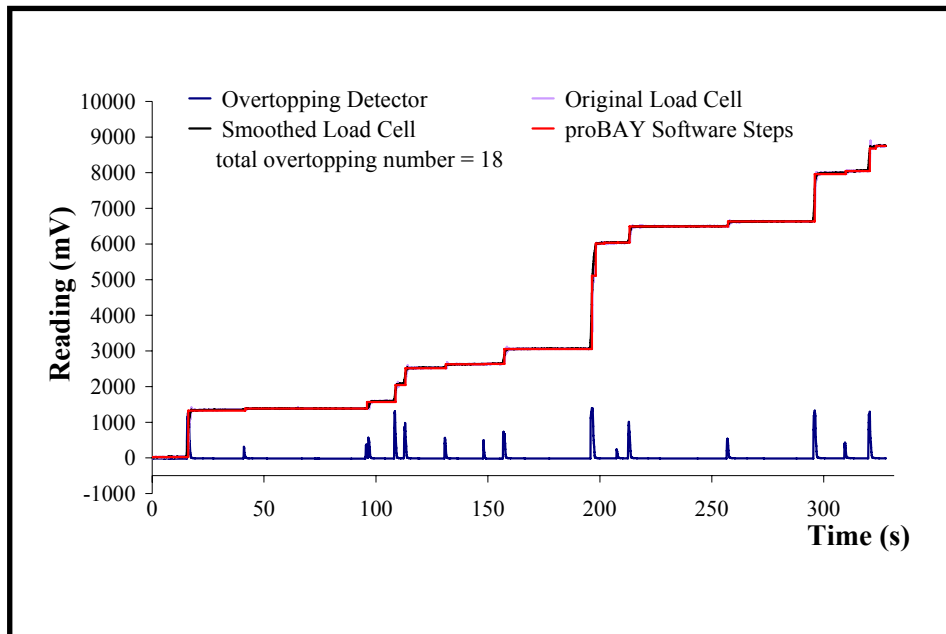


Figure 4-24 Output from the corrected data file

# *Chapter 5*

## **DATA ANALYSIS**

Detailed information about SHADOW project data files and how they have been processed using *proBAY* software were discussed in the previous chapter. *proBAY* outputs have been analysed to investigate the mean overtopping discharges. The most promising prediction methods have been employed and their estimated values have been compared with the measurements. In addition, this chapter provides further information about the wave-by-wave overtopping volumes, their distribution and the task of estimating the maximum individual overtopping volume within a storm.

### **5.1. Introduction**

*proBAY* software was executed for each wave condition and the results were saved for further analysis. Various methods to predict the mean overtopping volumes have been presented in Chapter 2. Amongst them, the most promising and the most widely used methods have been selected and the predicted values have been compared to the *proBAY* results.

When analysing data, there are a number of alternative ways of fitting a regression line. *Least Squares* (LS) is one method: it minimizes the sum of

the squared deviations of the data from the line (Jordan and Smith, 2002). *Least Absolute Deviations* (LAD) is another method: it minimizes the sum of the absolute values of the deviations. Hedges (2001) concluded that the LAD fitting technique has more advantages than the more common method of LS fitting. For example, it is less sensitive to the presence of outlying data points. Therefore, the LAD fitting procedure is preferred for analysis in the present study.

## 5.2. Predicted and measured mean overtopping discharges

### 5.2.1. Mean overtopping discharges

The 1:2 simply-sloping smooth-surface structure was tested to check the quality of the present experiments. The SHADOW data are compared with previous experimental results in Figure 5-1. It shows the agreement

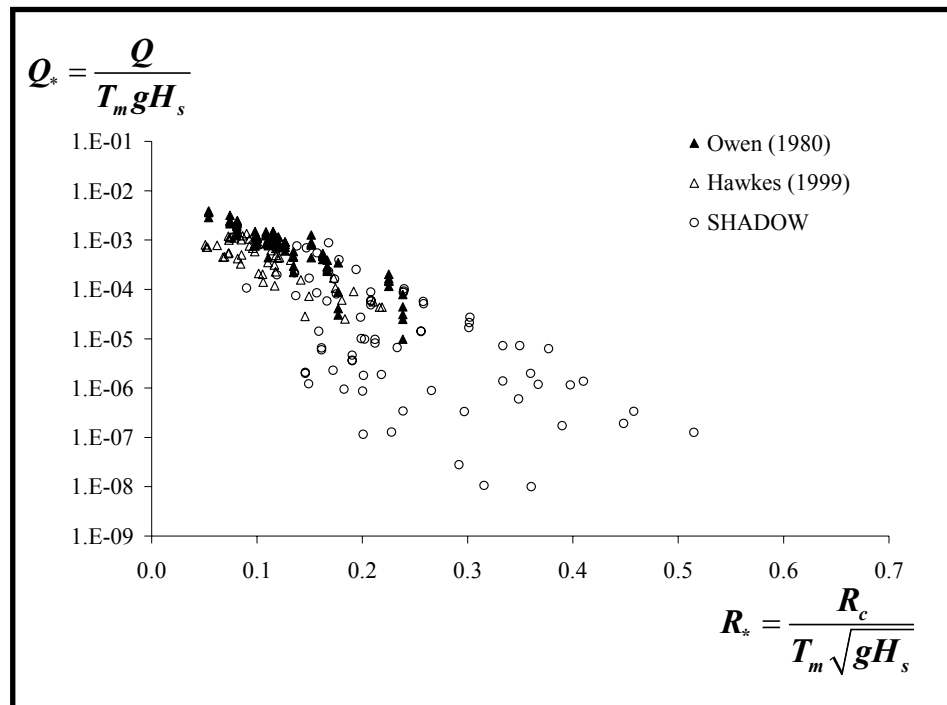


Figure 5-1 Comparison of SHADOW data with previous data for 1:2 slopes (using Owen's parameters)

between the new and old data sets, where Owen's (1980) dimensionless groups are employed. The new data appear consistent with previous results, although there is somewhat greater scatter associated with the generally smaller measured discharges.

### 5.2.2. Comparing predictions with measurements

The units of the measured overtopping discharges were set to be  $l/s/m$  in the *proBAY* output files and they were converted to  $m^3/s/m$  for the rest of the analysis. All measured and predicted overtopping discharges are reported at model scale. If the prototype/model length ratio is  $L_r$ , then discharges scale by  $L_r^{3/2}$ . Owen's and Hawkes' data were provided at prototype scale and adjusted accordingly (Shareef, 2005).

Owen (1980), Van der Meer & Janssen (1995) and Hedges & Reis (1998) have developed the principal overtopping prediction methods that are currently in use in Europe. Besley (1999) later improved Owen's model by providing new coefficients. Allsop & Pullen (2003), by adding the SHADOW test data, extended Owen's *A* and *B* coefficients for shallow front slope structures. Mase *et al.* (2003) revised the coefficients for the H&R prediction method. Bay *et al.* (2004) predicted overtopping volumes using the H&R method and employed the coefficients provided by Mase *et al.* (2003), comparing results with experimental data. For these reasons, Owen's (1980), Van der Meer & Janssen's (1995) and Hedges & Reis's (1998) models are employed here to predict overtopping volumes and the predicted values are compared with the available data.



5.2.2.1. Estimating mean overtopping discharges using Owen’s prediction method

Besley’s (1999) suggested values are used for  $A$  and  $B$  in applying Owen’s (1980) method to predict overtopping discharges for the 1:1, 1:2 and 1:4 front slopes. Coefficients for the 1:10 and 1:15 front slopes are taken from Allsop & Pullen’s (2003) proposed values. Although the revised coefficients are employed, Figure 5-2 shows that Owen’s method generally overestimates overtopping discharges, particularly for swell conditions (see Hawkes’ data).

Note that the boxed area in Figure 5-2 indicates the region covered later in Figures 5-5 and 5-8 where predicted and measured values are in better agreement.

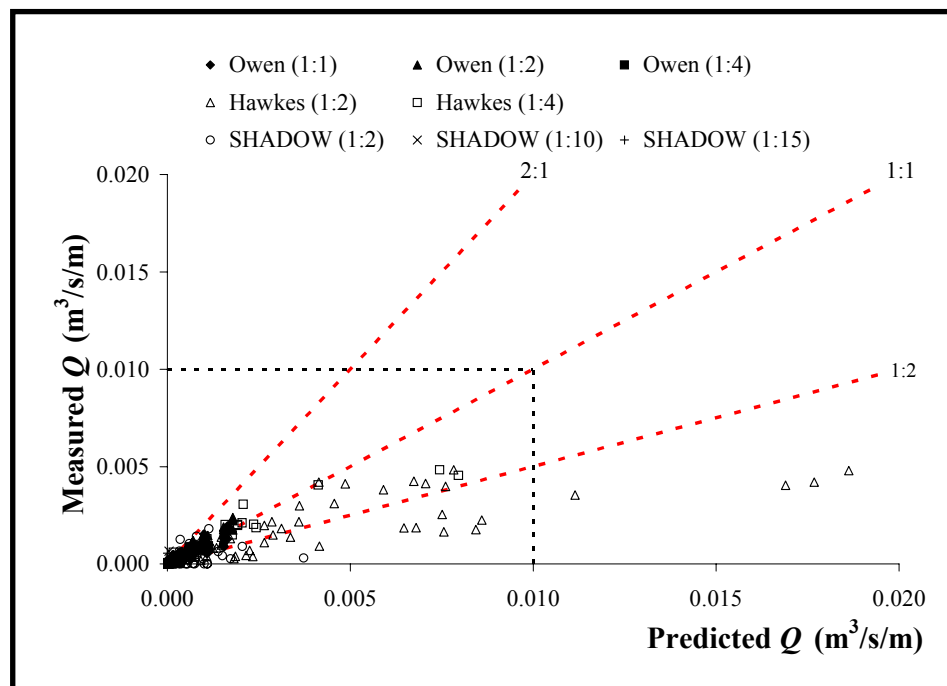


Figure 5-2 Predicted overtopping discharges using Owen’s (1980) method with revised coefficients

Figures 5-3 and 5-4 show the ratio of the predicted to the measured overtopping discharges  $Q_p/Q_m$  using Owen's (1980) method, plotted against the measured discharges  $Q_m$ . Figure 5-3 is for measured discharges up to  $0.005 \text{ m}^3/\text{s}/\text{m}$  whilst Figure 5-4 looks at the smaller discharges up to  $0.0005 \text{ m}^3/\text{s}/\text{m}$ . The table in the figures shows the average and the standard deviation of  $Q_p/Q_m$  for each slope separately and for all slopes. Note that the average value of  $Q_p/Q_m$  is consistently greater than the expected value of 1.0. There are also very high standard deviations, indicating wide scatter in predictions relative to measured values.

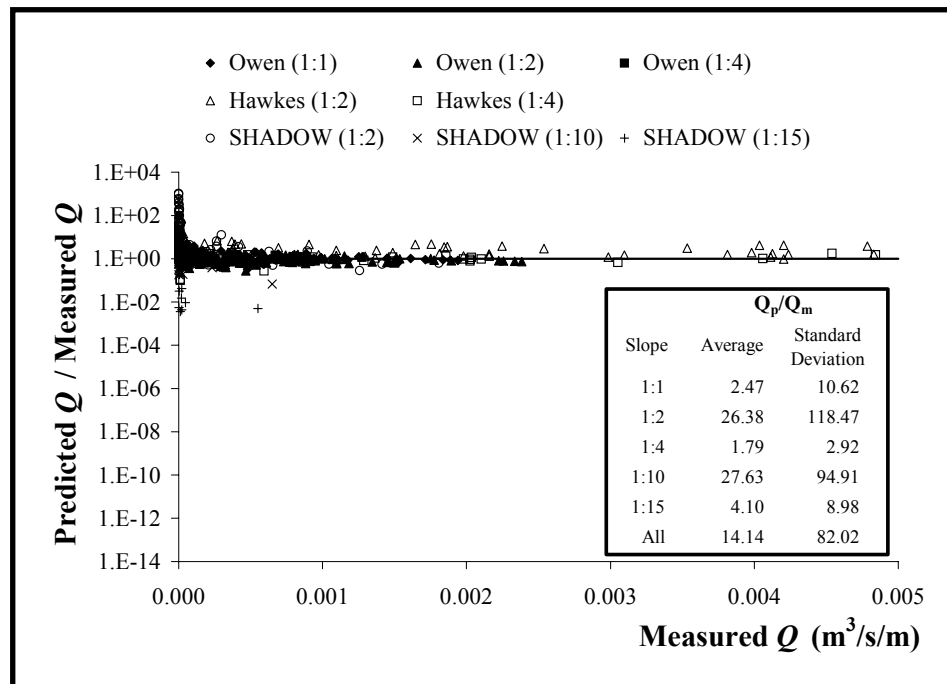


Figure 5-3 Ratio of predicted to measured overtopping discharges using Owen's (1980) method with revised coefficients

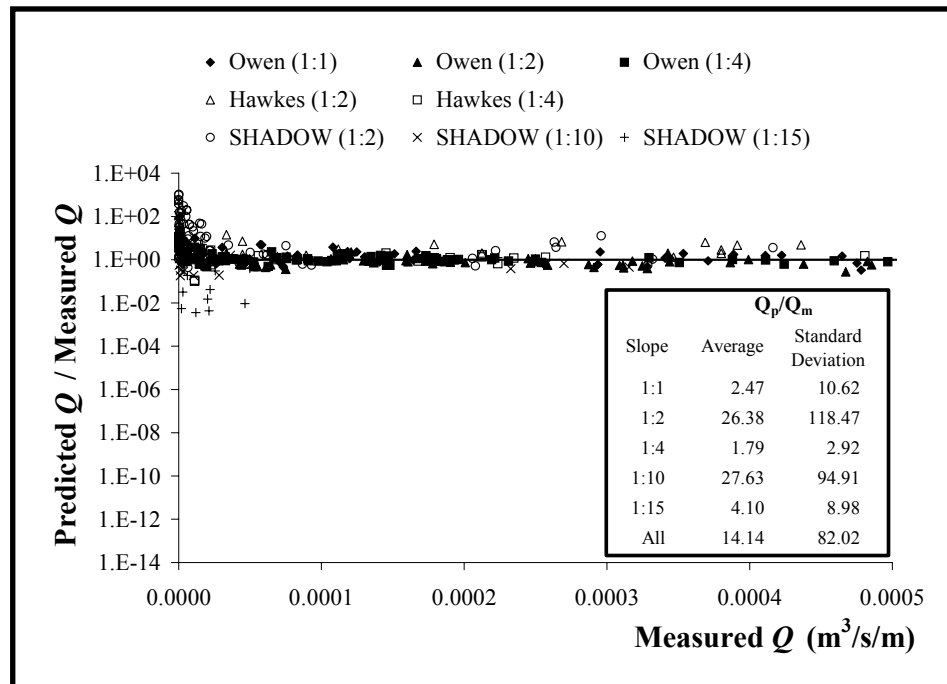


Figure 5-4 Ratio of predicted to measured overtopping discharges using Owen's (1980) method with revised coefficients ( $Q_m < 0.0005 m^3/s/m$ )

#### 5.2.2.2. Estimating mean overtopping discharges using Van der Meer & Janssen's prediction method

Figure 5-5 shows the predicted overtopping discharges using Van der Meer & Janssen's (1995) method plotted against the measured values. It shows that, particularly for larger overtopping discharges, Van der Meer & Janssen's (1995) method tends to be conservative. However, the estimates still appear better than Owen's predictions.

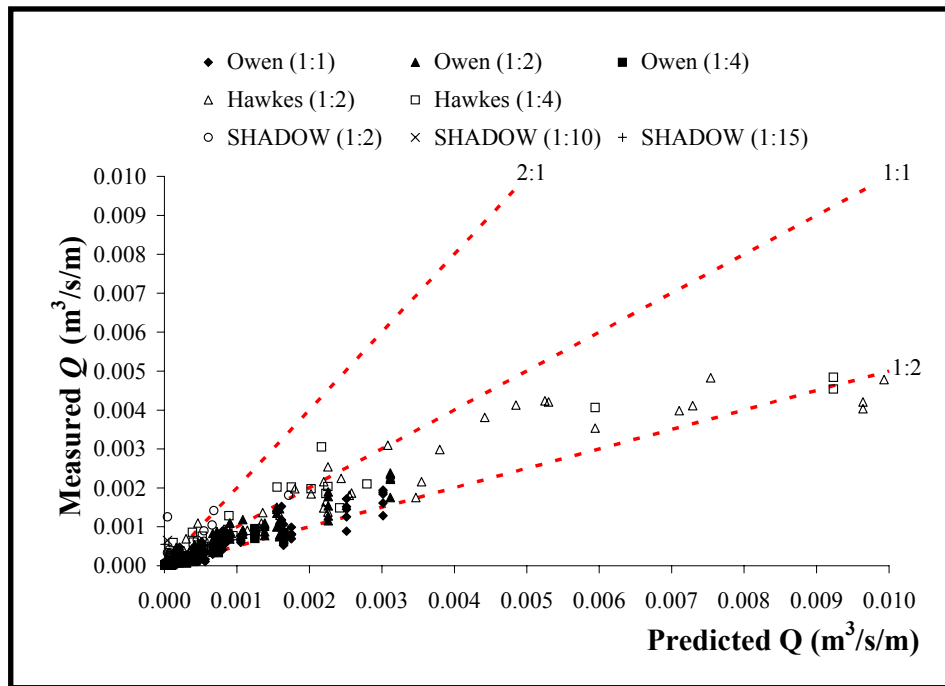


Figure 5-5 Predicted overtopping discharges using Van der Meer & Janssen's (1995) method

Figures 5-6 and 5-7 again show the average and the standard deviation of  $Q_p/Q_m$  for each slope separately and for all slopes. In this case, the average value of  $Q_p/Q_m$  is generally closer to 1.0 than in Figures 5-3 and 5-4. However, the average for the 1:10 slope is high at 26.73. The standard deviations in  $Q_p/Q_m$  are also generally smaller, indicating less scatter in predictions. However, the scatter for the 1:10 slope remains very high.

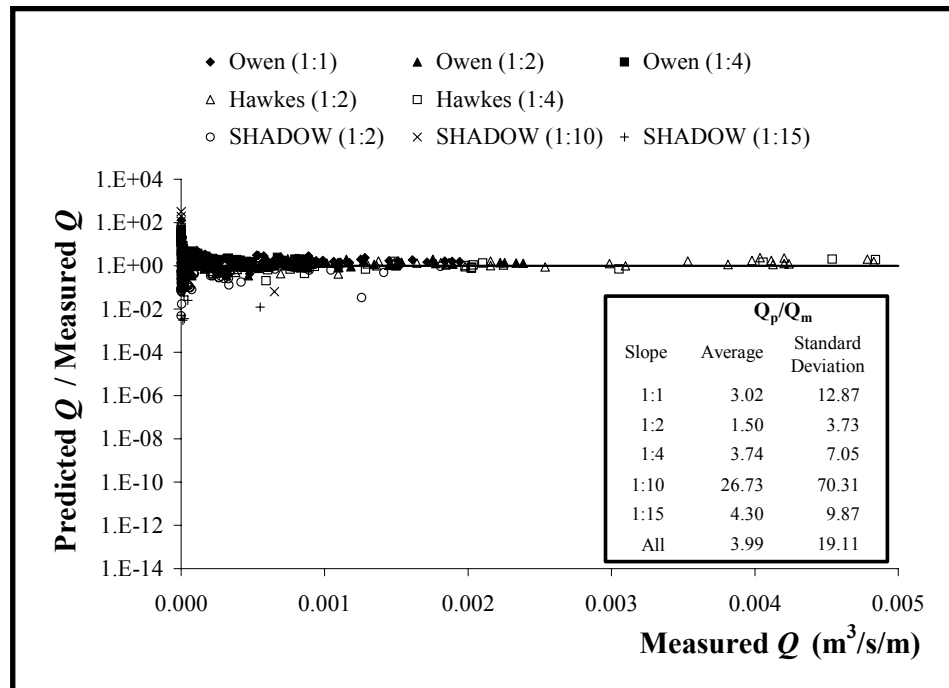


Figure 5-6 Ratio of predicted to measured overtopping discharges using Van der Meer & Janssen's (1995) method

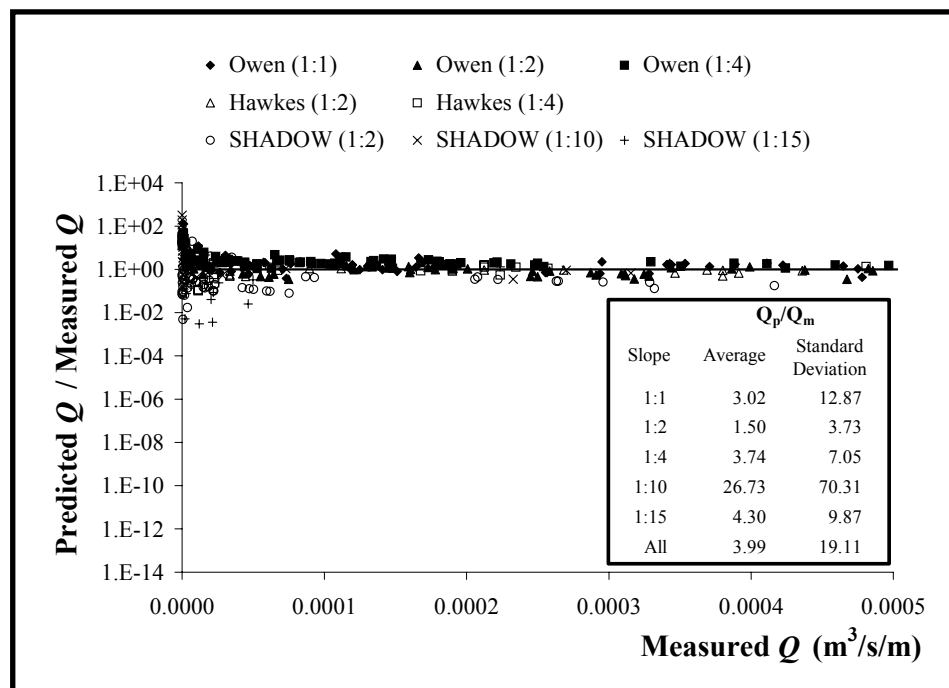


Figure 5-7 Ratio of predicted to measured overtopping discharges using Van der Meer & Janssen's (1995) method ( $Q_m < 0.0005 \text{ m}^3/\text{s/m}$ )

5.2.2.3. Estimating mean overtopping discharges using Hedges & Reis's prediction method

Reis *et al.* (2005) provided revised values of coefficients  $A$  and  $B$  for use with  $(R_{\max})_{37\%,100}$  in the H&R model. They gave the following expressions:

$$\begin{aligned}
 A &= \begin{cases} 0.0033 + 0.0025 \cot \alpha & \text{for } 1 \leq \cot \alpha \leq 12 \\ 0.0333 & \text{for } 12 < \cot \alpha \leq 20 \end{cases} \\
 B &= \begin{cases} 2.8 + 0.65 \cot \alpha & \text{for } 1 \leq \cot \alpha \leq 8 \\ 10.2 - 0.275 \cot \alpha & \text{for } 8 < \cot \alpha \leq 20 \end{cases}
 \end{aligned}
 \tag{5.1}$$

Figure 5-8 shows the predicted overtopping discharges using the Hedges & Reis (1998) method plotted against the measured values, using the above expressions for  $A$  and  $B$ . It shows better predictions than Van der Meer & Janssen's (1995) method at high ( $Q_m > 0.0025 \text{ m}^3 / \text{s} / \text{m}$ ) and moderate ( $0.0005 < Q_m < 0.0025 \text{ m}^3 / \text{s} / \text{m}$ ) measured overtopping rates. However, it is unclear from Figure 5-8 whether predictions are better for the low rates.

The average and the standard deviation of  $Q_p/Q_m$  for each slope separately and for all slopes are again shown in Figures 5-9 and 5-10. The average values are mostly closer to 1.0 than in Figures 5-3, 5-4, 5-6 and 5-7, and the standard deviations are generally smaller. However, the average for the 1:10 slope is very low at 0.06 and the standard deviation shows that this underestimation of discharges is systematic, at least for the very small mean discharges measured in the SHADOW experiments.

Comparison of Figures 5-7 and 5-10 for low overtopping rates ( $Q_m < 0.0005 \text{ m}^3 / \text{s} / \text{m}$ ) suggests that there is little to choose between Van der Meer & Janssen's method and the H&R method in this range. Note that for very small overtopping rates ( $Q_m < 0.0001 \text{ m}^3 / \text{s} / \text{m}$ ), the H&R model tends to underestimate overtopping rates and appears poorer than Van der Meer & Janssen's method. However, underestimation is unimportant for very small overtopping discharges which generally cause trivial damage only (see Figure 2-15).

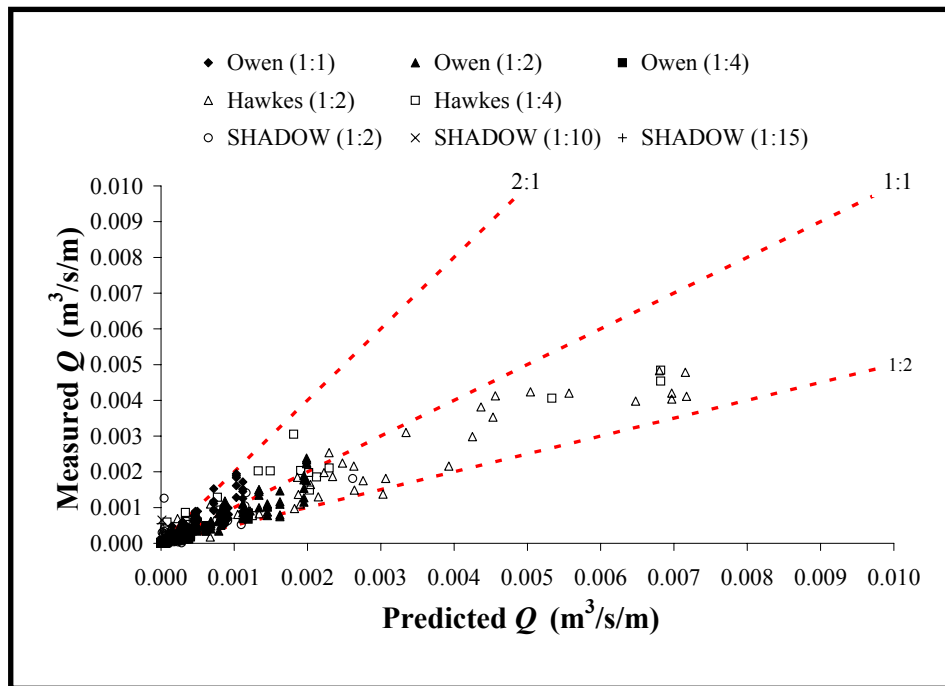


Figure 5-8 Predicted overtopping discharges using Hedges & Reis's (1998) method with revised coefficients

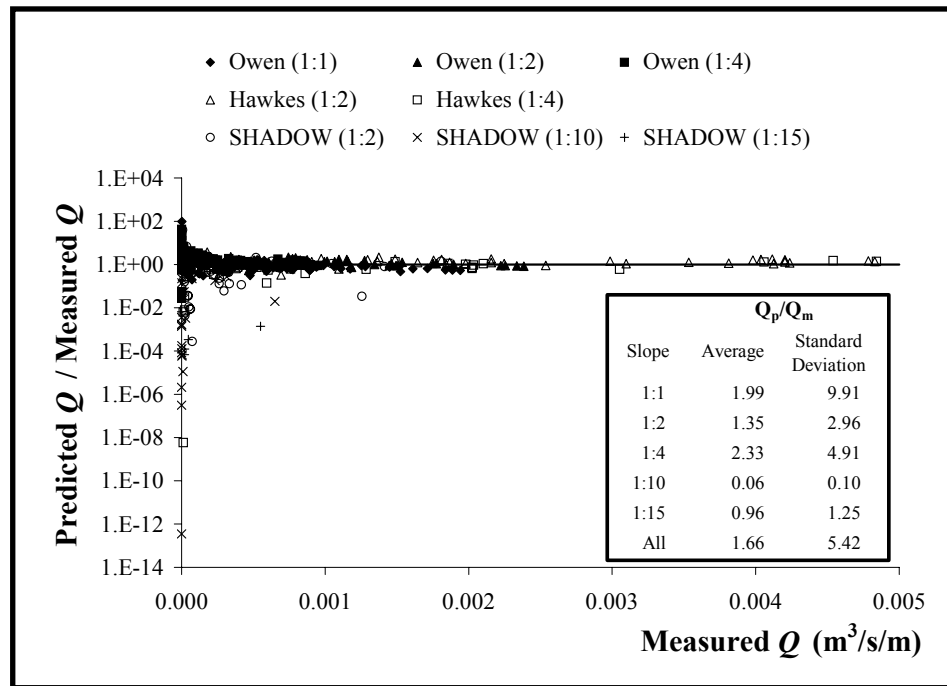


Figure 5-9 Ratio of predicted to measured overtopping discharges using Hedges & Reis's (1998) method with revised coefficients

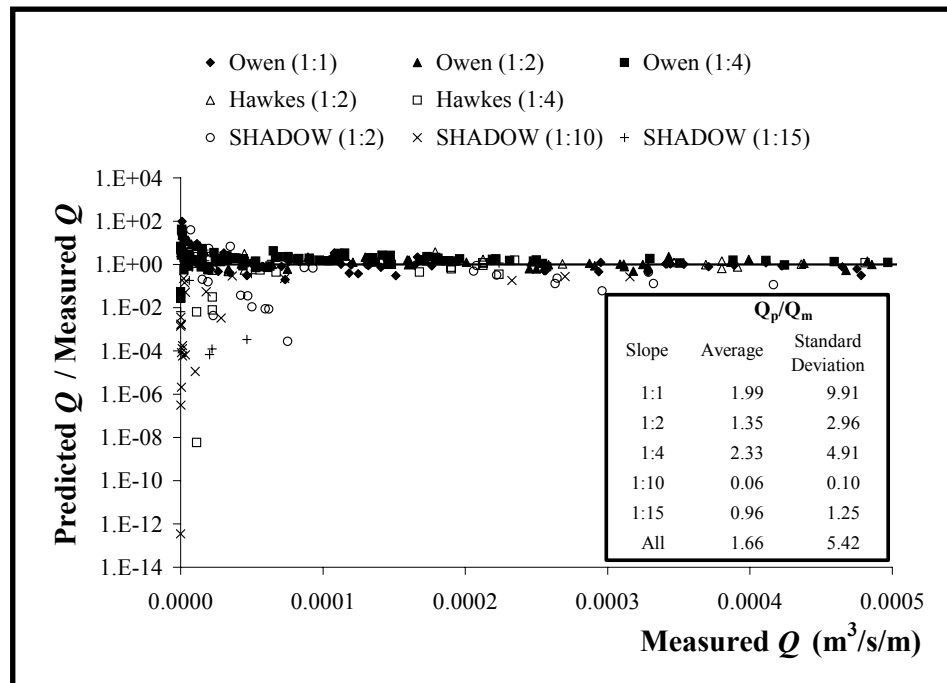


Figure 5-10 Ratio of predicted to measured overtopping discharges using Hedges & Reis's (1998) method with revised coefficients ( $Q_m < 0.0005 \text{ m}^3/\text{s/m}$ )



Noting all of the above facts, the H&R (1998) method appears to be the best of the three methods considered in this study, with the averages being closer to 1.0 and the standard deviations of  $Q_p/Q_m$  being lower than for the other two methods.

### 5.3. Predicting the number of overtopping events

The number of overtopping events within a storm,  $N_o$ , may be calculated on the assumption that the Rayleigh distribution is the best way of representing the distribution of run-up values:

$$\text{Prob}[R > R_c] \approx \exp\left[-2\left(\frac{R_c}{R_s}\right)^2\right] \quad (5.2)$$

Using equations (2.9) provided by Mase *et al.* (2003), the significant run-up,  $R_s$ , is found. Knowing that the number of run-ups exceeding the seawall crest level is equal to the number of overtopping waves,  $N_o$ :

$$\text{Prob}[R > R_c] = \frac{N_o}{N_R} \quad (5.3)$$

where  $N_R$  is the total number of run-ups, and, therefore,

$$\frac{N_o}{N_R} \approx \exp\left[-2\left(\frac{R_c}{R_s}\right)^2\right] \quad (5.4)$$

Considering the reduction factor,  $n$ , in equation (2.11), the relationship between the number of incident waves and the number of overtopping events can be written as:

$$\frac{N_o}{N} \approx n \exp \left[ -2 \left( \frac{R_c}{R_s} \right)^2 \right] \quad (5.5)$$

Equation (5.5) is an approximation: it predicts that some portion of waves will always cause overtopping regardless of the freeboard.  $N_o/N$  is zero only if  $R_c/R_s$  is infinite.

Equation (5.5) can be re-written by taking natural logarithms of both sides:

$$\ln \left( \frac{N_o}{N} \right) \approx \ln(n) - 2 \left( \frac{R_c}{R_s} \right)^2 \quad (5.6)$$

Recalling that  $n$  is a function of  $\xi_p$  (see Figure 2.13), a plot of  $\ln(N_o/N)$  against  $(R_c/R_s)^2$  allows coefficient  $n$  to be established for fixed values of  $\xi_p$  (see Figure 5-11).

Equation (2.11) was used to evaluate  $n$  and the number of overtopping waves,  $N_o$ , was estimated using equation (5.5). Figure 5-12 compares the results of the estimations with the measured values. As might be expected, considerable scatter occurs in the predictions for very low overtopping rates, which would have few overtopping events, but scatter reduces considerably as the mean overtopping rate and the measured number of overtopping events increases.

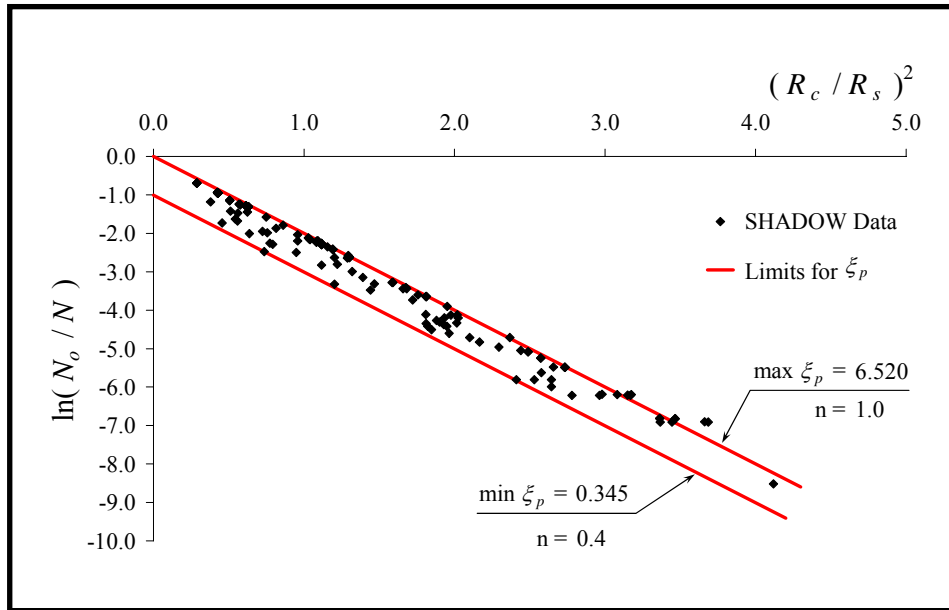


Figure 5-11 Establishing the coefficient  $n$

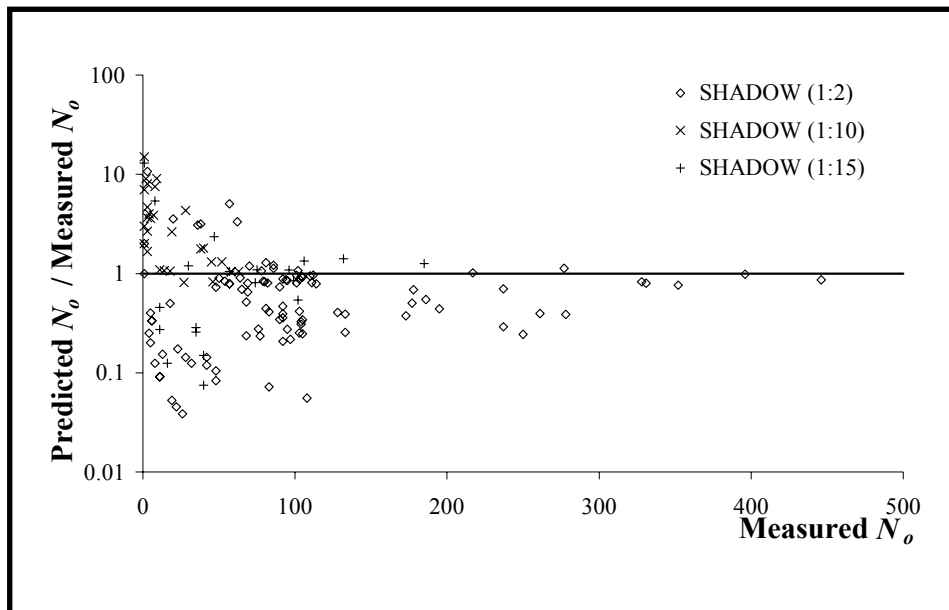


Figure 5-12 Ratio of predicted to measured numbers of overtoppings against measured values

#### 5.4. Mean overtopping volumes

Using equations 2.41, 2.42 and 2.43 and, taking  $C = R_{\max}/H_s$ , the H&R overtopping model may be written as:

$$\frac{Q}{\sqrt{gR_{\max}^3}} = \begin{cases} A \left(1 - \frac{R_c}{R_{\max}}\right)^B & \text{for } 0 \leq \frac{R_c}{R_{\max}} < 1 \\ 0 & \text{for } \frac{R_c}{R_{\max}} \geq 1 \end{cases} \quad (5.7)$$

Note that, after a storm duration of  $t_{st}$ ,  $N_o$  waves overtopping the crest of a seawall will accumulate a total overtopping volume of  $V_{tot}$ .  $V_{tot}$  is equal to the mean overtopping discharge,  $Q$ , multiplied by  $t_{st}$ . Taking  $t_{st} = NT_m$ ,  $V_{tot}$  can be expressed as:

$$V_{tot} = \begin{cases} Q t_{st} \\ Q NT_m \end{cases} \quad (5.8)$$

Therefore, the mean overtopping volume,  $V_{mean}$ , can be written as:

$$V_{mean} = \frac{Q NT_m}{N_o} = \frac{Q T_m}{N_o/N} \quad (5.9)$$

After predicting  $Q$  using equation (5.7) and  $N_o$  using equation (5.5),  $V_{mean}$  can be found for an estimated storm duration. Estimating  $V_{mean}$  is important for predicting  $V_{\max}$  (see section 5.7.).

### 5.5. Individual overtopping volumes

The testing equipment and methods of data analysis employed in the SHADOW project were capable of distinguishing very small overtopping volumes. Therefore, taking  $V_{\min} = 0$ , equation 2.21 reduces to the simpler two-parameter Weibull distribution function:

$$P_o = \text{Prob}[V \geq V_{\#}] = \exp \left[ - \left( \frac{V_{\#}}{V_{char}} \right)^{\beta} \right] \quad (5.10)$$

in which  $V_{char}$  characterizes the scale of the overtopping and  $\beta$  is the shape parameter (a pure number). Although equation (5.10) has  $\text{Prob}[V \geq 0] = 1$ , it remains an approximation. Just as the Rayleigh distribution predicts the possibility of an infinite run-up, the Weibull distribution predicts the possibility of an infinitely large overtopping volume.

The value of  $V_{char}$  in equation (5.10) depends upon the incident wave conditions and the seawall characteristics, i.e. freeboard, front slope, roughness, etc. Taking natural logarithms of both sides, equation (5.10) becomes:

$$\ln(\text{Prob}[V \geq V_{\#}]) = - \left( \frac{V_{\#}}{V_{char}} \right)^{\beta} \quad (5.11)$$

$$\ln \left\{ \ln(\text{Prob}[V \geq V_{\#}])^{-1} \right\} = \beta \ln V_{\#} - \beta \ln V_{char} \quad (5.12)$$

Hence, if equation (5.10) is correct then  $\ln V_{\#}$  plots against  $\ln \left\{ \ln \left( \text{Prob} [V \geq V_{\#}] \right)^{-1} \right\}$  as a straight line, from which  $V_{char}$  and  $\beta$  may be evaluated. Figure 5-13 is a sample, plotted for the wave condition TAP0675. It is also an excellent example to show how accurate the LAD fit is to most of the data points when compared to Figure 4-19.

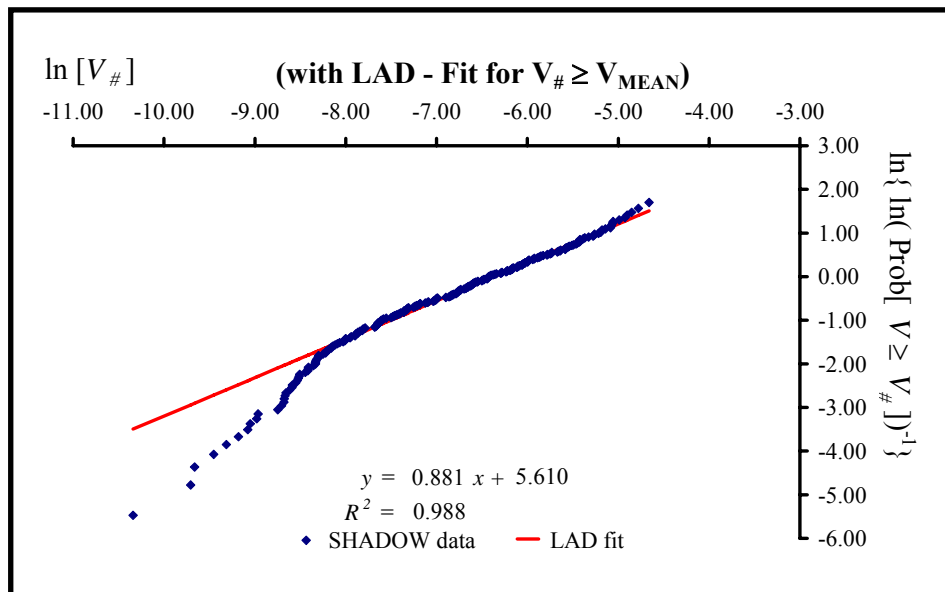


Figure 5-13 Individual overtopping volumes (for SHADOW wave condition TAP0675)

Figures for the other test conditions are plotted in Appendix B3. Note that in Figure 5-13 and elsewhere, the fit to the data is for  $V_{\#} \geq V_{mean}$ , ensuring that the more unreliable values associated with the smaller measured volumes do not have an unreasonable influence in estimating  $V_{char}$  and  $\beta$ .

It is also possible to estimate the exceedance probabilities for particular volumes. The measured overtopping volumes are ranked in descending order, from the biggest ( $i = 1$ ) to the smallest ( $i = N_o$ ). Then:

$$\text{Prob}[V \geq (V_{\#})_i] \approx \frac{i}{N_o} \quad (5.13)$$

Equation (5.13) gives the probabilities observed in the sample. However, it implies that all overtopping volumes are greater than or equal to the minimum recorded overtopping volume. Adding 1 to the denominator allows the possibility of an overtopping volume which is smaller than the smallest measured value:

$$\text{Prob}[V \geq (V_{\#})_i] \approx \frac{i}{N_o + 1} \quad (5.14)$$

In reality,  $\text{Prob}[V \geq 0] = 1$ .

Figure 5-14 shows the distribution of individual overtopping volumes with  $V_{char}$  and  $\beta$  established using LAD fitting for  $V_{\#} \geq V_{mean}$ . It may be compared with the much poorer agreement with data shown in Figure 4-20 for which LS fitting was used with the data on all overtopping volumes.

If the individual overtopping volumes are Weibull distributed, then the mean overtopping volume,  $V_{bar}$ , can be derived from:

$$V_{bar} = V_{char} \Gamma\left(1 + \frac{1}{\beta}\right) \quad (5.15)$$

in which  $\Gamma( )$  denotes the Gamma function. “Gamma Function – Interpolation.xls” was employed to return the value of the Gamma

function. The value of  $V_{char}$  was determined from the relationship between  $\ln V_{\#}$  and  $\ln \left\{ \ln \left( \text{Prob}[V \geq V_{\#}] \right)^{-1} \right\}$ .

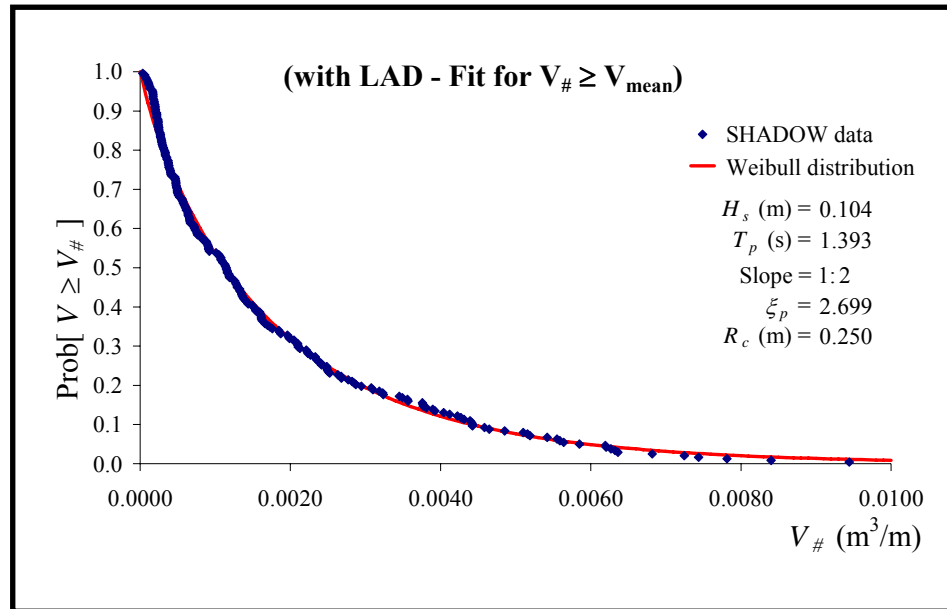


Figure 5-14 Distribution of individual overtopping volumes (for TAP0675)

Besley (1999) used  $V_{\#} \geq V_{mean}$  in his  $V_{max}$  calculations because data were diverging from the Weibull distribution for low overtopping volumes. Franco *et al.* (1994) used  $N_o \geq 30$  for the same reason. In the present study,  $N_o \geq 20$  was imposed as a further constraint when evaluating  $V_{bar}$ , as even a single additional overtopping event can result in significant influences if  $N_o$  is smaller than 20. The excellent agreement between the measured mean overtopping volumes,  $V_{mean}$ , established from equation (5.9) and  $V_{bar}$ , derived from equation (5.15), is shown in Figure 5-15.

More information about the Gamma function and the macro codes for the Microsoft Excel workbook are given in the Appendices.



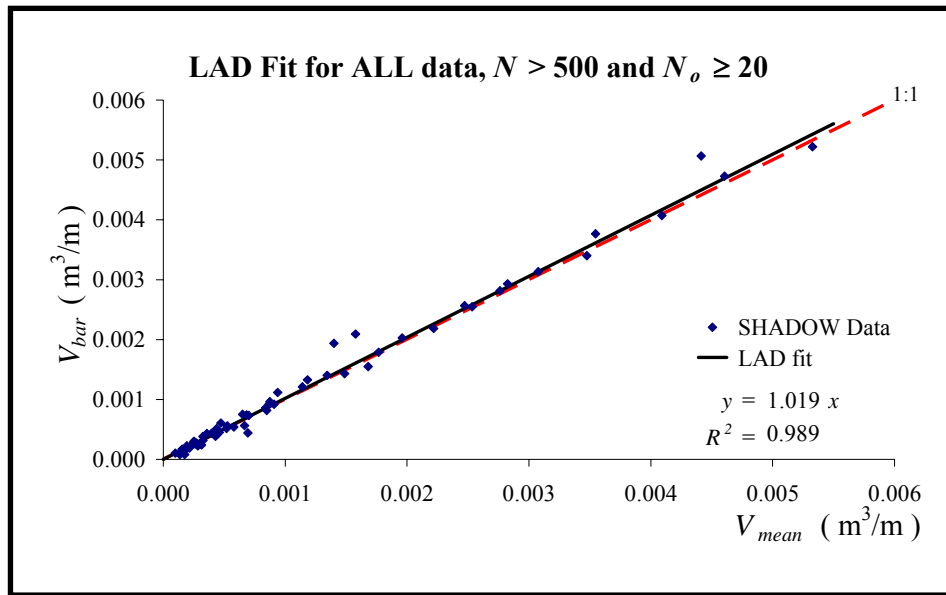


Figure 5-15 Comparison of  $V_{bar}$  with  $V_{mean}$  for the SHADOW data ( $N > 500$  and  $N_o \geq 20$ )

## 5.6. Investigating the shape parameter, $\beta$

Franco *et al.* (1994) investigated the shape parameter,  $\beta$ , and found its value to be 0.75 for vertical and composite breakwaters subject to reflecting waves. This value was confirmed by Van der Meer and Janssen (1994) for dikes. In his manual, Besley (1999) also suggested using  $\beta = 0.75$  for vertical walls but recommended  $\beta = 0.85$  for sloping structures.

Although it was stated by Franco *et al.* (1999) that there is no direct relationship between the value of the shape parameter and the wave and wall characteristics, this assertion was investigated further during the present study.

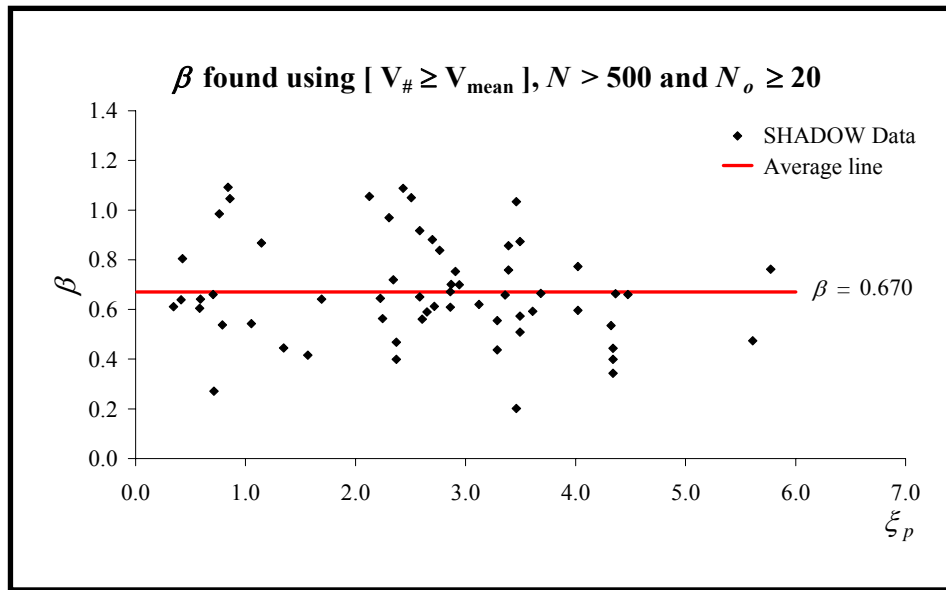


Figure 5-16  $\beta$  values against  $\xi_p$  for the SHADOW data

$\beta$  values for the SHADOW test conditions were found by using an LAD fit for  $V_{\#} \geq V_{mean}$ . They were plotted against various parameters describing the different wave and structure characteristics, such as the breaker parameter,  $\xi_p$ , the cotangent of the slope ( $m$ ),  $R_c/H_s$ ,  $H_s/L_{op}$  and  $R_c/L_{op}$ . In no case was there a strong correlation. Figure 5-16 demonstrates how  $\beta$  plots against  $\xi_p$ . Although, Besley (1999) reported  $\beta = 0.75$  for vertical walls and 0.85 for sloping structures, the average of the  $\beta$  values in the SHADOW project was found to be 0.67. Consideration of equation (5.10) shows that a lower value of  $\beta$  increases the probability that any particular volume,  $V_{\#}$ , will be exceeded for a specified value of  $V_{mean}$  (i.e. predictions are more conservative).

### 5.7. Predicting the maximum individual overtopping volume

The maximum individual overtopping volume,  $V_{\max}$ , has a probability of occurrence given by:

$$\text{Pr ob}[V \geq V_{\max}] = \frac{1}{N_o} \quad (5.16)$$

Substituting equation (5.16) in equation (5.10) gives:

$$\frac{1}{N_o} = \exp \left[ - \left( \frac{V_{\max}}{V_{char}} \right)^\beta \right] \quad (5.17)$$

Taking natural logarithms of both sides:

$$\ln N_o = \left( \frac{V_{\max}}{V_{char}} \right)^\beta \quad (5.18)$$

$$V_{\max} = V_{char} (\ln N_o)^{1/\beta} \quad (5.19)$$

and substituting for  $V_{char}$  using equation (5.15):

$$V_{\max} = \frac{V_{bar}}{\Gamma \left( 1 + \frac{1}{\beta} \right)} (\ln N_o)^{1/\beta} \quad (5.20)$$

In order to predict  $V_{max}$ ,  $\beta$  was taken as its average value of 0.67 (see Figure 5-16). Assuming  $V_{bar} = V_{mean}$ ,  $V_{bar}$  was calculated using equation (5.9).  $Q$  in equation (5.9) was predicted using the Hedges and Reis method employing  $(R_{max})_{37\%,100}$  and the coefficients of Reis *et al.* (2005), and  $N_o$  was estimated using equation (5.5). The denominator in equation (5.20) is the Gamma function and its value was obtained using macros in “Gamma Function – Interpolation.xls”.

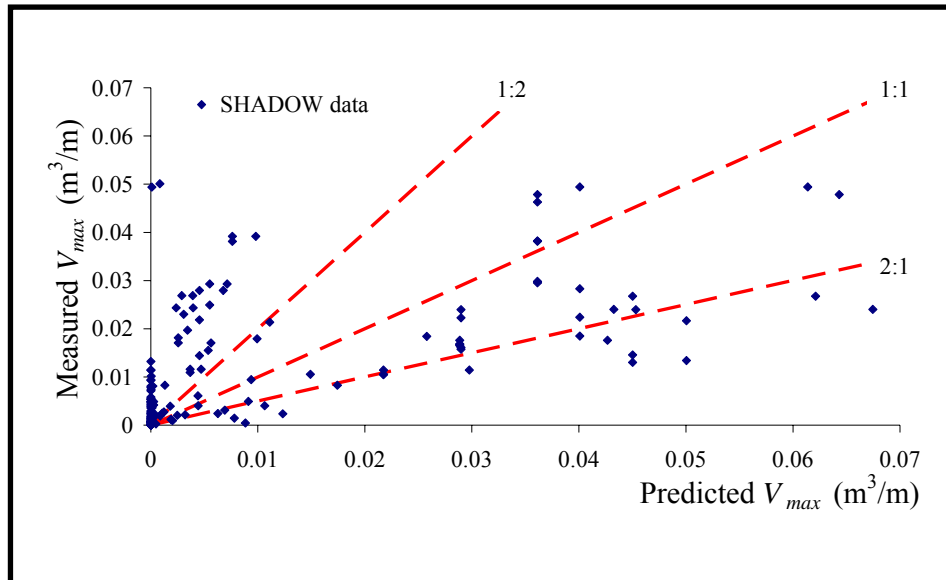


Figure 5-17 Measured and predicted  $V_{max}$  values

Figure 5-17 compares the predicted  $V_{max}$  values with the measured ones. It should be noted that the measured  $V_{max}$  values in Figure 5-17 are the output values obtained from the *proBAY* software and these values, themselves, will be subject to some error. Nevertheless, there are many predictions of zero for  $V_{max}$ . Zeros arise as a result of the H&R model predicting zero overtopping when, in reality, some overtopping was recorded in these particular tests.

Estimating  $V_{\max}$  is not being done here for the first time. Researchers have published their approaches and formulae to estimate  $V_{\max}$  but they tend not to plot their predictions against their data. However, one comparison was provided by Besley (1999b). Although he achieved reasonable agreement, he used the measured values of  $V_{\text{mean}}$  and  $N_o$  to predict  $V_{\max}$  values rather than estimating  $V_{\text{mean}}$  and  $N_o$ .

Figure 5-17 shows poor agreement between the predicted and measured  $V_{\max}$  values. Using Besley's approach, i.e. employing the measured values of  $V_{\text{mean}}$  and  $N_o$ , whilst still using  $\beta = 0.67$ , agreement is far better (see Figure 5-18). However, the parameters used in evaluating  $V_{\max}$  are not known before a storm and have to be estimated at the design stage.

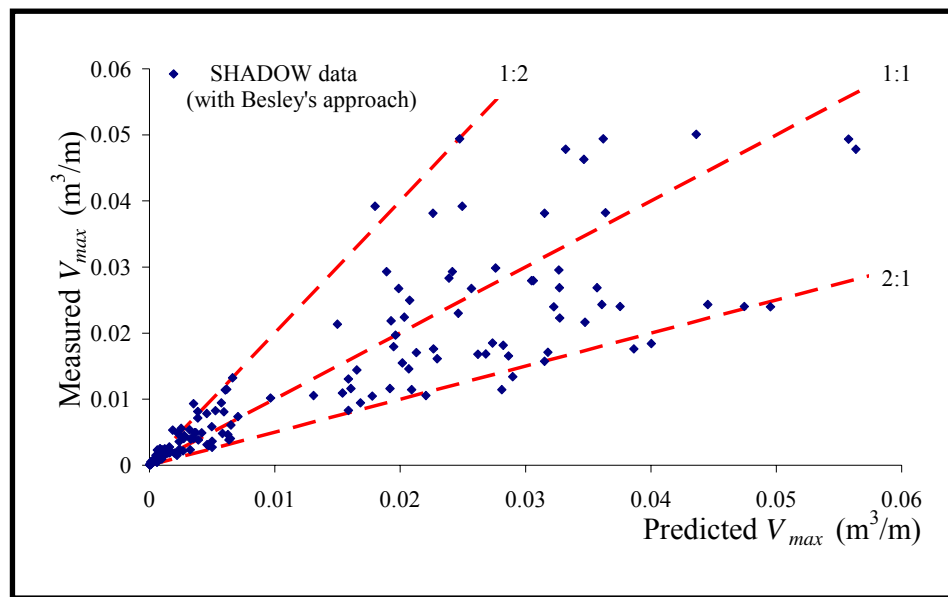


Figure 5-18 Measured and predicted  $V_{\max}$  values (Besley's approach,  $N_o > 1$ )

# *Chapter 6*

## CONCLUSIONS

Existing empirical methods often provide poor predictions of the mean overtopping discharges from waves on sloping structures. The SHADOW project provided a chance to extend the existing data range. Data files were processed by the *proBAY* software. Results were compared with the predicted values. In addition, wave-by-wave overtopping volumes and the maximum individual overtopping volume have been investigated. This chapter provides conclusions from this study.

### **6.1. Introduction**

Wave overtopping performance is one of the most important measures when designing coastal structures. The absence of a wholly satisfactory method to predict wave overtopping, and therefore to fix the freeboard, led to this study. DEFRA commissioned HRW to perform a series of experiments to extend the available data range and to investigate the wave overtopping performances of shallow-sloping coastal structures. Many prediction methods have previously been developed using similar experimental data but they often provide poor predictions of low overtopping discharges as the focus of those investigations was on large

overtopping rates. Furthermore, applications of these methods are inevitably restricted to their particular experimental ranges. Thus, the present work was aimed (if possible) at extending and validating one of the available methods, and at providing information on the distributions of individual overtopping volumes. Data were unavailable elsewhere for 1:10 and 1:15 slopes and the SHADOW project covered gaps in existing data for 1:2 slopes at low overtopping rates.

## **6.2. *proBAY* results**

It is difficult to identify small overtopping volumes and an effective detection system was produced during the present study. Due to high gain settings, the SHADOW data were recorded with a high level of noise. Consequently, considerable effort went into getting the best from the recorded overtopping detector and load cell data by using the *proBAY* software written specifically for this project. Noise in the data was largely eliminated and results are now very satisfactory. When the original load cell signals are plotted together with the smoothed load cell signal and output from the *proBAY* software, the signals almost lie on top of each other (see Figures 4-5 and 4-13).

## **6.3. Existing prediction methods**

Previously published methods, widely used in Europe to predict wave overtopping, have been considered and compared in this study. Owen's (1980) method (see section 2.6.1) has been a benchmark for most other global studies. Although Besley has only undertaken further analysis and improved Owen's (1980) curve fitting coefficients, many researchers refer to Besley's (1999) prediction method (see section 2.6.2). Van der Meer & Janssen's (1995) method (see section 2.6.4) is widely used in the

Netherlands. The method provided by Hedges & Reis (1998) is semi-empirical rather than wholly empirical and satisfies the obvious physical boundary conditions (see section 2.6.5).

Figures 2-19 and 2-20 show that all of these methods are in reasonable agreement for storm conditions when waves are relatively large and steep and overtopping is substantial. However, for low overtopping discharges, there are noticeable differences.

Amongst the methods compared, the Hedges & Reis (1998) procedure generally provides the best predicted mean overtopping discharges (see Figures 5-2 to 5-10). The only difficulty with their method is to estimate the maximum run-up before the storm. It predicts better than other methods when high and moderate overtopping discharges exist and it provides predictions at least as good as Van der Meer & Janssen's model for low discharges (see Figures 5-7 and 5-10).

#### **6.4. Estimating the number of overtopping events**

Estimation of the number of overtopping events is based on an assumption that run-ups are Rayleigh distributed. Although it would have been preferable to have measured the run-up distribution, funds were not available for this purpose, but Figure 5-11, showing the relationship between  $\ln(N_o/N)$  and  $(R_c/R_s)^2$ , supports this assumption. However, the scatter in Figure 5.12, particularly when there are low numbers of overtopping events, demonstrates poor agreement between the predicted and measured  $N_o$  values.



### 6.5. Individual overtopping volumes

Individual overtopping volumes are well represented by the two-parameter Weibull distribution function (see Figure 5-14). Figure 5-15 relating  $V_{bar}$  to  $V_{mean}$  also provides support for this distribution.

Although measurements of individual overtopping volumes for each test condition were accurate, it is difficult to draw conclusions about trends in  $\beta$  values. Although  $\beta$  values were examined, no firm relationship was found with the independent parameters which define the wave and seawall properties. Indeed, there was a large scatter in  $\beta$  values. The mean value of  $\beta$  found in the present study is lower than the values presented in earlier studies. Consequently, it provides a more conservative estimate both for the probability of particular individual volumes of overtopping water being exceeded and for the value of the maximum individual overtopping volume.

### 6.6. Estimating the maximum overtopping volume

It is difficult to talk about an accurate estimation of the maximum overtopping volume. Experimental results were plotted against the estimated values (see Figures 5-17 and 5-18). Considerable scatter was observed in Figure 5-17. However, predictions were in closer agreement with measurements when  $V_{mean}$  and  $N_o$  were known (Figure 5-18). Therefore, it may be concluded that estimates of the maximum overtopping volume in a storm are likely to remain uncertain until better methods are available for predicting both the mean overtopping discharge and the number of overtoppings.

## 6.7. Recommendations

Equation (5.5) is only an approximation for predicting the number of waves overtopping, since  $N_o/N$  can be zero only if  $R_c/R_s$  is infinite. However, the Hedges & Reis overtopping model predicts that there is no overtopping unless the freeboard,  $R_c$ , is exceeded by the maximum run-up,  $R_{\max}$ . Consequently, an alternative to equation (5.5) should be developed in which  $N_o = 0$  when  $R_c \geq R_{\max}$ .

Although high efficiency was achieved using the *proBAY* software, it may be upgraded to analyze 3D data for more complicated studies. This may allow investigations of the overtopping distribution along a structure. In addition, another feature could be added to account for the continuous decrease in the load cell signal when water is pumped from the overtopping tank.

The H&R model, using  $(R_{\max})_{37\%,100}$  as the estimate of the actual maximum run-up, was used to estimate overtopping discharges in Chapter 5 with the  $A$  and  $B$  coefficients provided by Reis *et al.* (2005). However, zero overtopping volumes were predicted for several wave conditions for which overtopping was actually recorded in the models. Therefore, in order to improve predictions for low overtopping rates, it may be worth employing  $(R_{\max})_{99\%,100}$  instead of  $(R_{\max})_{37\%,100}$  to estimate the maximum run-ups. This would require further analysis of the various data sets used to calibrate the model in order to produce the new associated  $A$  and  $B$  coefficients.

Although outside the scope of the present study, numerical modelling offers the possibility of improved predictions of mean overtopping rates, peak overtopping volumes and numbers of overtoppings. Continued development

is recommended. Whilst, at present, the more complicated numerical models are very time consuming, further increases in computing speed are expected to soon render them suitable as design tools.

### **6.8. Final remarks**

It is expensive to build and maintain sea defences and any information to make design more reliable will be beneficial. Therefore, although there is a considerable scatter in their values, it is still recommended that variables such as  $N_o$  and  $V_{\max}$  are estimated when designing coastal structures whilst research continues to improve predictions. One way of accounting for the scatter is to apply a suitable factor of safety. Another is to build the scatter into risk assessment software such as PARASODE (Reis, 1998).

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# *Appendices*

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# APPENDIX A

## Software Packages

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---

## Appendix - A1. *proBAY* codes

---

```
PROGRAM proBAY
!
! Last Update: 21/04/2004
!
! *****
! *
! *           Codes of this program were written by Ibrahim Bay (C)
! *
! *****
! *
! * proBAY is a program that was written in FORTRAN 95 and compiled using
! * FTN95 compiler. This version of proBAY uses data files recorded while testing
! * SHADOW project physical model structures. It investigates wave overtopping
! * performances of coastal structures, in particular, the wave-by-wave overtopping
! * volume distributions. Program particularly uses the overtopping detector signal
! * to identify overtopping events, then uses the load cell data to calculate individual
! * overtopping volumes.
! *
! * This program requires FORTRAN dynamic library file. Therefore, whether
! * FORTRAN 95 has to be installed or "salflib.dll" file has to be copied to the system
! * before executing it. Program will not run otherwise!
! *
! * If required, execution of this program can be terminated at any time by pressing
! * "Ctrl" and "C" buttons concurrently.
! *
! *****
! MAXSAMP is the maximum number of data points to be analysed in a single data set
  PARAMETER (MAXSAMP=72000)
! NC is the total number of channels to be analysed
  PARAMETER (NC=3)
  DIMENSION SIGN(NC,MAXSAMP), TIME(MAXSAMP), SMOLC(MAXSAMP)
  DIMENSION EVENT(MAXSAMP), CHOPDET(MAXSAMP)
  DIMENSION CHOPLOAD(MAXSAMP), CHOPDET2(MAXSAMP)
  DIMENSION EVENTIME(MAXSAMP), VOL(MAXSAMP)
  DIMENSION IND(MAXSAMP), VOLR(MAXSAMP)
  DIMENSION EVENTIMER(MAXSAMP), EVENTIMETMP(MAXSAMP)
  DIMENSION CHOPSMOLC(MAXSAMP), BEF(MAXSAMP)
  DIMENSION AFT(MAXSAMP), BEFTMP(MAXSAMP), AFTTMP(MAXSAMP)
  CHARACTER(LEN=12) :: INDET, INLOAD, DUMMY
  REAL :: LOADCAL, MOV, MOR, LIMOV
  REAL :: MPXSD, MPXSD1, MPXSD2, MPXSD3
  INTEGER :: CNDET, CNLOAD, CHUTE, DELAY, SPARE, CHDATA
  INTEGER :: CHDATA2, NDREQ, SETL, RUNAV, NOWA, POWA, PLAG
  INTEGER :: FLAG, SLAG, SECURE, TOP, SYC, EVENT, EVENTIME
  INTEGER :: EVENTIMER, MINLIM, MAXLIM, ONC, SPAN, COUNT
  INTEGER :: COUNTER1, COUNTER2, COUNTER3, ILK, SON
! *****
! *
```

```

! *                                     INTRODUCTION                                     *
! *                                                                              *
! *****
! *                                                                              *
! * This section contains an introductory information and informs user with the name *
! * and version of the program.                                                *
! *                                                                              *
! *****
      WRITE(1,*)
      WRITE(1,11)
11  FORMAT(2X,75('~')/ &
        2X,~,73X,~/ &
        2X,~,33X,4('B'),8X,'A',3X,'Y',7X,'Y',15X,~/ &
        2X,~,33X,'B',3X,'B',6X,'A',1X,'A',3X,'Y',5X,'Y',16X,~/ &
        2X,~,33X,'B',3X,'B',5X,'A',3X,'A',3X,'Y',3X,'Y',17X,~/ &
        2X,~,33X,6('B'),3X,'A',5X,'A',3X,'Y',1X,'Y',18X,~/ &
        2X,~,15X,4('p'),2X,'r',1X,3('r'),1X,3('o'),3X,'B',5X,'B', &
        2X,7('A'),4X,'Y',19X,~/ &
        2X,~,15X,'p',3X,'p',1X,2('r'),3X,'o',3X,'o',2X,'B',5X, &
        'B',2X,'A',5X,'A',4X,'Y',19X,~/ &
        2X,~,15X,'p',3X,'p',1X,'r',4X,'o',3X,'o',2X,'B',5X,'B', &
        2X,'A',5X,'A',4X,'Y',19X,~/ &
        2X,~,15X,4('p'),2X,'r',5X,3('o'),3X,6('B'),3X,'A',5X,'A', &
        4X,'Y',19X,~/ &
        2X,~,15X,'p',57X,~/ &
        2X,~,15X,'p',57X,~/ &
        2X,~,15X,'p',57X,~/ &
        2X,~,54X,'Copyright (C) 2004',1X,~/ &
        2X,75('~'))

! *****
! *                                     READING PARAMETERS FILE AND DATA FILES       *
! *                                                                              *
! *****
! *                                                                              *
! *                                     READING PARAMETERS                           *
! *                                                                              *
! * Program uses parameters those were previously saved in “Parabay.txt” file. These *
! * parameters and their brief explanations are given below.                    *
! *                                                                              *
! * CNDET      is the channel number for the overtopping detector data file      *
! * CNLOAD     is the channel number for the load cell data file                  *
! * LOADCAL    is the load cell calibration factor                               *
! * RUNAVF     is the number of data points required to smooth load cell data using *
! *             running average technique                                         *
! * FILMF      is the multiplication factor for the noise filter calculations      *
! * SDMF       is the standard deviation multiplication factor used for filter     *
! *             calculations                                                       *
! * DELA       is used to synchronize the delay between two channels. It incorporates *
! *             Tm as a multiplication factor                                       *
! * SPAR       is a function of Tm and helps to skip the data corresponding to the *
! *             oscillation in the overtopping tank that was caused by a volume of  *

```

*Appendix A1 – proBAY Codes*

---

```

! *          water coming into the overtopping tank          *
! * CHUTE    specifies the width of the overtopping collector chute (in millimetres) *
! * CHOBE    Time (in seconds) between the start of data collection and placing *
! *          the overtopping chute                          *
! * NOWA     is the number of waves that is going to be analysed using relevant *
! *          data files                                     *
! * SUBS     is a multiplication factor that incorporates Tm and was used to set a *
! *          time limit in between two subsequent events   *
! * AVPSD    is a factor to set a limit at mean plus standard deviation threshold. It *
! *          was used to identify overtopping events those were not recorded by *
! *          the overtopping detector                     *
! * PERC     is the percentage of the data points in between two events that are *
! *          continuously below/above the threshold        *
! * LIMOV    is the limit for the minimum acceptable overtopping volume          *
! * SPANA    is a factor to find percentage of the total number of data points *
! *          between two detected events and to set a limit against next possible *
! *          event close to first one                     *
! * SPANB    is a factor to find percentage of the total number of data points *
! *          between two detected events and to set a limit against a possible new *
! *          event to be recorded close to next one       *
! *          *
! *****

```

```

OPEN(UNIT=5,FILE='parabay.txt')
READ(5,*) CNDET
READ(5,*) CNLOAD
READ(5,*) LOADCAL
READ(5,*) RUNAVF
READ(5,*) FILMF
READ(5,*) SDMF
READ(5,*) DELA
READ(5,*) SPAR
READ(5,*) CHUTE
READ(5,*) CHOBE
READ(5,*) NOWA
READ(5,*) SUBS
READ(5,*) AVPSD
READ(5,*) PERC
READ(5,*) LIMOV
READ(5,*) SPANA
READ(5,*) SPANB

```

```

! *****
! *
! * Next statement gives a warning message to the user to make sure parameters in the *
! * "PARAMETERS.TXT" file are checked. *
! *
! *****

```

```

WRITE(1,21)
21  FORMAT(/24X,'***  !!! WARNING !!!  ***/35X,9(=)// &
      15X,'Did you check PARAMETERS in the "parabay.txt" file?')
WRITE(1,*)
WRITE(1,*)

```

```
! *****
! *
! *          READING OVERTOPPING DETECTOR DATA FILE          *
! *
! * Next statements are to read overtopping detector data file. These data files are *
! * created by HR Waves software, so written in a unique format. Only required *
! * information was collected from the header part and remaining lines were skipped. *
! * User have to input full overtopping detector file name. *
! *
! *****
```

```
      PRINT*, 'Please type the OVERTOPPING DETECTOR file name:'
      READ(1,100) INDET
100  FORMAT (A)
      OPEN(UNIT=10,FILE=INDET)
```

```
! Next statement is to refine the header part by extracting the inconvenient part
      DO I=1,9
        READ(10,100)DUMMY
      ENDDO
```

```
! NDATA is the total number of data points in the data file
      READ(10,*)NDATA
```

```
! TICS is the scanning interval information
      READ(10,*)TICS
```

```
! Next statement refining the header part once again by extracting the inconvenient part
      DO I=1,8
        READ(10,100)DUMMY
      ENDDO
```

```
! Reading the overtopping detector data
      DO I=1,NDATA
        READ(10,*)SIGN(CNDET,I)
      ENDDO
      CLOSE (10)
```

```
! *****
! *
! *          READING LOAD CELL DATA FILE          *
! *
! * Next statements are to read load cell data file. User have to input full load cell data *
! * file name. Since they have the same header format and relevant information was *
! * obtained from the overtopping detector data file, whole header of the load cell data *
! * file was skipped. *
! *
! *****
```

```
      PRINT*, 'Please type the LOAD CELL file name:'
      READ(1,100) INLOAD
      OPEN(UNIT=20,FILE=INLOAD)
```

```

! Refining the header part by extracting the inconvenient part
  DO I=1,19
    READ(20,100)DUMMY
  ENDDO

! Reading the data for load cell values
  DO I=1,NDATA
    READ(20,*)SIGN(CNLOAD,I)
  ENDDO
  CLOSE (20)

! *****
! *
! *          READING TEST INFORMATION          *
! *
! * Next statement asks user to input the wave period, Tm (in seconds). *
! *
! *****

  PRINT*, 'Please type the Wave Period (Tm) value:'
  READ(1,*) TM

! *****
! *
! *          PRELIMINARY CALCULATIONS          *
! *
! * This section does some preliminary calculations. Scanning interval value is *
! * corrected so the frequency of the recorded data can be found. Subsequent event *
! * time limit was set to ignore the second recorded overtopping event if two recorded *
! * within a certain period of time. Overtopping water recorded by the overtopping *
! * detector needs some time to arrive into the overtopping tank and this time delay has *
! * been synchronised by DELAY. Water coming into the overtopping tank causes an *
! * oscillation on the water surface which influences the load cell traces. This is *
! * considered as noise and some of the data points are skipped to exclude this *
! * misleading information. Data converted into an array and corresponding time array *
! * has also been saved onto temporary memory. Finally, load cell calibration factor *
! * has been adjusted to obtain results with required units. *
! *
! *****

! Scanning interval correction
  TICS=TICS/10000.0

! FREQ is the frequency of the recorded data
  FREQ=1.0/TICS

! Subsequent event time limit
  SETL=SUBS*TM/TICS+1

! Synchronizing the DELAY between two channels
  DELAY=DELA/TICS+1

! SPARE is to skip some data points to exclude the noise in the Load Cell signal after an
! individual event

```

Appendix A1 – proBAY Codes

---

```
SPARE=SPAR*TM/TICS+1

! Data converted into Real Time array
DO I=1,NDATA
  TIME(I)=REAL(I)/FREQ
ENDDO

! Load Cell calibration
DO I=1,NDATA
  SIGN(CNLOAD,I)=SIGN(CNLOAD,I)*LOADCAL
ENDDO

! *****
! *
! *                               RUNNING AVERAGE                               *
! *
! * Noise in the load cell data will be filtered using "Running Average" technique. *
! * Smoothed load cell data then converted into an array for further analysis.   *
! *
! *****

RUNAV=RUNAVF*TM/TICS+1
DO I=1,NDATA-RUNAV
  SMOLC(I)=0.0
  DO J=1,RUNAV
    SMOLC(I)=SIGN(CNLOAD,(J+I-1))+SMOLC(I)
  ENDDO

! Smoothed Load Cell data "SMOLC"
SMOLC(I)=SMOLC(I)/REAL(RUNAV)
ENDDO

! *****
! *
! *                               NUMBERS OF DATA POINTS                               *
! *
! * Depending on the requirements, program may be run to analyse smaller number *
! * of waves. TIREQ second needed to run NOWA waves and number of data         *
! * points required to analyse NOWA waves is calculated by dividing TIREQ to TICS. *
! * There was a gap (30 seconds for SHADOW tests) between the start of data      *
! * collection and placing the overtopping chute. Therefore, data corresponding to *
! * this gap has to be skipped. CHDATA finds how many data points to be         *
! * removed from the data files. SECURE sets another limit and Data points      *
! * corresponding to five waves were subtracted, to prevent the program reading data *
! * from the very end of the record. Number of data points available to analyse is *
! * then calculated.
! *
! *****

! "TIREQ" is the time required to run "NOWA" number of waves
TIREQ=TM*NOWA

! "NDREQ" is the number of data points required to analyse NOWA number of waves
NDREQ=TIREQ/TICS
```

*Appendix A1 – proBAY Codes*

---

```
! "CHDATA" is the number of data points that needed to be chopped from the beginning
! of the data set
  CHDATA=CHOBE/TICS+1

! Data points corresponding to five waves were subtracted, to prevent the program reading
! data from the very end of the record
  SECURE=5*TM/TICS

! "NDAVA" is the total number of data points available
  NDAVA=NDATA-CHDATA-SPARE-SECURE

! "CHDATA2" is the number of data points needed to be chopped from the end section of
! the data set. "CHDATA2" is only informative and not used at any part of this program.
  CHDATA2=NDATA-CHDATA-NDAVA
  chdata2=chdata2

! *****
! *
! *                               WARNING MESSAGE
! *
! * A warning message will be given to the user if NDAVA number of data points are
! * not enough to complete analysis for NOWA number of waves. Program will
! * calculate the possible number of waves that could be analysed with current
! * parameter settings and wave conditions and suggest user to change NOWA
! * parameter accordingly.
! *
! *****
  IF(NDAVA.LT.NDREQ)THEN

! Next section is to give reason why the program failed to proceed
  WRITE(1,*)
  WRITE(1,*)
  WRITE(1,*)
  WRITE(1,*)
  WRITE(1,41)
41  FORMAT(24X,'***  !!! CAUTION !!!  ***')
  WRITE(1,*)
  WRITE(1,*)
  WRITE(1,51) NOWA
51  FORMAT(9X,'Not enough DATA SUPPLIED to provide an analysis for',&
  I5,1X,'waves.')
```

! Next, how many waves can be analysed under these conditions are calculated

```
  POWA=NDAVA*TICS/TM
  WRITE(1,61) POWA
61  FORMAT(13X,'Only',I5,&
  1X,'waves can be analysed under these conditions.')
```

```
  WRITE(1,71)
71  FORMAT(5X,&
'Please revise your parameters in "parabay.txt" and execute again!',4(/))
  GOTO 2840
  ELSE
  GOTO 101
```

```

ENDIF

101 CONTINUE

! *****
! *
! *                               DATA HANDLING
! *
! * Both the overtopping detector and the load cell signals are edited, irrelevant parts
! * are excluded, required parts are converted into arrays and backed-up into text files.
! *
! *****
! The overtopping detector signal is chopped
  DO I=1,NDREQ
    CHOPDET(I)=SIGN(CNDET,I+CHDATA)
! CHOPDET2 was created just for the threshold calculations
    CHOPDET2(I)=SIGN(CNDET,I+CHDATA)
  ENDDO

! The original load cell signal is chopped
  DO I=1,NDREQ
    CHOPLOAD(I)=SIGN(CNLOAD,I+CHDATA)/LOADCAL
  ENDDO

! The smoothed load cell signal is chopped
  DO I=1,NDREQ
    CHOPSMOLC(I)=SMOLC(I+CHDATA)/LOADCAL
  ENDDO

! Chopped smoothed load cell signal saved in a comma separated value (CSV) file
  OPEN(UNIT=16, FILE='CHOPSMOLC.CSV')
  DO I=1,NDREQ
    WRITE(16,*)I,',',CHOPSMOLC(I)
  ENDDO
  CLOSE(16)

! Next statement is to back up the chopped load cell and chopped overtopping detector
! data in "CONDITIONED.CSV" file
  OPEN(UNIT=7, FILE='CONDITIONED.CSV')
  DO I=1,NDREQ
    WRITE(7,*)I,',',CHOPDET(I),',',CHOPLOAD(I)
  ENDDO
  CLOSE(7)

! *****
! *
! *                               NOISE FILTER
! *                               (for the overtopping detector signal)
! *
! * Noise in the overtopping detector signal has been minimised in the next section.
! * Mean plus "x" times the standard deviation technique was used for this purpose.
! *
! *****

```



*Appendix A1 – proBAY Codes*

---

```

! * SDMF parameter was employed for the value of "x". Mean of the whole data is *
! * found first. Standard deviation of the data then multiplied by the factor (SDMF) *
! * and added to the value of standard deviation. Any data value higher than that limit *
! * is equated to that value. In other words, tails of the spikes are chopped. This *
! * process repeated three times and the differences between each process recorded as *
! * DIFF1 and DIFF2, respectively. Filter multiplication factor (FILMF) is employed *
! * to define the sensitivity of the filter. Iterations are stopped if the value of DIFF2 is *
! * less than the value of DIFF1 divided by FILMF. Otherwise, new set of DIFF *
! * values are found by iterations. Once the required condition is satisfied, threshold *
! * value is set as a noise filter and spikes exceeding that limit is counted as an *
! * overtopping event. *
! * *
! *****

```

```

    ITERATION=1
    DETAV=0.0
    STDEV=0.0
    SUM=0.0
    SS=0.0
    MPXSD=0.0

```

```

! WARNING
! Back-up data was used for the security of the original data

```

```

! Statistics for the CHOPDET2 array was found in the next section
! Average of the CHOPDET2
    DO 120 I=1,NDREQ
120  SUM=SUM+CHOPDET2(I)
    DETAV=SUM/NDREQ

```

```

! Sum of squares of the CHOPDET2
    DO 130 I=1,NDREQ
130  SS=SS+(CHOPDET2(I)-DETAV)**2

```

```

! Standard deviation of the CHOPDET2
    STDEV=SQRT(SS/(NDREQ-1))

```

```

! Mean Plus SDMF times the Standard Deviation
    MPXSD=DETAV+SDMF*STDEV
    MPXSD1=MPXSD
    MPXSD2=MPXSD

```

```

! Data values higher than MPXSD are equated to MPXSD. Therefore, maximum value in
the data set became MPXSD.
! Also, iterations are counted
140  ITERATION=ITERATION+1

```

```

    DO 150 I=1,NDREQ
150  IF(CHOPDET2(I).GT.MPXSD2)CHOPDET2(I)=MPXSD2

    DETAV2=0.0
    STDEV2=0.0
    SUM2=0.0
    SS2=0.0

```

```
MPXSD2=0.0

! Second iteration in CHOPDET2 statistics (2)
! Average of the CHOPDET2 (2)
DO 160 I=1,NDREQ
160 SUM2=SUM2+CHOPDET2(I)
DETAV2=SUM2/NDREQ

! Sum of squares of the CHOPDET2 (2)
DO 165 I=1,NDREQ
165 SS2=SS2+(CHOPDET2(I)-DETAV2)**2

! Standard deviation (2)
STDEV2=SQRT(SS2/(NDREQ-1))

! Mean Plus SDMF time the Standard Deviation (2)
MPXSD2=DETAV2+SDMF*STDEV2

! DIFF1 is the difference between the first and the second MPXSD values
DIFF1=MPXSD1-MPXSD2

! Data values higher than MPXSD2 are equated to MPXSD2. Therefore, maximum value
in the data set became MPXSD2.

DO 210 I=1,NDREQ
210 IF(CHOPDET2(I).GT.MPXSD2)CHOPDET2(I)=MPXSD2

DETAV3=0.0
STDEV3=0.0
SUM3=0.0
SS3=0.0
MPXSD3=0.0

! Third iteration in CHOPDET2 statistics (3)
! Average of the CHOPDET2 (3)
DO 220 I=1,NDREQ
220 SUM3=SUM3+CHOPDET2(I)
DETAV3=SUM3/NDREQ

! Sum of squares of the CHOPDET2 (3)
DO 230 I=1,NDREQ
230 SS3=SS3+(CHOPDET2(I)-DETAV3)**2

! Standard deviation (3)
STDEV3=SQRT(SS3/(NDREQ-1))

! Mean Plus SDMF times the Standard Deviation (3)
MPXSD3=DETAV3+SDMF*STDEV3

! Difference between the second and the third MPXSD value
DIFF2=MPXSD2-MPXSD3

! Changing initial MPXSD values for the next possible iteration
MPXSD1=MPXSD2
```

```

! Check for the differences in threshold width
  IF(DIFF2.GT.(DIFF1/FILMF))GOTO 140

! Noise Filter value
  FILTER=MPXSD3

! Data falling below the filter is backed-up in a file "CONDITIONED2.CSV".
  OPEN(UNIT=17, FILE='CONDITIONED2.CSV')
  DO I=1,NDREQ
    WRITE(17,*)CHOPDET2(I)
  ENDDO
  CLOSE(17)

! *****
! *
! *              OVERTOPPING COUNTER              *
! *              (utilizing the overtopping detector signal only!) *
! *
! * The overtopping detector data has been investigated to find overtopping events. *
! * Data exceeding the filter line is counted as an overtopping event. The number *
! * of overtopping events is assigned to "NEVENT". Time in between two consecutive*
! * events is checked and the second signal which was recorded as an overtopping *
! * signal is skipped. SETL2 was used to check for the possible early-overtopping *
! * event. *
! *
! *****
! Number of overtopping event "NEVENT" have calculated by means of
! overtopping detector signal only.
  NEVENT=0
  FLAG=0
  PLAG=0
  SLAG=0
  DO 200 I=2,NDREQ-DELAY-1

! Skip the second event if two progressive events occur within a certain time limit (SETL
! has to be exceeded for a new event).
  SAY=0
  IF(NEVENT.LT.1)GOTO 202
  IF((I-EVENTIME(NEVENT)).LT.SETL)GOTO 180
202      IF((CHOPDET(I-1).LT.FILTER).AND.(CHOPDET(I-
1).LT.CHOPDET(I)))FLAG=1
      IF(CHOPDET(I).GT.FILTER)PLAG=1

! Next section is to check the very beginning of the data for an early overtopping (this is
! skip the subsequent event time limit barrier)
  IF(NEVENT.LT.1)THEN
    IF(FLAG.GT.0.AND.PLAG.GT.0)THEN
      SETL2=I-1
      DO J=1,SETL2
        IF(CHOPDET(I-J).LT.FILTER)SAY=SAY+1
      ENDDO

```

*Appendix A1 – proBAY Codes*

---

```

        ENDIF
        IF(SAY.GT.(SETL2-1))SLAG=1
        GOTO 205
    ENDIF

    IF(FLAG.GT.0.AND.PLAG.GT.0)THEN
        DO J=1,SETL
            IF(CHOPDET(I-J).LT.FILTER)SAY=SAY+1
        ENDDO
    ENDIF

    IF(SAY.GT.(SETL-1))SLAG=1
205   IF(FLAG.LT.1)GOTO 180
        IF(PLAG.LT.1)GOTO 180
        IF(SLAG.LT.1)GOTO 180

! If all conditions are satisfied, next statement counts a new overtopping event
        IF(FLAG.GT.0.AND.PLAG.GT.0.AND.SLAG.GT.0)THEN
            NEVENT=NEVENT+1

! Next statement converts event counter into an array
            EVENT(I)=NEVENT

! Next statement is to record the data point that corresponds to an overtopping event into
! the array "EVENTIME"
            EVENTIME(EVENT(I))=I
        ELSE
            GOTO 180
        ENDIF

180   IF(CHOPDET(I).LT.FILTER)GOTO 200
        FLAG=0
        PLAG=0
        SLAG=0

200   CONTINUE

! *****
! *
! *           OVERTOPPING COUNTER cont.
! *      (utilizing the load cell signal to assist overtopping detector signal!)
! *
! * Because of 3D effect, some waves were overtopped without being recorded. Next
! * section utilizes the load cell signal to identify those overtopping events that are not
! * recorded by the overtopping detector.
! *
! * The load cell data has been traced to see if there is any radical increase in the data.
! * Threshold for these checks varies and being calculated depending on the position of
! * the mean being exceeded. If this happens within the first interval (within the first
! * SPANA percent of the SPAN number of data points), AVPSD times the standard
! * deviation of the span was subtracted from the mean and threshold fixed at that level.
! * If overtopping is found in the last interval (after SPANB percent of the SPAN
! * number of data points) then, threshold was fixed at mean plus AVPSD times the

```

*Appendix A1 – proBAY Codes*

---

```
! * standard deviation of the span level. If the mean of the span is exceeded outside *
! * these limits, then mean itself was set as a threshold. Lastly, continuation of the *
! * signal was checked. This check was applied to see whether it was a noise in the *
! * load cell data or data remained below the mean until exceeding the mean and *
! * remained above the mean for the rest of the span. If all these conditions are *
! * satisfied, then, an additional overtopping event and its corresponding time are *
! * assigned. *
! * *
! *****
```

```
NEVENT2=NEVENT
290 SECOND=0
```

```
DO 300 I=1,NEVENT2+1
  IF(SECOND.GT.0) GOTO 300
  ILK=0
  SON=0
  SPAN=0
  AVERA=0.0
  SUMA=0.0
  COUNT=0
  PLAG=0
  SLAG=0
  TRAK=0
  ZLAG=0
  SUMAS=0.0
  SDINT=0.0
  MINLIM=0
  MAXLIM=0
  ONC=0
  AVERAL=0
  HOPA=0
  HOPB=0
  FLAG=0
```

```
! Span between two recorded overtopping events is found next
  ILK=EVENTIME(I-1)+DELAY+1+SPARE
  IF(I.LE.NEVENT2)THEN
    SON=EVENTIME(I)-1-SPARE
  ELSE
    SON=NDREQ-1
  ENDIF
  SPAN=SON-ILK
```

```
! If the span is not long enough (less than two SPARE number of data points) then no
! overtopping is counted within that span.
  IF(SPAN.LT.2*SPARE)GOTO 300
```

```
! Intervals of the span are found in the two next lines
  MINLIM=SPAN*SPAN A
  MAXLIM=SPAN*SPAN B
```

```
! Mean of the span is found next
  DO J=ILK,SON
```

*Appendix A1 – proBAY Codes*

---

```
        SUMA=SUMA+CHOPSMOLC(J)
        COUNT=COUNT+1
    ENDDO
    AVERA=SUMA/COUNT

! Standard deviation of the span is found next
    DO J=ILK,SON
        SUMAS=SUMAS+(CHOPSMOLC(J)-AVERA)**2
    ENDDO
    SDINT=SQRT(SUMAS/COUNT)

! Position of the data point where the mean is being exceeded is found in the next stage
    DO 350 K=ILK, SON
        FLAG=0

    IF((CHOPSMOLC(K).LT.AVERA).AND.(CHOPSMOLC(K+1).GT.AVERA))THEN
        FLAG=1
        ONC=K-ILK
    ELSE
        GOTO 350
    ENDIF

! First check if the overtopping happened within the first interval
        IF(FLAG.GT.0.AND.ONC.LT.MINLIM)AVERAL=AVERA-SDINT*AVPSD

! Second check if the overtopping happened after the first interval

    IF(FLAG.GT.0.AND.ONC.LT.MAXLIM.AND.ONC.GT.MINLIM)AVERAL=AVERA

! Third check if the overtopping happened within the last interval
        IF(FLAG.GT.0.AND.ONC.GT.MAXLIM)AVERAL=AVERA+SDINT*AVPSD

350    CONTINUE

        DO 400 K=ILK,SON

            IF(ZLAG.GT.0)GOTO 400

! Continuation of the data has been checked in the next stage
            IF(TRAK.GT.0)GOTO 405

    IF((CHOPSMOLC(K).LT.AVERAL).AND.(CHOPSMOLC(K+1).GT.AVERAL))THEN
        TRAK=1
    ELSE
        GOTO 400
    ENDIF

        IF(TRAK.GT.0)THEN
            DO L=ILK,K
                IF(CHOPSMOLC(L).LT.AVERAL)PLAG=PLAG+1
            ENDDO
        ELSE
            GOTO 400
        ENDIF
```

```
IF(PLAG.GT.(K-ILK)*PERC)HOPA=1

405  IF(TRAK.GT.0.AND.HOPA.GT.0)THEN
      DO L=K+1,SON
          IF(CHOPSMOLC(L).GT.AVERAL)SLAG=SLAG+1
      ENDDO
      ELSE
          GOTO 400
      ENDIF

      IF(SLAG.GT.(SON-K+1)*PERC)HOPB=1

      IF(HOPA.GT.0.AND.HOPB.GT.0)THEN
          NEVENT2=NEVENT2+1
          EVENTIME(NEVENT2)=K-DELAY
          SECOND=1
          ZLAG=1
      ELSE
          GOTO 410
      ENDIF
410  SLAG=0
      PLAG=0
      HOPA=0
      HOPB=0
      TRAK=0
400  CONTINUE

300  CONTINUE

! This section is to re-sort the event times
830  FLAG=0
      DO 840 I=2,NEVENT2
          IF(EVENTIME(I-1).LE.EVENTIME(I))GOTO 840
          TEMP1=EVENTIME(I)
          EVENTIME(I)=EVENTIME(I-1)
          EVENTIME(I-1)=TEMP1
          FLAG=1
840  CONTINUE
      IF(FLAG.EQ.1)GOTO 830

! Next statement loops the load cell check for another possible overtopping event
! happening within the same span
      IF(SECOND.GT.0)GOTO 290

! Two consecutive events within a limited period of time will be checked once again
930  DO 940 I=1,NEVENT2
940  EVENTIMETMP(I)=EVENTIME(I)

      SYC=0
      DO 900 I=2,NEVENT2
          IF((EVENTIME(I-1)+SETL).GT.EVENTIME(I))SYC=1
          EVENTIMETMP(I)=EVENTIME(I+SYC)
900  CONTINUE
```

```

NEVENT2=NEVENT2-SYC

DO 955 I=1,NEVENT2
955  EVENTIME(I)=EVENTIMETMP(I)

      IF(SYC.GT.0)GOTO 930

! *****
! *
! *              INDIVIDUAL OVERTOPPING VOLUMES
! *
! * Individual overtopping volumes are calculated in next section. Average of the span
! * corresponding to data before the overtopping is found first. Average of the span
! * corresponding to data after the overtopping is found next. The difference between
! * these values is assigned to individual overtopping volumes.
! *
! *****

      NEVENT3=NEVENT2
1099  TOP=0
      DO 1300 I=1,NEVENT3

! Reset counters...
      BEFORE=0.0
      AFTER=0.0
      AFTER2=0.0
      COUNTER1=0
      COUNTER2=0
      COUNTER3=0

! This section is to calculate number of data points to take the average
! "BEFORE" is the average of the lower bound
      DO J=EVENTIME(I-1)+DELAY+1,EVENTIME(I)+DELAY-1
          BEFORE=BEFORE+CHOPLOAD(J)/1000
          COUNTER1=COUNTER1+1
      ENDDO
      BEFORE=BEFORE/COUNTER1

! "AFTER" is the average of the upper bound
      IF(I.GE.NEVENT3)GOTO 1250

      DO J=EVENTIME(I)+DELAY+1,EVENTIME(I+1)+DELAY-1
          AFTER=AFTER+CHOPLOAD(J)/1000
          COUNTER2=COUNTER2+1
      ENDDO
      AFTER=AFTER/COUNTER2

1250  CONTINUE

! "AFTER2" is the average of the last span
      IF(I.LT.NEVENT3)GOTO 1260
      DO J=EVENTIME(I)+DELAY+1,NDREQ
          AFTER2=AFTER2+CHOPLOAD(J)/1000

```



Appendix A1 – proBAY Codes

---

```
COUNTER3=COUNTER3+1
ENDDO
AFTER2=AFTER2/COUNTER3

1260  CONTINUE

! Individual overtopping volumes are found next
  IF(I.GT.NEVENT3-1)GOTO 1270
  TOP=TOP+1
  IND(TOP)=TOP
  BEF(TOP)=BEFORE
  AFT(TOP)=AFTER
  VOL(TOP)=AFTER-BEFORE

1270  IF(I.LE.NEVENT3-1)GOTO 1280
  TOP=TOP+1
  IND(TOP)=TOP
  BEF(TOP)=BEFORE
  AFT(TOP)=AFTER2
  VOL(TOP)=AFTER2-BEFORE

1280  CONTINUE

1300  CONTINUE

! *****
! *
! *      APPROVED INDIVIDUAL OVERTOPPING VOLUMES      *
! *
! * Individual overtopping volumes are checked once again for a possible negatively
! * calculated overtopping volumes. They are taken out and approved individual overtopping
! * volumes are ranked in the next section.
! *
! *****
! This section is to check negative volumes and to eliminate them.
  SYC=0
  DO 1500 I=1,NEVENT3
    IF(VOL(I).LT.LIMOV)SYC=1
    EVENTIMETMP(I)=EVENTIME(I+SYC)
    BEFTMP(I)=BEF(I+SYC)
    AFTTMP(I)=AFT(I+SYC)
1500  CONTINUE

  NEVENT3=NEVENT3-SYC

  DO I=1,NEVENT3
    EVENTIME(I)=EVENTIMETMP(I)
    BEF(I)=BEFTMP(I)
    AFT(I)=AFTTMP(I)
  ENDDO

! This section re-calculates individual overtopping volumes (if any negative volume has
! been identified)
```



*Appendix A1 – proBAY Codes*

---

```
WRITE(40,*)',,,, '(s)',,,, '(lt)'
DO I=1,NEVENT3
  WRITE(40,*)IND(I),,,, TIME(EVENTIMER(I)),,,, VOLR(I)
ENDDO
```

! The total Overtopping Volume, "TOV", is found by adding individual ones

```
TOV=0.0
DO I=1,NEVENT3
  TOV=TOV+VOL(I)
ENDDO
```

! Next section calculates the Mean Overtopping Volume, "MOV"

```
MOV=0.0
MOV=TOV/NEVENT3
```

! Next statement calculates the Mean Overtopping Rate "MOR"

```
MOR=0.0
MOR=TOV/(TIME(NDREQ)*CHUTE/1000)
```

! Output of the program is written in "ISSUE.CSV" file

```
1700 OPEN(UNIT=50, FILE='ISSUE.CSV')
WRITE(50,*)'Detector File Name = ',,,,INDET
WRITE(50,*)'Load Cell File Name = ',,,,INLOAD
WRITE(50,*)'Chute Width (mm) = ',,,,CHUTE
WRITE(50,*)'Total data sampling time (s) = ',,,,TIME(NDATA)
WRITE(50,*)'Analysis start time (s) = ',,,,TIME(CHDATA)
WRITE(50,*)'Analysis finish time (s) = ',,,,TIME(CHDATA+NDREQ)
WRITE(50,*)'Total analysis time (s) = ',,,,TIME(NDREQ)
WRITE(50,*)'Number of waves analysed = ',,,,NOWA
WRITE(50,*)'Noise filter threshold = ',,,,FILTER
WRITE(50,*)'Number of Overtopping = ',,,,NEVENT3
WRITE(50,*)'Total Overtopping Volume (lt) = ',,,,TOV
WRITE(50,*)'Maximum Overtopping Volume (lt) = ',,,,VOLR(1)
WRITE(50,*)'Mean Overtopping Volume (lt) = ',,,,MOV
WRITE(50,*)'Mean Overtopping Rate (lt/s.m) = ',,,,MOR
```

! Next section displays the output of the program on the screen and informs user that the results are also saved in "TIME.CSV", "RANKED.CSV" and "ISSUE.CSV" files

```
DO 2500 I=1,30
2500 WRITE(1,*)
2610 FORMAT(29X,'proBAY ANALYSIS OUTPUT'/10X,60('~'))
WRITE(1,2610)
WRITE(1,*)' Ovtp Detector file name = ',INDET
WRITE(1,*)' Load Cell file name = ',INLOAD
WRITE(1,*)' Chute size = ',CHUTE,' ',&
' (mm)'
WRITE(1,*)' Total data sampling time = ',TIME(NDATA),&
' (s)'
WRITE(1,*)' Analysis start time = ',TIME(CHDATA),&
' (s)'
WRITE(1,*)' Analysis finish time = ',&
TIME(CHDATA+NDREQ),' (s)'
WRITE(1,*)' Total analysis time = ',TIME(NDREQ),&
' (s)'
```

*Appendix A1 – proBAY Codes*

---

```
WRITE(1,*)      Number of waves analysed =',NOWA
WRITE(1,*)      Noise filter threshold =',FILTER
WRITE(1,*)      Number of Ovtp Waves =',NEVENT3
WRITE(1,*)      Total Ovtp Volume =',TOV,' (lt)'
WRITE(1,*)      Max Individual Ovtp Volume =',&
VOLR(1),' (lt)'
WRITE(1,*)      Mean Ovtp Volume =',MOV,' (lt)'
WRITE(1,*)      Mean Ovtp Rate =',&
MOR,' (lt/s.m)'
WRITE(1,*)
WRITE(1,2810)
2810  FORMAT(11X,&
        'TIME.CSV, RANKED.CSV and ISSUE.CSV files have been updated!'/&
        10X,60('~'))
2840  WRITE(1,*)
        WRITE(1,2850)

! Next statement confirms the end of process
2850  FORMAT(/31X,'PROCESS COMPLETED !')
        WRITE(1,*)
        WRITE(1,2870)

! Lastly, program asks user to press any key to terminate the program
2870  FORMAT(27X,'Press ANY KEY to terminate!')
        CALL GET_KEY@(K)
        END
```

---

## Appendix - A2. Macro codes of “Gamma Function - Interpolation.xls”

---

```
Sub GammaFcn()
'
' *****
' *
' *   Codes for this macro program were written by Ibrahim Bay on 14/07/2004
' *
' *****
' *
' * This macro program was written to help  $V_{bar}$  calculations for the overtopping data
' * analysis. It has been shown that the slope of the individual overtopping volume
' * distribution is  $\beta$  and the intercept is  $V_{char}$ . They must have been copied to the
' * relevant spaces provided in Sheet2.  $\beta$  values, will automatically be copied to the
' * appropriate cell in Sheet1. Knowing that  $n = 1 + 1/\beta$ ,  $\Gamma(n)$  is found accordingly
' * by using simple integration. Then, the value of  $\Gamma(n)$  is assigned to a cell. It has
' * also been copied to another cell in the next spreadsheet. Then,  $V_{bar}$  was calculated
' * by multiplying  $\Gamma(n)$  with  $V_{char}$ .
' *
' *****
' Next statement is to activate the sheet where theoretical Gamma function data is
  Sheet1.Activate

  b = Cells(5, 3)
  n = 1 / b + 1
  Cells(5, 7) = n

' Finding Gamma function return for “n” (Gn) by using simple integration
  Range("C5").Select

  i = 7

  Do
    i = i + 1
    If Cells(i, 27) <= n And Cells(i + 1, 27) >= n Then
      x1 = Cells(i, 27)
      x3 = Cells(i + 1, 27)
      y1 = Cells(i, 28)
      y3 = Cells(i + 1, 28)
      dx31 = x3 - x1
      dn1 = n - x1
      dy31 = y3 - y1
      dGn1 = dn1 * dy31 / dx31
      Gn = y1 + dGn1
    End If
  Loop
```

*Appendix A2 – Macro Codes for “Gamma Function- Interpolation.xls”*

---

```
Exit Do
End If
Loop

' Next statement is to dedicate the value of Gn to a cell
Range("G8").Select
ActiveCell.Value = Gn
Range("C5").Select

Sheet2.Activate

End Sub
```

---

## Appendix - A3. Macro codes of “LS – LAD Comparison.xls”

---

```
'
' *****
' *
' *      Codes for this macro program were written by Ibrahim Bay on 02/07/2004
' *
' *****
' *
' * These macro codes are written to help analysing the proBAY results. Macros help
' * to compare the Least Squares (LS) fit with the Least Absolute Deviation (LAD) fit.
' * Data in the second page of “proBAY Results – Graphical Expression.xls” has to be
' * copied to the first data page on this workbook to start. A click on the “Perform”
' * button will do most of the calculations. The total number of overtopping events and
' *  $V_{mean}$  are confirmed. Number of  $[V_{\#} \geq V_{mean}]$  is calculated. Slope, intercept, and
' *  $R^2$  values are found by using both all data points and using the data considering
' *  $[V_{\#} \geq V_{mean}]$ .  $V_{char}$  values are calculated. It asks user to copy results of the LAD fit
' * values to the relevant cells. Once operations are completed, 8 other tabs containing
' * graphs are updated automatically. 4 of these are  $\ln V_{\#}$  against
' *  $\ln \{ \ln (\text{Prob}[V \geq V_{\#}])^{-1} \}$  and the other 4 are to plot the probability distribution of
' * individual overtopping volumes ( $V_{\#}$  vs  $\text{Prob}[V \geq V_{\#}]$ ) together with the theoretical
' * Weibull distribution. Results are copied to the “Analysis Summary.xls” file. It
' * saves the “Analysis Summary.xls” file every time whenever the transfer is
' * performed. It saves results with a formatted file name to the dedicated place on the
' * hard disk.
' *
' *****
' Macro commands for the first button
Sub Perform()

    Dim count2 As Integer
' Informs if there is no available data
    If (IsEmpty(Cells(1, 2)) Or IsEmpty(Cells(23, 6))) Then
        MsgBox "There is NO DATA to PERFORM!"
        GoTo 999
    End If

    c1 = Range("i23")
    c2 = Range("k23")
    c3 = Range("m23")
    c4 = Range("n23")
    c5 = Range("t23")
    If (c1 > 0 Or c2 > 0 Or c3 > 0 Or c4 > 0 Or c5 > 0) Then

' If certain cells are occupied, message informs user to clear the worksheet and to click on
```

```
' perform button again
  MsgBox "Forms need to be CLEARED and made ready for the next PERFORM!"
  GoTo 999
End If

' Formats and finds surf similarity parameter Xp
Range("b6:b7").Select
Selection.NumberFormat = "0.000"
TP = Cells(4, 2)
Pi = 3.14159265358979
lop = 9.81 * TP * TP / (2 * Pi)
tanalfa = 1 / Cells(5, 2)
xp = tanalfa / Sqr((Cells(3, 2) / lop))
Range("t23").Select
Selection.NumberFormat = "0.000"
ActiveCell.FormulaR1C1 = xp

' Counts the total number of overtopping events and assigns it to a cell
Range("d23").Select
Range(Selection, Selection.End(xlDown)).Select
Count = Selection.Count
Range("k1").Select
ActiveCell.FormulaR1C1 = Count

' Change values of volume from litres to  $m^3/m$ 
isim1 = "Volume (lt)"
isim2 = Cells(22, 4)
If (isim1 = isim2) Then
Range("r23").Select
ActiveCell.FormulaR1C1 = "=RC[-14]/(R10C2/1000)/1000"
ActiveCell.Offset(Count - 1, 0).Select
Range(Selection, Selection.End(xlUp)).Select
Selection.FillDown
Selection.copy
Range("d23").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
  False, Transpose:=False
Application.CutCopyMode = False
Range("r23").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Clear
Selection.End(xlUp).Select
Selection.copy
Range("d22").Select
ActiveSheet.Paste

' Converts VTOT, VMAX, VMEAN, Q from litres to  $m^3$ 
VTOT = Cells(18, 2)
VMAX = Cells(19, 2)
VMEAN = Cells(20, 2)
Q = Cells(21, 2)
VTOT = VTOT / 1000 / (Cells(10, 2) / 1000)
```



```
VMAX = VMAX / 1000 / (Cells(10, 2) / 1000)
VMEAN = VMEAN / 1000 / (Cells(10, 2) / 1000)
Q = Q / 1000 / (Cells(10, 2) / 1000)
Cells(18, 2) = VTOT
Cells(19, 2) = VMAX
Cells(20, 2) = VMEAN
Cells(21, 2) = Q
Range("b18:b21").Select
Selection.NumberFormat = "0.000000"
```

' Finds corrected  $\ln[V_{\#}]$  values

```
Range("f23").Select
ActiveCell.FormulaR1C1 = "=LN(RC[-2])"
Range(Selection, Selection.End(xlDown)).Select
Selection.FillDown
Selection.Copy
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Application.CutCopyMode = False
```

End If

' Finds  $V_{mean}$

```
i = 22
Sum = 0
total = Count + i
10 i = i + 1
Sum = Sum + Cells(i, 4)
If i < total Then GoTo 10
aver = Sum / Count
Range("K2").Select
ActiveCell.Value = aver
```

' Finds number of overtopping events for  $V_{\#} \geq V_{mean}$

```
count2 = 0
i = 22
Do
    i = i + 1
    If i = total Then Exit Do
    If Cells(i, 4) < aver Then Exit Do
    If Cells(i, 4) > aver Then count2 = count2 + 1
Loop
Range("k3").Select
ActiveCell.FormulaR1C1 = count2
```

' Copies if  $V_{\#} \geq V_{mean}$

```
Range("d23").Select
If (ActiveCell.Value > aver) Then
ActiveCell.Offset(0, 7).Activate
ActiveCell.FormulaR1C1 = "=RC[-7]"
End If
```

*Appendix A3 – Macro Codes for “LS – LAD Comparison.xls”*

---

```
ActiveCell.Offset(count2 - 1, 0).Activate  
Range(Selection, Selection.End(xlUp)).Select  
Selection.FillDown
```

```
*****  
' Stat  
*****  
N = 0  
totx = 0  
toty = 0  
totxs = 0  
totys = 0  
totxy = 0  
stotx = 0  
stoty = 0  
slope = 0  
ntercept = 0  
rsquared = 0  
  
' 1 Finding n  
Range("f23").Select  
Range(Selection, Selection.End(xlDown)).Select  
Count = Selection.Count  
N = Count  
  
' 2 Finding totx  
last = Count + 23  
i = 22  
50 i = i + 1  
totx = totx + Cells(i, 6)  
If i < last Then GoTo 50  
  
' 3 Finding toty  
i = 22  
100 i = i + 1  
toty = toty + Cells(i, 7)  
If i < last Then GoTo 100  
  
' 4 Finding totxs  
i = 22  
150 i = i + 1  
totxs = totxs + (Cells(i, 6) * Cells(i, 6))  
If i < last Then GoTo 150  
  
' 5 Finding totys  
i = 22  
200 i = i + 1  
totys = totys + (Cells(i, 7) * Cells(i, 7))  
If i < last Then GoTo 200  
  
' 6 Finding totxy  
i = 22  
250 i = i + 1  
totxy = totxy + (Cells(i, 6) * Cells(i, 7))
```

```

If i < last Then GoTo 250

' 7 Finding stotx
stotx = totx * totx

' 8 Finding stoty
stoty = toty * toty

' Finding slope
slope = (N * totxy - totx * toty) / (N * totxs - stotx)

' Finding intercept
ntercept = (toty / N) - slope * (totx / N)

' Finding R2 value
rsquared = (N * totxy - totx * toty) / (Sqr((N * totxs - stotx) * (N * totys - stoty)))
rsquared = rsquared * rsquared

' Assigns slope to a cell
Range("j9").Select
ActiveCell.FormulaR1C1 = slope

' Assigns intercept to a cell
Range("k9").Select
ActiveCell.FormulaR1C1 = ntercept

' Assigns R2 to a cell
Range("l9").Select
ActiveCell.FormulaR1C1 = rsquared

*****
' Stat2 for Vhash > Vmean ( $V_{\#} \geq V_{mean}$ )
*****
n2 = 0
totx2 = 0
toty2 = 0
totxs2 = 0
totys2 = 0
totxy2 = 0
stotx2 = 0
stoty2 = 0
slope2 = 0
ntercept2 = 0
rsquared2 = 0
last2 = 0

' 1 Finding n2
Range("k23").Select
Range(Selection, Selection.End(xlDown)).Select
Count = Selection.Count
n2 = Count

' 2 Finding tota

```

```
last2 = Count + 23 - 1
i = 22
350 i = i + 1
totx2 = totx2 + Cells(i, 6)
If i < last2 Then GoTo 350

' 3 Finding toty2
i = 22
400 i = i + 1
toty2 = toty2 + Cells(i, 7)
If i < last2 Then GoTo 400

' 4 Finding totxs2
i = 22
450 i = i + 1
totxs2 = totxs2 + (Cells(i, 6) * Cells(i, 6))
If i < last2 Then GoTo 450

' 5 Finding totys2
i = 22
500 i = i + 1
totys2 = totys2 + (Cells(i, 7) * Cells(i, 7))
If i < last2 Then GoTo 500

' 6 Finding totxy2
i = 22
550 i = i + 1
totxy2 = totxy2 + (Cells(i, 6) * Cells(i, 7))
If i < last2 Then GoTo 550

' 7 Finding stotx2
stotx2 = totx2 * totx2

' 8 Finding stoty2
stoty2 = toty2 * toty2

' Finding slope2
slope2 = (n2 * totxy2 - totx2 * toty2) / (n2 * totxs2 - stotx2)

' Finding intercept2
ntercept2 = (toty2 / n2) - slope2 * (totx2 / n2)

' Finding  $R_2^2$  value
rsquared2 = (n2 * totxy2 - totx2 * toty2) / (Sqr((n2 * totxs2 - stotx2) * (n2 * totys2 - stoty2)))
rsquared2 = rsquared2 * rsquared2

' Assigning slope2 value to a cell
Range("j10").Select
ActiveCell.FormulaR1C1 = slope2

' Assigning intercept2 value to a cell
Range("k10").Select
```

```

ActiveCell.FormulaR1C1 = ntercept2

' Assigning  $R_2^2$  value to a cell
Range("I10").Select
ActiveCell.FormulaR1C1 = rsquared2

*****
*****
*****
' Message box informs user to type LAD fit results into appropriate cells. Following
' calculations are placed to get necessary information to plot graphs as soon as these
' values are typed in
' Operations for LAD All graph (y-axis)
Range("I23").Select
ActiveCell.FormulaR1C1 = "=RC[-3]*R15C10+R15C11"
ActiveCell.Offset(N - 1, 0).Activate
Range(Selection, Selection.End(xlUp)).Select
Selection.FillDown

' Operations for LS All graph (y-axis)
Range("J23").Select
ActiveCell.FormulaR1C1 = "=RC[-4]*R9C10+R9C11"
ActiveCell.Offset(N - 1, 0).Activate
Range(Selection, Selection.End(xlUp)).Select
Selection.FillDown

' Operations for LS with  $V_{hash} > V_{mean}$  ( $V_{\#} \geq V_{mean}$ ) graph (y-axis)
Range("m23").Select
ActiveCell.FormulaR1C1 = "=RC[-7]*R10C10+R10C11"
ActiveCell.Offset(N - 1, 0).Activate
Range(Selection, Selection.End(xlUp)).Select
Selection.FillDown

' Operations for LAD with  $V_{hash} > V_{mean}$  ( $V_{\#} \geq V_{mean}$ ) graph (y-axis)
Range("n23").Select
ActiveCell.FormulaR1C1 = "=RC[-8]*R16C10+R16C11"
ActiveCell.Offset(N - 1, 0).Activate
Range(Selection, Selection.End(xlUp)).Select
Selection.FillDown

' Copies values to sheet2 for exceedance probability calculations and graphs.
Sheets("Sheet1").Select
Range("D23:E23").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.copy
Sheets("Sheet2").Select
Range("H10").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Range("A1").Activate
Application.CutCopyMode = False

```

```
' Formats
  Sheets("Sheet1").Select
  Range("b1").Activate
  Range("D23:G23").Select
  Range(Selection, Selection.End(xlDown)).Select
  Selection.NumberFormat = "0.000000000"
  Range("j9:110").Select
  Selection.NumberFormat = "0.000000000"
  Range("j15:116").Select
  Selection.NumberFormat = "0.000000000"
  Range("b1").Select

' Warning message appears to inform user about the LAD Fit data
  If (IsEmpty(Cells(15, 10))) Then
    MsgBox "Please upload LAD Fitting Details to complete PERFORM!"
  End If

999 Range("b1").Activate

End Sub

' Macro commands for the button 2
' to transfer results from this file to “Analysis Summary.xls”
Sub TRANSFER()

' Collecting values
  Windows("LS - LAD comparison.xls").Activate
  Sheet1.Activate

  TENU = Cells(1, 2)
  TENA = Cells(2, 2)
  HS = Cells(3, 2)
  TM = ""
  TP = Cells(4, 2)
  M = Cells(5, 2)
  h = Cells(6, 2)
  RC = Cells(7, 2)
  N = Cells(15, 2)
  NO = Cells(17, 2)
  VTOT = Cells(18, 2)
  VMAX = Cells(19, 2)
  VMEAN = Cells(20, 2)
  Q = Cells(21, 2)
  X = Cells(23, 20)
  S1 = Cells(9, 10)
  I1 = Cells(9, 11)
  R1 = Cells(9, 12)
  S2 = Cells(10, 10)
  I2 = Cells(10, 11)
  R2 = Cells(10, 12)
  S3 = Cells(15, 10)
  I3 = Cells(15, 11)
```

```
R3 = Cells(15, 12)
S4 = Cells(16, 10)
I4 = Cells(16, 11)
R4 = Cells(16, 12)

' Pasting values and formats
' If the "Analysis Summary.CSV" file is not available, message box informs
  On Error Resume Next
  Err = 0
  Windows("Analysis Summary.CSV").Activate
  If Err <> 0 Then
    Err = 0
    On Error GoTo 0
    MsgBox ""Analysis Summary.CSV" file is Missing!"
    Exit Sub
  End If
  On Error GoTo 0

  Windows("Analysis Summary.xls").Activate
  Range("a4").Select
  Selection.End(xlDown).Select
  ActiveCell.Offset(1, 0).Select
  ActiveCell.Value = TENU
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = TENA
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = HS
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = TM
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = TP
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = M
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = X

  Selection.NumberFormat = "0.000"
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = h
  Selection.NumberFormat = "0.000"
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = RC
  Selection.NumberFormat = "0.000"
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = N
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = NO
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = VTOT
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = VMAX
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Value = VMEAN
  ActiveCell.Offset(0, 1).Select
```

```
ActiveCell.Value = Q
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = S1
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = I1
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = R1
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = S2
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = I2
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = R2
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = S3
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = I3
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = R3
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = S4
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = I4
ActiveCell.Offset(0, 1).Select
ActiveCell.Value = R4
Range("A4").Select

' Saves “Analysis Summary.xls” file
ActiveWorkbook.Save

' Returns
Windows("LS - LAD comparison.xls").Activate
Sheet1.Activate

End Sub

' Macro commands for the button 3
' to save the work under assigned name to the dedicated place on the hard disc
Sub SaveFile()

' If there is no file name printed, message box informs
z = Cells(2, 2)
If (z = "") Then
    MsgBox "There is no FILE NAME to save!"
    Exit Sub
End If
Cells(2, 14).Select
ActiveCell.FormulaR1C1 = _
    "=concatenate("""C:\Documents and Settings\ibay\My Documents\Ibrahim\My
Software\Analysis\Probability and LS - LAD Fittings\"",r[0]c[-12],"" Analysis.xls"")"
Cells(2, 14).Select
y = Selection
```



*Appendix A3 – Macro Codes for “LS – LAD Comparison.xls”*

---

```
Range("A1").Select
ActiveWorkbook.SaveCopyAs ([y])
End Sub

' Macro commands for the button 4
' to clear all data from the worksheet
Sub clear_data()

' Clearing sheet2
Sheets("Sheet2").Select
Range("h10:i10").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Clear
Application.CutCopyMode = False
Range("a1").Select

' Clearing sheet1
Sheets("Sheet1").Select
Range("b:g").Select
Selection.Clear

Range("k1:k3").Select
Selection.Clear

Range("j9:l10").Select
Selection.Clear

Range("j15:l16").Select
Selection.Clear

Range("i23").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Clear

Range("j23").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Clear

Range("k23").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Clear

Range("m23:n23").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Clear

Range("t23").Select
Selection.Clear

Range("b1").Select

End Sub
```

---

## Appendix - A4. Macro codes of “*proBAY* Full List.xls”

---

```
' *****
' *
' *      Codes for this macro program were written by Ibrahim Bay on 02/05/2003
' *
' *****
' *
' * These macro codes are written to assist storing the proBAY results in such a way
' * that the data analysis will be done easily. Information page contains three command
' * buttons; “Start” button takes user to the storage page, “Exit” button closes the file
' * without saving the latest changes and “Save and Exit” button simply saves the work
' * and closes the file. There is a template information column in the storage page and
' * column is frozen to help user to view those information at all the time. There are
' * five command buttons on this page and “View Summary” simply takes user to the
' * summary page where all data, apart from individual overtopping volumes, is saved.
' * “Transfer Data” button copies information from proBAY output files, “Issue.CSV”
' * and “Ranked.CSV”, and pastes onto this worksheet. Since this macro program is
' * aimed to be used concurrently with proBAY software, “Close proBAY Files”
' * simply closes related files to make them available for the next proBAY run.
' * “Summarize” button summarises the test information and “Save” button saves the
' * file with the latest updated information. Summary worksheet contains only two
' * buttons and they are to navigate user to the other pages.
' *
' *****
' First button on the entrance page
Sub Macro1()
' This is to start

    Sheets("Ranked").Select
    Range("A1").Select

End Sub

' Commands for the button 2
Sub Macro2()
' This is to update header
    Sheets("Ranked").Select
    Range("B22:E22").Select
    Selection.Copy
    Range("B22").Select
    Selection.End(xlToRight).Select
    ActiveCell.Offset(0, 1).Activate
    ActiveSheet.Paste

' This is to transfer data from the “Issue.CSV” file
```

*Appendix A4 – Macro Codes for “proBAY Full List.xls”*

---

```
Windows("ISSUE.CSV").Activate
Range("B1:B14").Select
Selection.Copy

Windows("proBAY Full List.xls").Activate
Sheets("Ranked").Select
Range("B22").Select
Selection.End(xlToRight).Select
ActiveCell.Offset(-21, -3).Activate
ActiveCell.FormulaR1C1 = "=RC[-4]+1"

' Formats and pastes
Range("B22").Select
Selection.End(xlToRight).Select
ActiveCell.Offset(-14, -3).Activate
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Range("A1").Select

' This is to transfer data from the “Ranked.CSV” file
Windows("RANKED.CSV").Activate
Range("A3").Select
Range(Selection, Selection.End(xlToRight)).Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy

Windows("proBAY Full List.xls").Activate
Sheets("Ranked").Select
Range("B22").Select
Selection.End(xlToRight).Select
ActiveCell.Offset(1, -3).Activate
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Application.CutCopyMode = False

' Formats column widths
Cells.Select
Cells.EntireColumn.AutoFit

Range("A1").Select

End Sub

' Commands for the button 3
Sub Macro3()
' This is to close proBAY output files
Windows("ISSUE.CSV").Activate
ActiveWindow.Close
Windows("RANKED.CSV").Activate
ActiveWindow.Close
Windows("proBAY Full List.xls").Activate
Range("A1").Select
```

End Sub

' Commands for the button 4

Sub Macro4()

' This is to summarize

```
Range("B22").Select
Selection.End(xlToRight).Select
ActiveCell.Offset(-1, -3).Activate
Range(Selection, Selection.End(xlUp)).Select
Range(Selection, Selection.End(xlUp)).Select
Selection.Copy
Sheets("Summary").Select
Range("A11").Select
Selection.End(xlDown).Select
ActiveCell.Offset(1, 0).Activate
ActiveCell.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:=
    False, Transpose:=True
ActiveCell.Offset(1, 0).Activate
Application.CutCopyMode = False
Sheets("Ranked").Select
Range("A1").Select
```

End Sub

' Commands for the button 5

Sub Macro5()

' This is to save only!

```
Application.CutCopyMode = False
Sheets("Intro").Select
Range("H14").Select
ActiveWorkbook.Save
```

End Sub

' Commands for the button 6

' This is to view summary

```
Sheets("Summary").Select
Range("A11").Select
Selection.End(xlDown).Select
ActiveCell.Offset(1, 0).Activate
```

End Sub

*Appendix A4 – Macro Codes for “proBAY Full List.xls”*

---

```
' Commands for the button 7
Sub Macro7()
' This is to navigate user to starting page
  Application.CutCopyMode = False
  Sheets("Intro").Select
  Range("H14").Select

End Sub
```

```
' Commands for the button 8
Sub Macro8()
' This is to navigate user to data storage page
  Application.CutCopyMode = False
  Sheets("Ranked").Select
  Range("A1").Select

End Sub
```

```
' Commands for the button 9
Sub Macro9()
' This is to exit only
  ActiveWorkbook.Close

End Sub
```

```
' Commands for the button 10
Sub Macro10()
' This is to save and exit
  ActiveWorkbook.Save
  ActiveWorkbook.Close

End Sub
```

---

## Appendix - A5. Macro codes of “*proBAY* Results – Graphical Expression.xls”

---

```

Sub GraphExp()
'
' *****
' *
' *      Codes for this macro program were written by Ibrahim Bay on 06/05/2004
' *
' *****
' *
' * This macro program was written simply to collect data from proBAY output files, *
' * do some simple probabilistic calculations and plot graphs accordingly. Firstly, *
' * name of the test condition should be written in the appropriate cell. Then, by *
' * clicking “to copy data from the Average.CSV”, proBAY output data will be copied *
' * from the source file. Next command button will count lines to confirm the number *
' * of overtopping events and put data in a unique form so Microsoft Excel can plot *
' * steps (created by proBAY) to show individual overtopping volumes. Relevant *
' * original data are copied from “Conditioned.CSV” file and smoothed load cell signal *
' * is copied from “Chopsmolc.CSV” file by clicking the next two icons. After all, a *
' * graph showing the original overtopping detector signal, original load cell signal, *
' * smoothed load cell signal and results to show proBAY results is now plotted. *
' * Graph also shows the total number of overtopping value. Next button renames the *
' * plot and following button saves a copy of the workbook according to the given *
' * filename. Next button clears the spreadsheet to make the template file ready for the *
' * next run (to repeat the same procedure for the next wave condition). Button at the *
' * bottom of the list closes the workbook. File can not be saved since its property has *
' * been set as read-only file. The top button at the right hand side simply takes user to *
' * the next page and the one at the bottom simply previews the plot. There is a “Back” *
' * button to take user back from the graph page to the data sheet.
' *
' * Macro buttons on the second page are prepared to do the same sort of operations. *
' * The command button at the top copies all statistical results and individual *
' * overtopping volume list from “proBAY Full List.xls” data file. Next button does *
' * some simple probability calculations. It calculates values for  $\text{Prob}[V \geq V_{\#}]$ ,  $\ln V_{\#}$  *
' * and  $\ln \left\{ \ln (\text{Prob}[V \geq V_{\#}])^{-1} \right\}$  for each overtopping event. After these calculation, *
' * a graph has already been plotted to show the relationship between  $\ln V_{\#}$  and *
' *  $\ln \left\{ \ln (\text{Prob}[V \geq V_{\#}])^{-1} \right\}$ . Line drawn with an LS fit to data and value of  $R^2$  *
' * shows the relationship between the axes. Next button renames the plot and the *
' * button below clears all the information on this spreadsheet.
' *
' *****
' *
' *      Macro codes for the first page command buttons
' *
' *****

```

*Appendix A5 – Macro Codes for  
“proBAY Results – Graphical Expression.xls”*

---

```
' Commands for the first button
Sub CopyAverages()

' Textbox gives message if the test name is not typed
  If (IsEmpty(Cells(21, 14))) Then
    MsgBox "Please input the Test Name!"
    GoTo 100
  End If
  z = Cells(20, 27)

' If there is any data in the related cell, message box appears to tell the command is
' disabled until the analysis
  If (z > 0) Then
    MsgBox "CopyConditioned command disabled until next analysis!"
    GoTo 100
  End If

' If the “averages.csv” file is not available, message box says “Source File is Missing!”
  On Error Resume Next
  Err = 0
  Windows("AVERAGES.CSV").Activate
  If Err <> 0 Then
    Err = 0
    On Error GoTo 0
    MsgBox "Source File is Missing!"
    Exit Sub
  End If
  On Error GoTo 0

' Next, copies from the source
  Range("A1").Select
  Range(Selection, Selection.End(xlToRight)).Select
  Range(Selection, Selection.End(xlDown)).Select
  Selection.Copy
  Windows("proBAY Results - Graphical Expression.xls").Activate
  Range("A1").Select
  ActiveSheet.Paste
  Application.CutCopyMode = False

' Closes the source file to make it available for the next proBAY run
  Windows("AVERAGES.CSV").Activate
  ActiveWorkbook.Close
  Windows("proBAY Results - Graphical Expression.xls").Activate
  Range("E1").Select
100 End Sub

' Commands for the button 2
' Calculates the total number of overtopping event and formats the available data
' Message box appears if there is no data available
Sub SetTheFormat()
  X = Cells(1, 1)
  If (X = "") Then
```

*Appendix A5 – Macro Codes for  
“proBAY Results – Graphical Expression.xls”*

---

```
MsgBox "There is no data!"
GoTo 110
End If
z = Cells(1, 4)

' If the relevant cell is occupied, message says the command button is disabled
If (z > 0) Then
    MsgBox "Calculate! command disabled until next analysis!"
    GoTo 110
End If

' Counts and confirms the total number of overtopping events
Cells(2, 1).Select
Range(Selection, Selection.End(xlDown)).Select
Count = Selection.Count
Range("D1").Select
ActiveCell.FormulaR1C1 = Count

' Formats next
Range("A1").Select
Selection.End(xlDown).Select
ActiveCell.Offset(1, 0).Activate
ActiveCell.FormulaR1C1 = "=R[-1]C[2]"
i = -1
j = Cells(1, 4)
j = j * 2
For counter = 1 To j
    counter = counter + 1
    i = i + 1
    Worksheets("Sheet1").Cells(counter, 5).Value = Cells(counter - i, 2)
    Cells(counter, 5).Activate
    Selection.Copy
    Cells(counter + 1, 5).Activate
    ActiveSheet.Paste
Next counter
i = -1
For counter = 1 To j + 1
    counter = counter + 1
    i = i + 1
    Worksheets("Sheet1").Cells(counter - 1, 6).Value = Cells(counter - i, 1)
    Cells(counter - 1, 6).Activate
    Selection.Copy
    Cells(counter, 6).Activate
    ActiveSheet.Paste
Next counter
i = -1
For counter = 1 To j + 1
    counter = counter + 1
    i = i + 1
    Worksheets("Sheet1").Cells(counter - 1, 7).Value = Cells(counter - i, 1) * 1000
    Cells(counter - 1, 7).Activate
    Selection.Copy
    Cells(counter, 7).Activate
    ActiveSheet.Paste
```



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---

```
Next counter
Range("E1").Select
ActiveCell.FormulaR1C1 = "1"
Selection.End(xlDown).Select
ActiveCell.Offset(1, 0).Activate
ActiveCell.FormulaR1C1 = 32000
Range("A1").Select
Selection.End(xlDown).Select
Selection.Clear
Range("A1").Select

' Writes the total number of overtopping events so the information will be used in the plot
Range("AA1").Select
ActiveCell.FormulaR1C1 = _
    "=CONCATENATE(""total overtopping number = ""&RC[-23])"
Range("A1").Select
110 End Sub

' Commands for the button 3
Sub CopyConditioned()
' If the relevant cell is occupied, message says the command button is disabled
z = Cells(20, 27)
If (z > 0) Then
    MsgBox "CopyConditioned command disabled until next analysis!"
    GoTo 120
End If

' If the “Conditioned.CSV” file is not available, message box says “Source File is
' Missing!”
On Error Resume Next
Err = 0
Windows("CONDITIONED.CSV").Activate
If Err <> 0 Then
    Err = 0
    On Error GoTo 0
    MsgBox "Source File is Missing!"
    Exit Sub
End If
On Error GoTo 0

' Copies next
Range("A1").Select
Range(Selection, Selection.End(xlToRight)).Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy
Windows("proBAY Results - Graphical Expression.xls").Activate
Range("H1").Select
ActiveSheet.Paste
Application.CutCopyMode = False

' Closes the source file to make it available for the next proBAY run
Windows("CONDITIONED.CSV").Activate
ActiveWorkbook.Close
Windows("proBAY Results - Graphical Expression.xls").Activate
```

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---

```
Range("K1").Select
120 End Sub

' Commands for the button 4
Sub CopyChopsmolc()
' If the relevant cell is occupied, message says the command button is disabled
z = Cells(20, 27)
If (z > 0) Then
    MsgBox "CopyChopsmolc command disabled until next analysis!"
    GoTo 130
End If

' If the “Chopsmolc.CSV” file is not available, message box says “Source File is
' Missing!”
On Error Resume Next
Err = 0
Windows("CHOPSMOLC.CSV").Activate
If Err <> 0 Then
    Err = 0
    On Error GoTo 0
    MsgBox "Source File is Missing!"
    Exit Sub
End If
On Error GoTo 0

' Copies next
Range("B1").Select
Range(Selection, Selection.End(xlDown)).Select
Application.CutCopyMode = False
Selection.Copy
Windows("proBAY Results - Graphical Expression.xls").Activate
Range("K1").Select
ActiveSheet.Paste
Application.CutCopyMode = False
Range("A1").Select

' Closes the source file to make it available for the next proBAY run
Windows("CHOPSMOLC.CSV").Activate
ActiveWorkbook.Close
Windows("proBAY Results - Graphical Expression.xls").Activate
Range("A1").Select
130 End Sub

' Commands for the button 5
Sub RenameThePlot()
Sheets("Sheet1").Select
If (IsEmpty(Cells(21, 14))) Then
    Sheets(1).Select
    Sheets(1).Name = "Chart1"
    Sheets("Sheet1").Select
    Cells(1, 1).Select
    GoTo 140
End If
z = Cells(20, 27)
```

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---

```
' If the relevant cell is occupied, message says the command button is disabled
  If (z > 0) Then
    MsgBox "Automatic rename disabled until next analysis!"
    GoTo 140
  End If

' Formats the name
  Cells(20, 27).Select
  ActiveCell.FormulaR1C1 = "=concatenate(r[1]c[-13], "" Analysis"*)"
  y = Cells(20, 27)
  Sheets("Chart1").Select

' Writes the new name
  Sheets("Chart1").Name = y
  Sheets("Sheet1").Select
  Range("A1").Select
140 End Sub

' Commands for the button 6
Sub Clear()
' Checks existing data on sheet1
  Sheets("Sheet1").Select
  Cells(1, 34).Select
  ActiveCell.FormulaR1C1 = "=COUNT(C[-33]:C[-6])"
  a = Cells(1, 34)
  Cells(1, 1).Select
' Checks existing data on Sheet2
  Sheets("Sheet2").Select
  Cells(1, 34).Select
  ActiveCell.FormulaR1C1 = "=COUNT(C[-32]:C[-6])"
  b = Cells(1, 34)
  Cells(1, 2).Select
  If (a > 0 And b > 0) Then
    GoTo 150
  Else
    If (a > 0 And b = 0) Then

' If there is no data on Sheet2, message box informs
      MsgBox "There is no data to clear in Sheet2!"
    End If
    If (a = 0 And b > 0) Then

' If there is no data on Sheet1, message box informs
      MsgBox "There is no data to clear in Sheet1!"
    End If
    If (a = 0 And b = 0) Then

' If there is no data on both sheets, message box informs
      MsgBox "Areas contain no data to clear!"
      GoTo 160
    End If
  End If
150 If (a > 0) Then
```

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---

```
' Clears data on Sheet1
  Sheets("Sheet1").Select
  Cells.Select
  Selection.ClearContents
  Cells(1, 1).Select
End If
If (b > 0) Then
  Sheets("Sheet2").Select
  If (IsEmpty(Cells(20, 27))) Then
    GoTo 155
  Else

' Renames the second graph page back to “Chart2”
  g = Cells(20, 27)
  Sheets(g).Select
  Sheets(g).Name = "Chart2"
  Sheets("Sheet2").Select
  Cells(1, 2).Select
End If

' Clears data on Sheet2
155 Cells.Select
  Selection.ClearContents
  Cells(1, 2).Select
End If
Sheets("sheet1").Select

' Renames the first graph page back to “Chart1”
z = Cells(20, 27)
If (z = "") Then
  Sheets(1).Select
  Sheets(1).Name = "Chart1"
  Sheets("Sheet1").Select
  Cells(1, 1).Select
  GoTo 157
End If
Sheets(z).Select
Sheets(z).Name = "Chart1"

' Clears data on Sheet1
  Sheets("Sheet1").Select
  Cells.Select
  Selection.ClearContents
  Cells(1, 1).Select

157 Sheets("sheet2").Select
  y = Cells(20, 27)

' Renames the second graph page back to “Chart2”
If (y = "") Then
  Sheets(3).Select
  Sheets(3).Name = "Chart2"
  Sheets("Sheet2").Select
  Cells(1, 1).Select
```

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---

```
        GoTo 160
    End If
    Sheets(y).Select
    Sheets(y).Name = "Chart2"

' Clears data on Sheet2
    Sheets("Sheet2").Select
    Cells.Select
    Selection.ClearContents
    Cells(1, 1).Select
160 Sheets("Sheet1").Select
    Range("A1").Select
End Sub

' Commands for the button 7
Sub SaveFile()
    z = Cells(21, 14)

' If there is no typed file name, message box informs
    If (z = "") Then
        MsgBox "There is no FILE NAME to save!"
        Exit Sub
    End If
    Cells(10, 27).Select

' Updates the typed file name with a place to save the file as
    ActiveCell.FormulaR1C1 = _
        "=concatenate(""C:\Documents and Settings\ibay\Desktop\My Software\proBAY
Results\"",r[11]c[-13],"" Results.xls"")"
    Cells(10, 27).Select
    y = Selection
    Range("A1").Select
    ActiveWorkbook.SaveCopyAs ([y])
End Sub

' Commands for the button 8
Sub CloseFile()
' Closes the file
    ActiveWorkbook.Close SaveChanges:=False
End Sub

' Commands for the button 9
Sub NextPage()
' Navigates user to the next page
    Sheets("Sheet2").Select
    Range("b1").Select
End Sub
```

*Appendix A5 – Macro Codes for  
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---

```
' Commands for the button 10
Sub Preview1()
' Navigates user to the first graph page
  Sheets(1).Select
End Sub

' Commands for the button 11
Sub GoBack1()
' Navigates user from the first graph page back to the first data page
  Sheets(2).Select
  Range("A1").Select
End Sub

' *****
' *
' *          Macro codes for the second page command buttons          *
' *
' *****
' Commands for the button 12
Sub FindCopyPasteResults()
' Simply finds information, copies and pastes
  If (IsEmpty(Cells(20, 10))) Then
' Message box appears to inform user that the file name has been taken from Sheet1.
  MsgBox "File Name has been taken from Sheet1"
  Sheets("sheet1").Select
  If (IsEmpty(Cells(21, 14))) Then
' If there is no file name typed on Sheet1, message appears to ask user to type file name
  MsgBox "Please specify a File Name!"
  Exit Sub
  End If
  X = Sheets("Sheet1").Cells(21, 14)
  Sheets("sheet2").Select
  Cells(20, 10) = X
  End If

' If the cell which supposed to hold the file name is not empty, then informs user to clear
' the data first and to try again
  X = Cells(20, 10)
  If (IsEmpty(Cells(2, 2))) Then
    GoTo 160
  Else
    MsgBox "You can not overwrite data. Please clear the area first and try copying
again!"
    GoTo 180
  End If
160 y = Cells(2, 2)

' If data is already pasted, unnecessary duplication message appears
  If (X = y) Then
    MsgBox "It is unnecessary to re-do the work!"
    GoTo 180
```

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---

```
End If
' Collects data from “proBAY Full List.xls” file
On Error Resume Next
Err = 0
Windows("proBAY Full List.xls").Activate
Sheets("Ranked").Select
If Err <> 0 Then
    Err = 0
    On Error GoTo 0

' Message box informs if the source file is not opened
    MsgBox "Source File is Missing!"
    Exit Sub
End If
On Error GoTo 0

' Copies from the source
Cells.Find(What:=X).Activate
Selection.End(xlDown).Select
Selection.End(xlToRight).Select
Range(Selection, Selection.End(xlUp)).Select
Range(Selection, Selection.End(xlUp)).Select
Range(Selection, Selection.End(xlToLeft)).Select
Selection.Copy
Windows("proBAY Results - Graphical Expression.xls").Activate
Sheets("Sheet2").Activate
Range("B1").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Application.CutCopyMode = False
Range("B1").Select
180 End Sub

' Commands for the button 13
Sub Calculations()
' Calculates some statistics
y = Cells(23, 4)

' If there is no data entered, message box appears to inform user
If (y = "") Then
    MsgBox "Please fill in the File Name and " & _
        "transfer related data by using the top Click Box!"
    GoTo 200
End If
X = Cells(22, 5)
If (X > 0) Then

' If there are some information on the sheet, message box appears to inform user
    MsgBox "You can not repeat calculations!"
    GoTo 200
End If
Range("E22").Select
```

*Appendix A5 – Macro Codes for  
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---

```
' Formats the header
  With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
    .WrapText = False
    .Orientation = 0
    .AddIndent = False
    .ShrinkToFit = False
    .MergeCells = False
  End With
  ActiveCell.FormulaR1C1 = "Prob[V³V#]"
  With ActiveCell.Characters(Start:=1, Length:=6).Font
    .Name = "Arial"
    .FontStyle = "Bold"
    .Size = 10
    .Strikethrough = False
    .Superscript = False
    .Subscript = False
    .OutlineFont = False
    .Shadow = False
    .Underline = xlUnderlineStyleNone
    .ColorIndex = xlAutomatic
  End With
  With ActiveCell.Characters(Start:=7, Length:=1).Font
    .Name = "Symbol"
    .FontStyle = "Bold"
    .Size = 10
    .Strikethrough = False
    .Superscript = False
    .Subscript = False
    .OutlineFont = False
    .Shadow = False
    .Underline = xlUnderlineStyleNone
    .ColorIndex = xlAutomatic
  End With
  With ActiveCell.Characters(Start:=8, Length:=1).Font
    .Name = "Arial"
    .FontStyle = "Bold"
    .Size = 10
    .Strikethrough = False
    .Superscript = False
    .Subscript = False
    .OutlineFont = False
    .Shadow = False
    .Underline = xlUnderlineStyleNone
    .ColorIndex = xlAutomatic
  End With
  With ActiveCell.Characters(Start:=9, Length:=1).Font
    .Name = "Arial"
    .FontStyle = "Bold"
    .Size = 10
    .Strikethrough = False
    .Superscript = False
    .Subscript = True
```



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---

```

.OutlineFont = False
.Shadow = False
.Underline = xlUnderlineStyleNone
.ColorIndex = xlAutomatic
End With
With ActiveCell.Characters(Start:=10, Length:=1).Font
.Name = "Arial"
.FontStyle = "Bold"
.Size = 10
.Strikethrough = False
.Superscript = False
.Subscript = False
.OutlineFont = False
.Shadow = False
.Underline = xlUnderlineStyleNone
.ColorIndex = xlAutomatic
End With

' Calculates Prob [  $V \geq V_n$  ]
ActiveCell.Offset(1, 0).Activate
ActiveCell.FormulaR1C1 = "=RC[-3]/(R17C2+1)"
ActiveCell.Offset(0, -1).Activate
Selection.End(xlDown).Select
ActiveCell.Offset(0, 1).Activate
Range(Selection, Selection.End(xlUp)).Select
Selection.FillDown
Selection.Copy
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
False, Transpose:=False
Application.CutCopyMode = False
' Formats next header
Range("F22").Select
With Selection
.HorizontalAlignment = xlCenter
.VerticalAlignment = xlCenter
.WrapText = False
.Orientation = 0
.AddIndent = False
.ShrinkToFit = False
.MergeCells = False
End With
ActiveCell.FormulaR1C1 = "ln[V#]"
With ActiveCell.Characters(Start:=1, Length:=4).Font
.Name = "Arial"
.FontStyle = "Bold"
.Size = 10
.Strikethrough = False
.Superscript = False
.Subscript = False
.OutlineFont = False
.Shadow = False
.Underline = xlUnderlineStyleNone
.ColorIndex = xlAutomatic

```

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---

```

End With
With ActiveCell.Characters(Start:=5, Length:=1).Font
    .Name = "Arial"
    .FontStyle = "Bold"
    .Size = 10
    .Strikethrough = False
    .Superscript = False
    .Subscript = True
    .OutlineFont = False
    .Shadow = False
    .Underline = xlUnderlineStyleNone
    .ColorIndex = xlAutomatic
End With
With ActiveCell.Characters(Start:=6, Length:=1).Font
    .Name = "Arial"
    .FontStyle = "Bold"
    .Size = 10
    .Strikethrough = False
    .Superscript = False
    .Subscript = False
    .OutlineFont = False
    .Shadow = False
    .Underline = xlUnderlineStyleNone
    .ColorIndex = xlAutomatic
End With
With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
    .WrapText = False
    .Orientation = 0
    .AddIndent = False
    .ShrinkToFit = False
    .MergeCells = False
End With
ActiveCell.Offset(1, 0).Activate

' Calculates  $\ln[V_{\#}]$ 
ActiveCell.FormulaR1C1 = "=LN(RC[-2])"
ActiveCell.Offset(0, -1).Activate
Selection.End(xlDown).Select
ActiveCell.Offset(0, 1).Activate
Range(Selection, Selection.End(xlUp)).Select
Selection.FillDown
Selection.Copy
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Application.CutCopyMode = False

' Formats the third header
Range("G22").Select
ActiveCell.FormulaR1C1 = "ln {ln(Prob[V^3V#])-1}"
With ActiveCell.Characters(Start:=1, Length:=12).Font
    .Name = "Arial"

```

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---

```
.FontStyle = "Bold"  
.Size = 10  
.Strikethrough = False  
.Superscript = False  
.Subscript = False  
.OutlineFont = False  
.Shadow = False  
.Underline = xlUnderlineStyleNone  
.ColorIndex = xlAutomatic  
End With  
With ActiveCell.Characters(Start:=13, Length:=1).Font  
.Name = "Symbol"  
.FontStyle = "Bold"  
.Size = 10  
.Strikethrough = False  
.Superscript = False  
.Subscript = False  
.OutlineFont = False  
.Shadow = False  
.Underline = xlUnderlineStyleNone  
.ColorIndex = xlAutomatic  
End With  
With ActiveCell.Characters(Start:=14, Length:=1).Font  
.Name = "Arial"  
.FontStyle = "Bold"  
.Size = 10  
.Strikethrough = False  
.Superscript = False  
.Subscript = False  
.OutlineFont = False  
.Shadow = False  
.Underline = xlUnderlineStyleNone  
.ColorIndex = xlAutomatic  
End With  
With ActiveCell.Characters(Start:=15, Length:=1).Font  
.Name = "Arial"  
.FontStyle = "Bold"  
.Size = 10  
.Strikethrough = False  
.Superscript = False  
.Subscript = True  
.OutlineFont = False  
.Shadow = False  
.Underline = xlUnderlineStyleNone  
.ColorIndex = xlAutomatic  
End With  
With ActiveCell.Characters(Start:=18, Length:=2).Font  
.Name = "Arial"  
.FontStyle = "Bold"  
.Size = 10  
.Strikethrough = False  
.Superscript = True  
.Subscript = False  
.OutlineFont = False
```

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---

```

.Shadow = False
.Underline = xlUnderlineStyleNone
.ColorIndex = xlAutomatic
End With
With ActiveCell.Characters(Start:=20, Length:=1).Font
.Name = "Arial"
.FontStyle = "Bold"
.Size = 10
.Strikethrough = False
.Superscript = False
.Subscript = False
.OutlineFont = False
.Shadow = False
.Underline = xlUnderlineStyleNone
.ColorIndex = xlAutomatic
End With
ActiveCell.Offset(1, 0).Activate

' Calculates  $\ln \left\{ \ln \left( \text{Prob} [ V \geq V_{\#} ] \right)^{-1} \right\}$ 
ActiveCell.FormulaR1C1 = "=LN(LN(1/RC[-2]))"
ActiveCell.Offset(0, -1).Activate
Selection.End(xlDown).Select
ActiveCell.Offset(0, 1).Activate
Range(Selection, Selection.End(xlUp)).Select
Selection.FillDown
Selection.Copy
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
False, Transpose:=False
Application.CutCopyMode = False
200 Range("B1").Select
End Sub

' Commands for the button 14
Sub Rename2()
' Renames the second graph page “Chart2” with the formatted file name
Sheets("Sheet2").Select
X = Cells(20, 10)
If (IsEmpty(Cells(20, 10))) Then
Sheets(3).Select
Sheets(3).Name = "Chart2"
Sheets("Sheet2").Select
Cells(1, 2).Select
GoTo 150
End If
y = Cells(20, 27)
If (y > 0) Then

' If already renamed and plot name is other than “Chart2”, informs the user
MsgBox "Automatic rename disabled until next analysis!"
GoTo 150
End If

```

*Appendix A5 – Macro Codes for  
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---

```
Cells(20, 27).Select

' Formats the name
ActiveCell.FormulaR1C1 = "=concatenate(r[0]c[-17], "" Distribution"")"
z = Cells(20, 27)
Sheets(3).Select

' Renames the graph page with the formatted file name
Sheets(3).Name = z
Sheets("Sheet2").Select
Range("B1").Select
150 End Sub

' Commands for the button 15
Sub Clear2()

' Clears the data from this page
Sheets("Sheet2").Select
Cells.Select
Selection.ClearContents
Cells(1, 2).Select
End Sub

' Commands for the button 16
Sub PreviousPage()
Sheets("Sheet1").Select

' Navigates user to the first data page
Range("A1").Select
End Sub

' Commands for the button 17
Sub Preview2()
' Navigates user to preview the second plot
Sheets(3).Select
End Sub

' Commands for the button 18
Sub GoBack2()
' Navigates user from the second graph page to the second data page
Sheets(4).Select
Range("B1").Select
End Sub
```

---

## Appendix - A6. SYSTAT<sup>®</sup> 10.2 for Windows

---

SYSTAT<sup>®</sup> 10.2 (SYSTAT Software Inc, 2002) is a comprehensive statistical software package. Besides its statistical features, SYSTAT<sup>®</sup> has an excellent graphics interface for data visualisation. It is very user friendly with its menus and dialog boxes.

SYSTAT<sup>®</sup> 10.2 was used to perform an LAD fit to the output data obtained using the *proBAY* software. Robust estimation by the Gauss-Newton method was chosen from the Nonlinear Model/Loss options and regression analyses were done accordingly. The default value of 20 iterations was not sufficient to minimize the error for some cases; therefore, the maximum number of iterations was changed to 200 for each run.

### A6.1. SYSTAT<sup>®</sup> 10.2 Input File

Below is a SYSTAT<sup>®</sup> 10.2 input data set sample which contains the data to plot  $V_{mean}$  against  $V_{bar}$  (see Chapter 5).

0.000250186	0.000278398
0.000324474	0.000314209
0.000444738	0.000419946
0.00093885	0.001116035
0.00027315	0.000272085
0.0011416	0.001212381
0.000214894	0.000187271
0.001183808	0.001327725
0.0002695	0.000253263
0.000188535	0.000173668
0.000357134	0.000431515
0.000692934	0.000440779
0.001577872	0.002090291
0.000148091	0.000122057

0.00043717	0.000510491
0.000909526	0.000920236
0.000153825	0.000167781
0.000135019	8.02002E-05
0.000175084	8.14814E-05
0.000156775	0.000149986
0.00028373	0.000226841
0.000254278	0.000257375
0.000428352	0.000386455
0.000579512	0.000541099
0.000458438	0.000451094
0.00148689	0.001428789
0.000666576	0.000561278
0.000839228	0.000857173
0.000873446	0.00096391
0.000313957	0.000239464
0.00039742	0.000434575
0.00134523	0.001401588
0.0016821	0.001546319
0.000848694	0.0008182
0.000869988	0.000926327
0.002471396	0.002567239
0.00176547	0.001785916
0.00064958	0.000751793
0.0006827	0.000739099
0.002825856	0.002930172
0.00221802	0.002185195
0.003545588	0.003767401
0.003475761	0.003400026
0.004413399	0.005066965
0.000701972	0.000730006
0.000473714	0.000605521
0.000325784	0.000381655
0.001961176	0.002028073
0.002761564	0.002813077
0.003076446	0.003133507
0.005325793	0.005222807
0.004089699	0.004073905
0.001398978	0.001937641
0.00460442	0.004728567
0.002533511	0.002545385
9.93328E-05	0.000105538
0.000518402	0.000515867
0.00052546	0.000558556
0.000251426	0.00030189
0.000194307	0.000226732

The program takes the first column as  $x$  values and the second column as  $y$  values and analyses the data with a user-defined relationship ( $y = ax + b$  in this study).

### A6.2. SYSTAT® 10.2 Output File

Below is a SYSTAT® 10.2 output file sample. The process completed in 96 iterations and  $R^2 = 0.989141992$  was obtained. The slope of the line was found to be “1.019310318” and the intercept was found as “-0.000001813”.

```
Iteration
No.  Loss  A      B
0 .490531D-02-.101000D-01 .102000D-01
1 .536578D+00-.101000D-01 .102000D-01
2 .178454D-01 .999897D+00 .313779D-03
3 .534083D-02 .103598D+01 .210747D-04
4 .504239D-02 .102625D+01 .199014D-04
5 .498865D-02 .102465D+01 .181403D-04
6 .495856D-02 .102527D+01 .149053D-04
7 .490717D-02 .102512D+01 .107953D-04
8 .488963D-02 .102474D+01 .920699D-05
9 .487936D-02 .102516D+01 .728336D-05
10 .486477D-02 .102576D+01 .454196D-05
11 .485586D-02 .102619D+01 .245342D-05
12 .485085D-02 .102644D+01 .101542D-05
13 .484481D-02 .102677D+01-.729662D-06
14 .483885D-02 .102709D+01-.245135D-05
15 .483402D-02 .102732D+01-.382799D-05
16 .483355D-02 .102718D+01-.386410D-05
17 .483308D-02 .102699D+01-.387784D-05
18 .483247D-02 .102679D+01-.393899D-05
19 .483175D-02 .102658D+01-.405232D-05
20 .483106D-02 .102638D+01-.415941D-05
21 .483088D-02 .102621D+01-.407682D-05
22 .483076D-02 .102604D+01-.393870D-05
23 .483064D-02 .102587D+01-.380221D-05
24 .483052D-02 .102570D+01-.367121D-05
25 .483041D-02 .102555D+01-.355113D-05
26 .483031D-02 .102540D+01-.344896D-05
27 .483022D-02 .102527D+01-.337078D-05
28 .483013D-02 .102515D+01-.331560D-05
29 .483005D-02 .102502D+01-.327350D-05
30 .482995D-02 .102489D+01-.323525D-05
31 .482985D-02 .102474D+01-.319693D-05
32 .482975D-02 .102459D+01-.315744D-05
33 .482963D-02 .102443D+01-.311664D-05
34 .482952D-02 .102427D+01-.307460D-05
35 .482940D-02 .102410D+01-.303152D-05
36 .482928D-02 .102393D+01-.298758D-05
37 .482916D-02 .102375D+01-.294295D-05
38 .482903D-02 .102358D+01-.289780D-05
39 .482891D-02 .102340D+01-.285230D-05
40 .482878D-02 .102322D+01-.280659D-05
41 .482866D-02 .102304D+01-.276083D-05
42 .482853D-02 .102286D+01-.271516D-05
43 .482841D-02 .102268D+01-.266972D-05
44 .482828D-02 .102250D+01-.262463D-05
```



45 .482816D-02 .102233D+01-.258002D-05  
 46 .482804D-02 .102215D+01-.253602D-05  
 47 .482792D-02 .102198D+01-.249276D-05  
 48 .482780D-02 .102182D+01-.245034D-05  
 49 .482769D-02 .102165D+01-.240888D-05  
 50 .482758D-02 .102149D+01-.236848D-05  
 51 .482747D-02 .102134D+01-.232925D-05  
 52 .482736D-02 .102119D+01-.229128D-05  
 53 .482726D-02 .102105D+01-.225465D-05  
 54 .482716D-02 .102091D+01-.221945D-05  
 55 .482707D-02 .102078D+01-.218574D-05  
 56 .482698D-02 .102065D+01-.215359D-05  
 57 .482690D-02 .102053D+01-.212305D-05  
 58 .482682D-02 .102042D+01-.209416D-05  
 59 .482674D-02 .102031D+01-.206693D-05  
 60 .482667D-02 .102021D+01-.204140D-05  
 61 .482661D-02 .102011D+01-.201755D-05  
 62 .482655D-02 .102003D+01-.199538D-05  
 63 .482649D-02 .101995D+01-.197486D-05  
 64 .482644D-02 .101987D+01-.195596D-05  
 65 .482639D-02 .101980D+01-.193864D-05  
 66 .482635D-02 .101974D+01-.192283D-05  
 67 .482631D-02 .101969D+01-.190848D-05  
 68 .482627D-02 .101963D+01-.189552D-05  
 69 .482624D-02 .101959D+01-.188387D-05  
 70 .482621D-02 .101955D+01-.187346D-05  
 71 .482619D-02 .101951D+01-.186420D-05  
 72 .482616D-02 .101948D+01-.185602D-05  
 73 .482614D-02 .101945D+01-.184883D-05  
 74 .482613D-02 .101943D+01-.184258D-05  
 75 .482611D-02 .101940D+01-.183718D-05  
 76 .482610D-02 .101939D+01-.183255D-05  
 77 .482609D-02 .101937D+01-.182864D-05  
 78 .482608D-02 .101936D+01-.182537D-05  
 79 .482607D-02 .101935D+01-.182267D-05  
 80 .482607D-02 .101934D+01-.182048D-05  
 81 .482606D-02 .101933D+01-.181874D-05  
 82 .482606D-02 .101933D+01-.181736D-05  
 83 .482605D-02 .101932D+01-.181629D-05  
 84 .482605D-02 .101932D+01-.181548D-05  
 85 .482605D-02 .101932D+01-.181486D-05  
 86 .482605D-02 .101932D+01-.181440D-05  
 87 .482605D-02 .101931D+01-.181406D-05  
 88 .482605D-02 .101931D+01-.181381D-05  
 89 .482605D-02 .101931D+01-.181362D-05  
 90 .482605D-02 .101931D+01-.181349D-05  
 91 .482605D-02 .101931D+01-.181339D-05  
 92 .482605D-02 .101931D+01-.181332D-05  
 93 .482605D-02 .101931D+01-.181327D-05  
 94 .482605D-02 .101931D+01-.181323D-05  
 95 .482605D-02 .101931D+01-.181321D-05  
 96 .482605D-02 .101931D+01-.181319D-05

ABSOLUTE robust regression:           60 cases have positive psi-weights  
 The average psi-weight is 307445734609058110.00000

Dependent variable is VAR00002

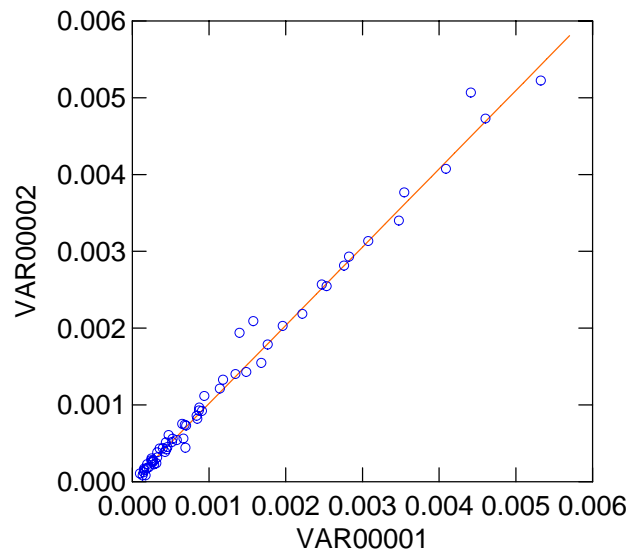
Source	Sum-of-Squares	df	Mean-Square
Regression	0.000196475	2	0.000098238

Appendix A6 – SYSTAT® 10.2 for Windows

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Residual	0.000001178	58	0.000000020
Total	0.000197653	60	
Mean corrected	0.000104669	59	
Raw R-square (1-Residual/Total)	=		0.994042353
Mean corrected R-square (1-Residual/Corrected)	=		0.988749839
R(observed vs predicted) square	=		0.989141992

Parameter	Estimate	A.S.E.	Param/ASE	Wald Confidence Interval	
				Lower < 95% >	Upper
A	1.019310318	.	.	.	.
B	-0.000001813	.	.	.	.



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## Appendix - A7. HR WaveData

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HR Waves (later changed to HR WaveData) is a suite of integrated programs for use with hydraulic models and is designed to collect and analyse analogue data signals. It comprises calibration and data collection routines for the input signals, a spectral analysis program and a statistical analysis program (Beresford & Spencer, 2002). It comprises three sub-routines; CAL, SPEC and WARP.

### A7.1. HR WaveData - CAL

The calibration routine, CAL, allows the creation and editing of calibration files for use with the analysis routines. It provides a comprehensive set of facilities for setting up calibration files that are used to convert the analogue voltage signals in the model to data at full scale. CAL assumes linear scaling.

CAL provides a text file with an extension “.cal” and a typical CAL file is provided below.

HR Cal Version HR Cal 2.2 30/07/99

Creation Date 10:26:01 03/13/01

CHAN NO	GAIN	CALIBRATION FACTOR	ZERO LEVEL	GOODFIT	LABEL
0	1	1.533028e-004	2067	9.999943e-001	Deep Water
1	1	1.000000e+000	2047	0.000000e+000	No label
2	1	1.000000e+000	2047	0.000000e+000	No label
3	1	1.291151e-004	2042	9.999965e-001	1.56m from toe structure
4	1	1.272103e-004	1998	1.000000e+000	1.56m up spending beach
5	1	1.453488e-004	2052	9.999999e-001	1.56m from toe of spending beach
6	1	1.438227e-004	2046	9.999995e-001	Spending beach toe
7	1	1.310272e-004	2044	9.999998e-001	Structure toe

*Appendix A7 – HR WaveData*

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8	1	1.000000e+000	2047	0.000000e+000	No label
9	1	1.000000e+000	2047	0.000000e+000	No label
.					
.					
47	1	1.000000e+000	2047	0.000000e+000	No label

MPSCALE = 1.000000e+000  
DEPTH = 7.500000e-001 m  
X1 = 1.000000e+000 m  
X2 = 1.000000e+000 m  
X3 = 1.000000e+000 m

*A7.2. HR WaveData - SPEC*

The SPEC routine is a spectral analysis program. It collects the data and saves it in an encrypted “.BIN” file first and then analyses the data as soon as data collection stops. SPEC uses the calibration factor in the “.CAL” file and analyses each chosen channel separately. Analysed data are then saved in a “.ASC” file in ASCII format. It produces the wave spectrum and associated spectral parameters in graphical (on screen) and tabular (text file) forms, saving the text file with an extension “.ANA”.

A typical SPEC file is provided below.

HR Spec Version PC Spec 2.2 Written In June 1992.  
Results for spectral analysis run on 13/03/2001 at 10:57:20

Gain = 0.94

Data file analyzed = tap0160c.bin - 13/3/2001 10:56:58  
Calibration file used = 1303.cal - 13/3/2001 10:26:0  
Number of data points per channel = 2048  
Number of bands = 64  
Time interval between samples = 0.1436 Prototype Seconds  
Model/Prototype scale ratio = 1.00

Calibration factor for channel 0 = 0.000153303  
Calibration factor for channel 3 = 0.000129115  
Calibration factor for channel 4 = 0.00012721  
Calibration factor for channel 5 = 0.000145349  
Calibration factor for channel 6 = 0.000143823  
Calibration factor for channel 7 = 0.000131027

Appendix A7 – HR Wave Data

Channel 0 - Deep Water

	Frequency Hz	Spectral density (msq-s)	Significant wave height (m)	zero crossing period (s)	spectral width	* Warning Flag
0	2.72E-02	2.36E-05	4.54E-03	3.68E+01	5.68E-09	0
1	8.16E-02	7.13E-06	5.18E-03	2.18E+01	7.64E-01	0
2	1.36E-01	1.13E-05	6.05E-03	1.24E+01	7.58E-01	0
3	1.90E-01	4.89E-06	6.40E-03	1.02E+01	7.69E-01	0
4	2.45E-01	3.33E-06	6.62E-03	8.79E+00	7.92E-01	0
5	2.99E-01	4.50E-06	6.91E-03	7.21E+00	8.09E-01	0
6	3.54E-01	5.86E-06	7.27E-03	5.83E+00	8.06E-01	0
7	4.08E-01	7.16E-06	7.68E-03	4.77E+00	7.91E-01	0
8	4.62E-01	4.53E-06	7.94E-03	4.28E+00	7.83E-01	0
9	5.17E-01	9.84E-06	8.46E-03	3.54E+00	7.63E-01	0
10	5.71E-01	7.57E-05	1.17E-02	2.25E+00	5.79E-01	0
11	6.26E-01	2.46E-04	1.88E-02	1.78E+00	3.78E-01	0
12	6.80E-01	4.28E-04	2.69E-02	1.60E+00	2.84E-01	1
13	7.35E-01	8.17E-04	3.79E-02	1.47E+00	2.32E-01	1
14	7.89E-01	1.54E-03	5.27E-02	1.36E+00	2.03E-01	1
15	8.43E-01	2.29E-03	6.90E-02	1.28E+00	1.92E-01	1
16	8.98E-01	2.79E-03	8.48E-02	1.22E+00	1.94E-01	1
17	9.52E-01	1.67E-03	9.30E-02	1.18E+00	2.04E-01	1
18	1.01E+00	6.93E-04	9.62E-02	1.17E+00	2.15E-01	1
19	1.06E+00	7.12E-04	9.93E-02	1.15E+00	2.34E-01	1
20	1.12E+00	3.66E-04	1.01E-01	1.14E+00	2.49E-01	1
21	1.17E+00	5.88E-04	1.03E-01	1.12E+00	2.77E-01	1
22	1.22E+00	2.58E-04	1.05E-01	1.11E+00	2.92E-01	0
23	1.28E+00	2.01E-04	1.05E-01	1.10E+00	3.07E-01	0
24	1.33E+00	1.13E-04	1.06E-01	1.09E+00	3.18E-01	0
25	1.39E+00	1.50E-04	1.06E-01	1.08E+00	3.35E-01	0
26	1.44E+00	8.91E-05	1.07E-01	1.08E+00	3.47E-01	0
27	1.50E+00	7.56E-05	1.07E-01	1.07E+00	3.59E-01	0
28	1.55E+00	9.19E-05	1.08E-01	1.07E+00	3.76E-01	0
29	1.61E+00	8.40E-05	1.08E-01	1.06E+00	3.93E-01	0
30	1.66E+00	4.06E-05	1.08E-01	1.06E+00	4.02E-01	0
31	1.71E+00	3.94E-05	1.08E-01	1.05E+00	4.12E-01	0
32	1.77E+00	5.45E-05	1.08E-01	1.05E+00	4.28E-01	0
33	1.82E+00	4.36E-05	1.09E-01	1.04E+00	4.41E-01	0
34	1.88E+00	4.01E-05	1.09E-01	1.04E+00	4.54E-01	0
35	1.93E+00	2.77E-05	1.09E-01	1.04E+00	4.64E-01	0
36	1.99E+00	1.85E-05	1.09E-01	1.03E+00	4.72E-01	0
37	2.04E+00	2.80E-05	1.09E-01	1.03E+00	4.84E-01	0
38	2.10E+00	1.61E-05	1.09E-01	1.03E+00	4.91E-01	0
39	2.15E+00	1.39E-05	1.09E-01	1.03E+00	4.99E-01	0
40	2.20E+00	1.47E-05	1.09E-01	1.02E+00	5.07E-01	0
41	2.26E+00	1.22E-05	1.09E-01	1.02E+00	5.14E-01	0
42	2.31E+00	9.50E-06	1.09E-01	1.02E+00	5.20E-01	0
43	2.37E+00	6.28E-06	1.09E-01	1.02E+00	5.25E-01	0
44	2.42E+00	6.85E-06	1.09E-01	1.02E+00	5.30E-01	0
45	2.48E+00	5.44E-06	1.09E-01	1.02E+00	5.35E-01	0
46	2.53E+00	5.55E-06	1.09E-01	1.02E+00	5.40E-01	0
47	2.58E+00	7.00E-06	1.09E-01	1.01E+00	5.47E-01	0
48	2.64E+00	5.09E-06	1.09E-01	1.01E+00	5.52E-01	0
49	2.69E+00	5.23E-06	1.09E-01	1.01E+00	5.58E-01	0
50	2.75E+00	4.52E-06	1.09E-01	1.01E+00	5.63E-01	0
51	2.80E+00	3.98E-06	1.09E-01	1.01E+00	5.68E-01	0

*Appendix A7 – HR WaveData*

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52	2.86E+00	3.28E-06	1.10E-01	1.01E+00	5.72E-01	0
53	2.91E+00	2.76E-06	1.10E-01	1.01E+00	5.76E-01	0
54	2.97E+00	2.44E-06	1.10E-01	1.01E+00	5.80E-01	0
55	3.02E+00	3.63E-06	1.10E-01	1.01E+00	5.86E-01	0
56	3.07E+00	2.95E-06	1.10E-01	1.01E+00	5.91E-01	0
57	3.13E+00	1.66E-06	1.10E-01	1.01E+00	5.94E-01	0
58	3.18E+00	1.85E-06	1.10E-01	1.00E+00	5.97E-01	0
59	3.24E+00	2.09E-06	1.10E-01	1.00E+00	6.01E-01	0
60	3.29E+00	1.82E-06	1.10E-01	1.00E+00	6.05E-01	0
61	3.35E+00	1.16E-06	1.10E-01	1.00E+00	6.08E-01	0
62	3.40E+00	1.29E-06	1.10E-01	1.00E+00	6.11E-01	0
63	3.46E+00	1.62E-06	1.10E-01	1.00E+00	6.15E-01	0

\* Warning flag = 0, for Spectral Density bands that are less than 10 per cent of the maximum band.

The header and the first few lines from a typical ASC file are given below.

The example belongs to the load cell data for the TAP0160 test condition.

HEADER OF BINARY DATA FILE.

=====  
 Stan. tap0160 Heading

Channel Numbers  
 00 01 02 03 05 06 07  
 7 Number of Channels  
 32768 Scan Rate  
 323 Clock Ticks  
 3 CLock Rate

=====  
 Channel 1 Raw Data.

=====  

Calibrated Data	Raw Data	Line No.
663.674561	3828	0
663.674561	3828	1
651.607727	3829	2
651.607727	3829	3
639.540894	3830	4
639.540894	3830	5
651.607727	3829	6

### A7.3. HR WaveData - WARP

WARP is a wave counting technique that produces the time history of the signal (on screen) and selected statistical information about the data (on screen and in text files). The analysis procedure identifies the first crossing of the mean value and subsequently stores the mean, maximum and minimum values. The wave periods and the number of waves are both recorded. The standard deviation can be about the mean of the record or any user-defined threshold. Histograms, exceedance plots and other statistical values can also be produced if required.

WARP provides a text file with an extension “.WAR” and a typical WARP file is provided below.

HR Warp Version 2.0a Written In April 1993.  
Results for real time wave analysis run on 13/03/2001 at 10:59:36

Gain 0.94

Calibration file used = 1303.cal - 13/3/2001 10:26:0  
Number of data batches = 1  
Batch length = 1000 Prototype Seconds  
Time interval between samples = 0.0500 Prototype Seconds  
Model/Prototype scale ratio = 1.0000

Crossing level for channel 0 = RUNNING MEAN  
Crossing level for channel 3 = RUNNING MEAN  
Crossing level for channel 4 = RUNNING MEAN  
Crossing level for channel 5 = RUNNING MEAN  
Crossing level for channel 6 = RUNNING MEAN  
Crossing level for channel 7 = RUNNING MEAN

\*\*\* Calibration data \*\*\*

Calibration factor for channel 0 = 0.000153303 - Deep Water  
Calibration factor for channel 3 = 0.000129115 - 1.56m from toe structure  
Calibration factor for channel 4 = 0.00012721 - 1.56m up spending beach  
Calibration factor for channel 5 = 0.000145349 - 1.56m from toe of spending beach  
Calibration factor for channel 6 = 0.000143823 - Spending beach toe  
Calibration factor for channel 7 = 0.000131027 - Structure toe

Digital zero level for channel 0 = 2067  
Digital zero level for channel 3 = 2042  
Digital zero level for channel 4 = 1998  
Digital zero level for channel 5 = 2052  
Digital zero level for channel 6 = 2046  
Digital zero level for channel 7 = 2044

*Appendix A7 – HR WaveData*

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- Note 1. A wave is counted if it passes through the crossing level.
- Note 2. +ve value for min v. or max v. means above zero level.
- Note 3. +ve value for min disp. or max disp. means above crossing level.
- Note 4. Crossing level is relative to the zero level.
- Note 5. Mean is relative to the zero level.

CHAN	BATCH	BAD	WAVES	H MAX	H10	H3	TBAR
0	1	0	940	1.795e-01	1.383e-01	1.115e-01	1.063e+00
3	1	0	915	1.810e-01	1.260e-01	1.005e-01	1.092e+00
4	1	0	893	1.603e-01	1.204e-01	9.410e-02	1.120e+00
5	1	0	897	1.826e-01	1.279e-01	1.003e-01	1.114e+00
6	1	0	902	1.942e-01	1.287e-01	1.010e-01	1.108e+00
7	1	0	902	1.766e-01	1.295e-01	1.016e-01	1.109e+00

RUN RESULTS

CHAN	BAD	WAVES	MEAN OF H MAX	MEAN OF H10	MEAN OF H3	TBAR
0	0	940	1.795e-01	1.383e-01	1.115e-01	1.063e+00
3	0	915	1.810e-01	1.259e-01	1.005e-01	1.092e+00
4	0	893	1.603e-01	1.203e-01	9.401e-02	1.120e+00
5	0	897	1.826e-01	1.279e-01	1.003e-01	1.114e+00
6	0	902	1.942e-01	1.286e-01	1.008e-01	1.108e+00
7	0	902	1.766e-01	1.295e-01	1.015e-01	1.109e+00

\*\*\*\* Histograms \*\*\*\*



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## Appendix - A8. HR WaveMaker

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HR WaveMaker is a wave synthesizer package written and developed by HR Wallingford Ltd. It runs on an IBM compatible PC and controls single or multi-element wave-making machines. Installation creates a short-cut icon on the desktop and the program can be started by double-clicking on it.

Waves generated by HR WaveMaker can conform to the choice of spectrum e.g. JONSWAP, Pierson-Moskowitz, International Ship Structure Congress (ISSC), Bretschneider/Mitsuyasu, Darbyshire Coastal Wave Spectrum, BTTP, etc. The program generates regular (sinusoidal) waves, bi-directional waves, multi-directional waves and WNSD (Random Waves with/without set-down compensation) (Beresford, 2001).

HR WaveMaker includes the facility to modify the motion of piston-type wave machines in real time to ensure that set-down propagates realistically without contamination by other, unwanted, second-order effects. The WNSD type wave generation technique was selected to create waves for the SHADOW project.

HR WaveMaker files are encrypted. Therefore, a sample file cannot be provided. Further information about how to install or how to use HRWaveMaker software can be found in the software manual (Beresford, 2001).

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# APPENDIX B

## Data Processing

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## Appendix - B1. Visual check

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Figures B1-1 to B1-9 provided a visual check to compare the *proBAY* results with the overtopping detector signal recorded for the TAP0160 test condition.

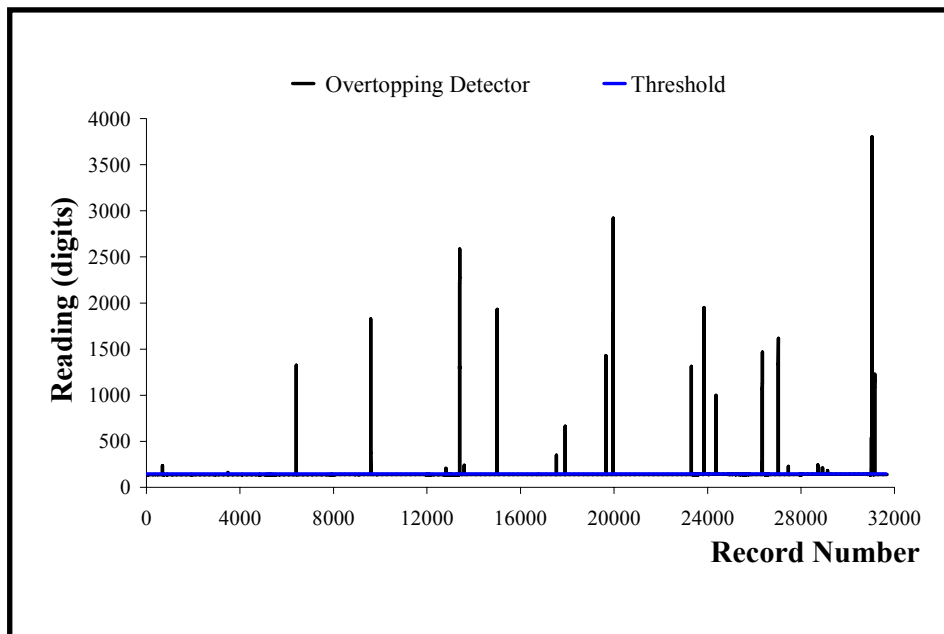


Figure B1-1 Visual check for the overtopping detector signal (for TAP0160 – SHADOW Phase I)

Appendix B1 – Visual Check

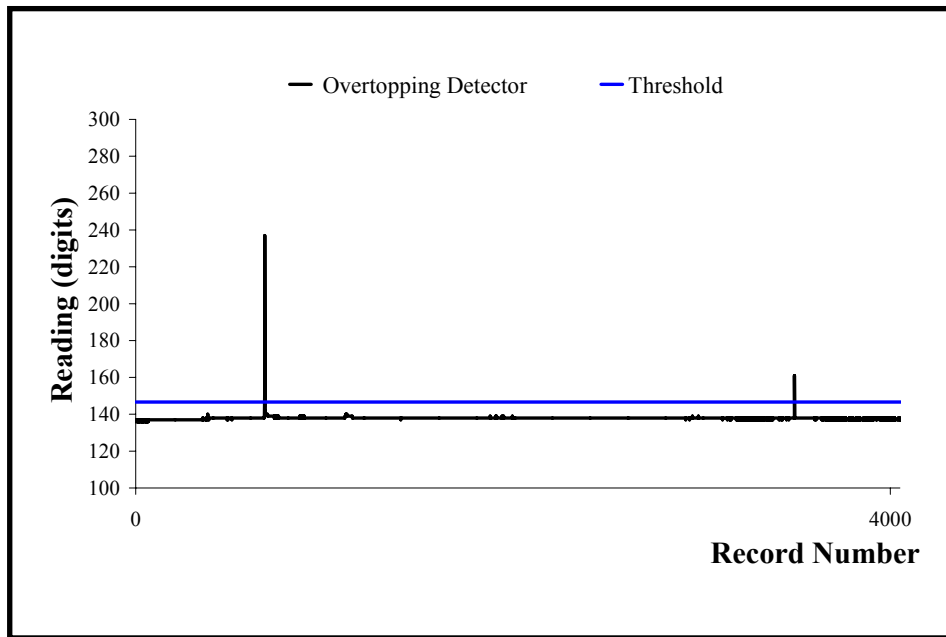


Figure B1-2 Visual check for the overtopping detector signal for 0-4000 interval (for TAP0160 – SHADOW Phase I)

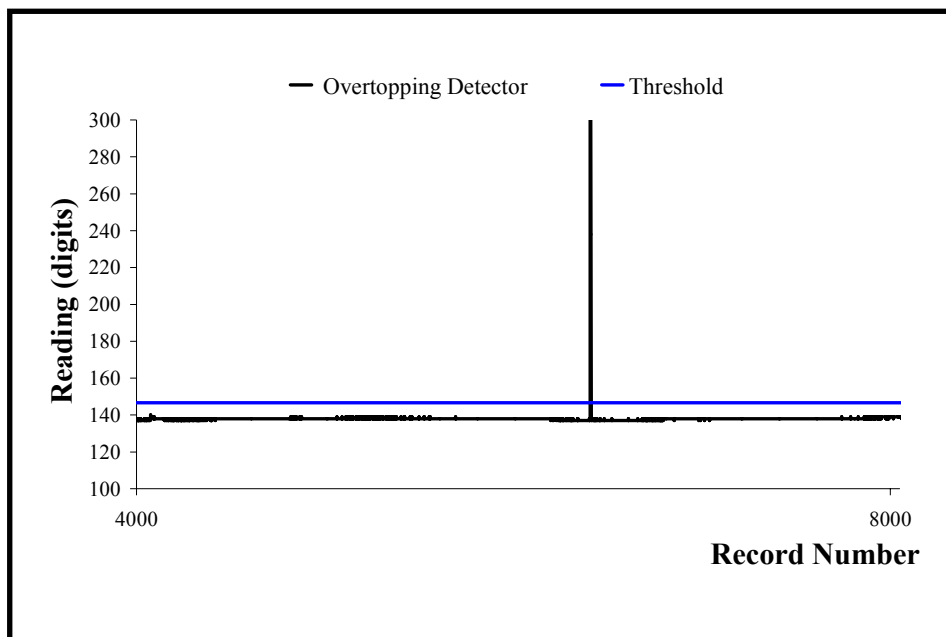


Figure B1-3 Visual check for the overtopping detector signal for 4000-8000 interval (for TAP0160 – SHADOW Phase I)

Appendix B1 – Visual Check

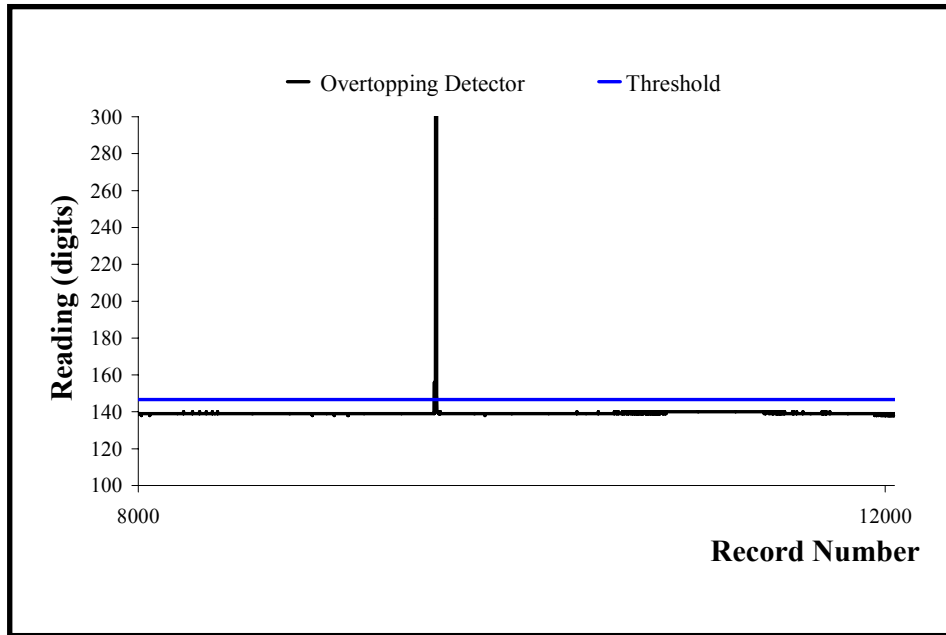


Figure B1-4 Visual check for the overtopping detector signal for 8000-12000 interval (for TAP0160 – SHADOW Phase I)

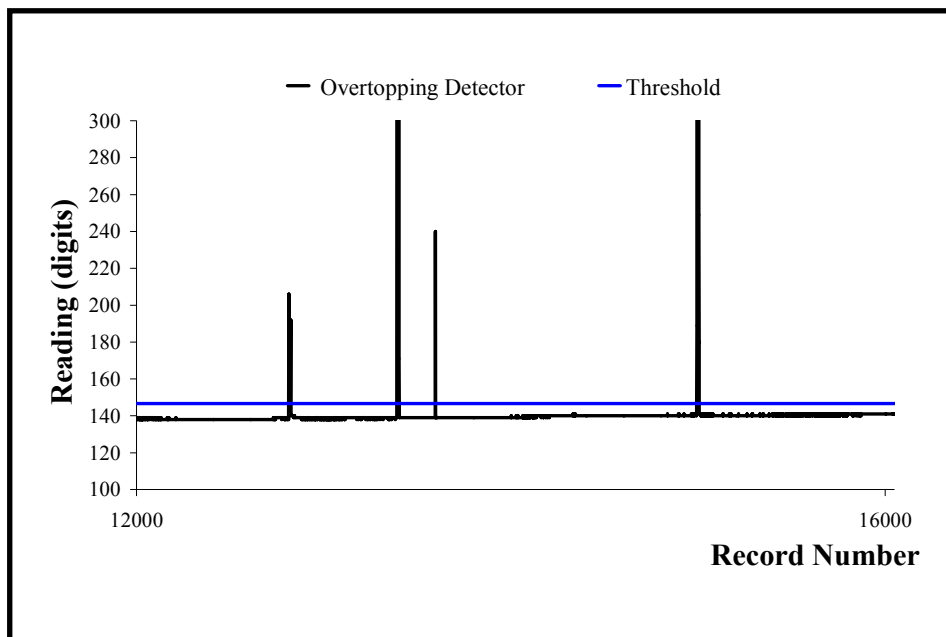


Figure B1-5 Visual check for the overtopping detector signal for 12000-16000 interval (for TAP0160 – SHADOW Phase I)

Appendix B1 – Visual Check

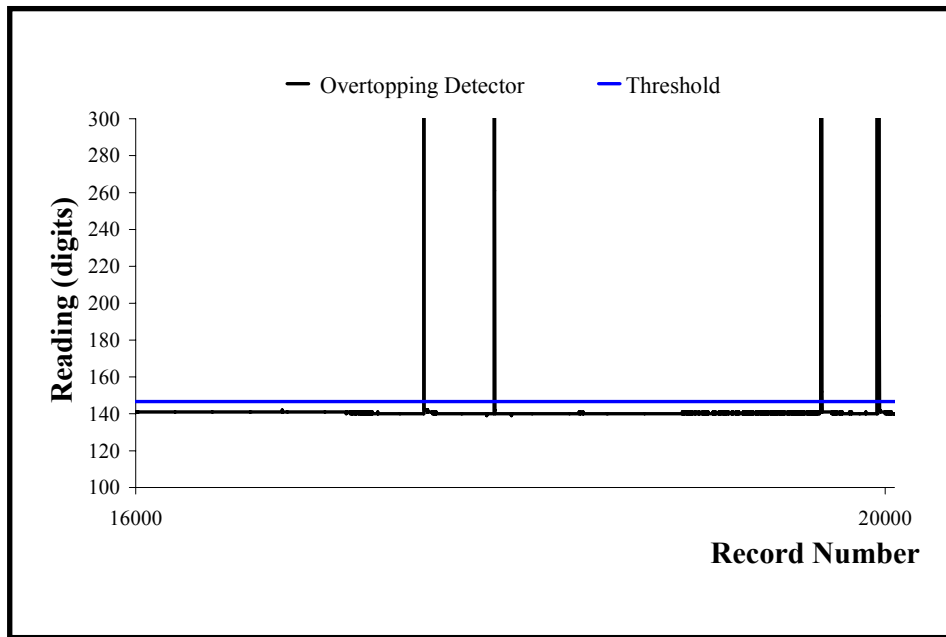


Figure B1-6 Visual check for the overtopping detector signal for 16000-20000 interval (for TAP0160 – SHADOW Phase I)

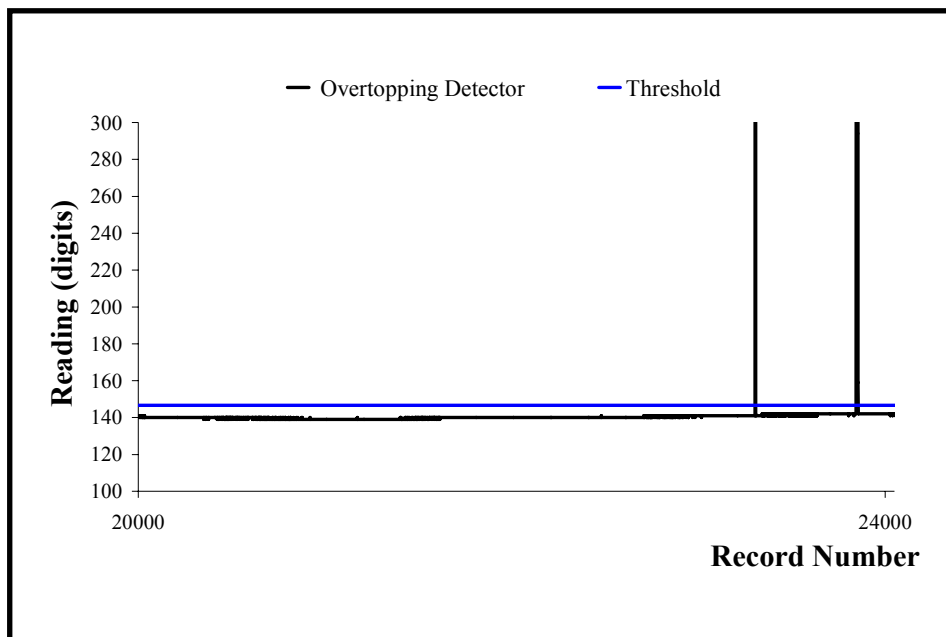


Figure B1-7 Visual check for the overtopping detector signal for 20000-24000 interval (for TAP0160 – SHADOW Phase I)

Appendix B1 – Visual Check

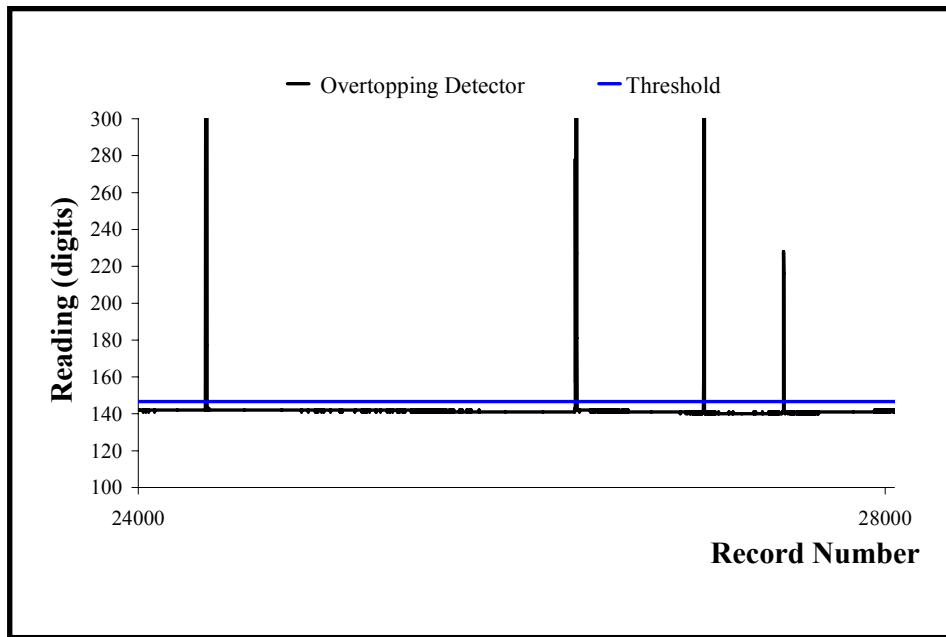


Figure B1-8 Visual check for the overtopping detector signal for 24000-28000 interval (for TAP0160 – SHADOW Phase I)

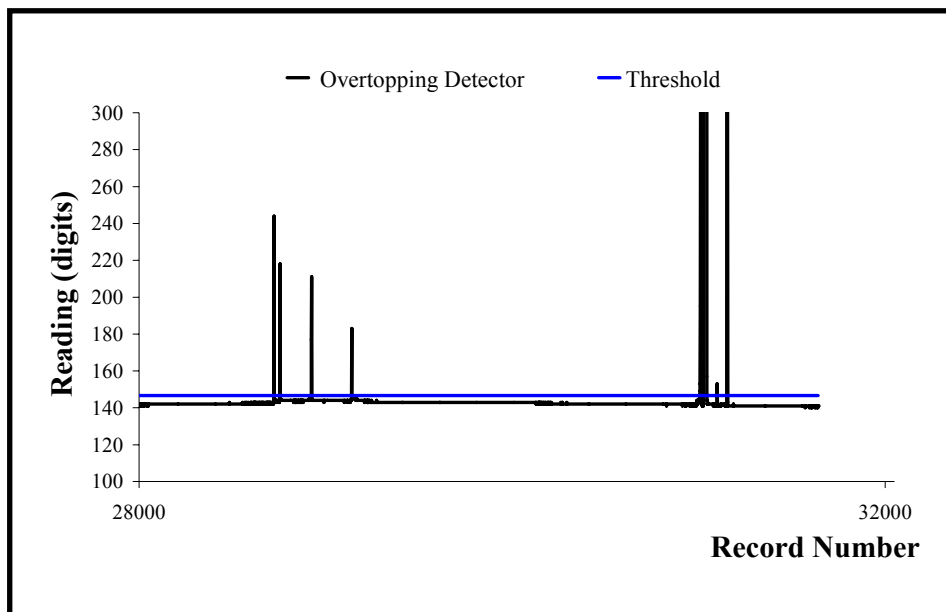


Figure B1-9 Visual check for the overtopping detector signal for 28000-32000 interval (for TAP0160 – SHADOW Phase I)

Appendix B1 – Visual Check

Figures B1-10 to B1-18 provided a visual check to compare the *proBAY* results with the load cell signal recorded for the TAP0160 test condition.

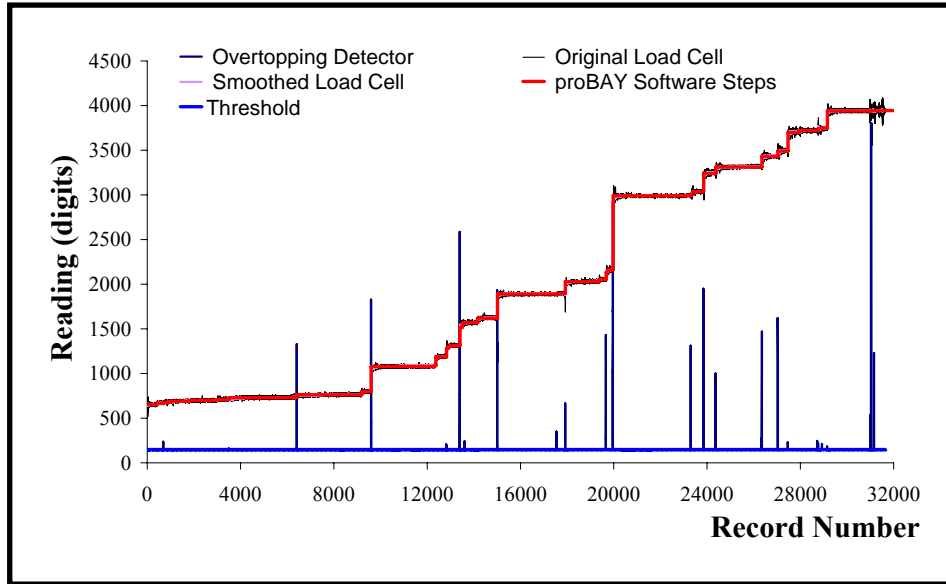


Figure B1-10 Visual check to compare *proBAY* results with the load cell signal (for TAP0160 – SHADOW Phase I)

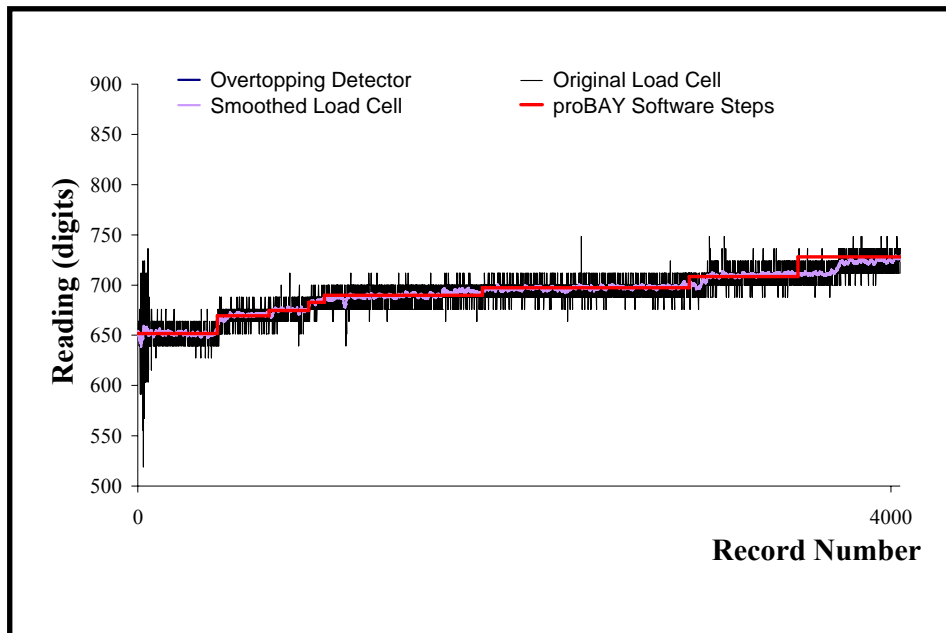


Figure B1-11 Visual check to compare *proBAY* results with the load cell signal for 0-4000 interval (for TAP0160 – SHADOW Phase I)



Appendix B1 – Visual Check

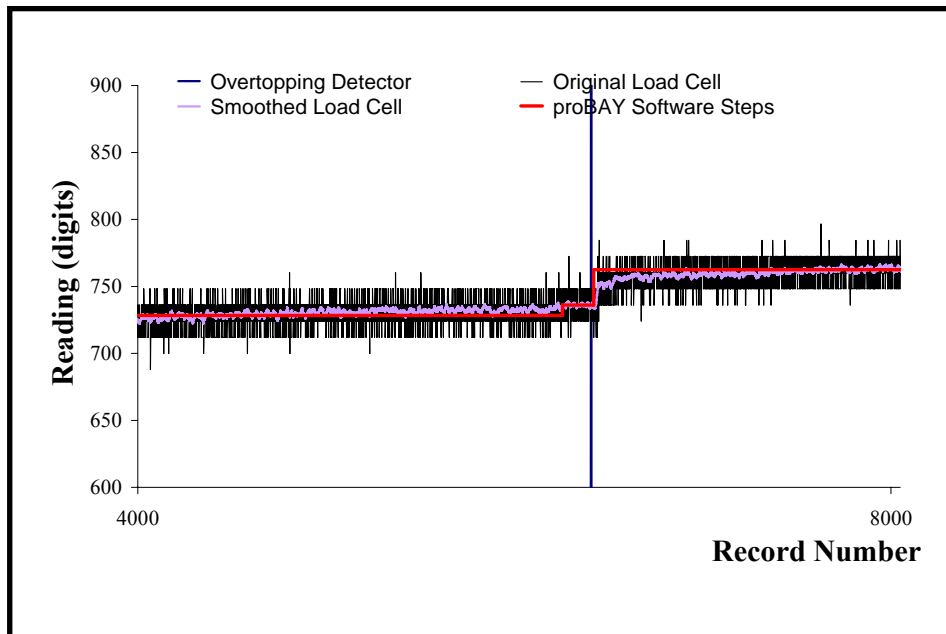


Figure B1-12 Visual check to compare *proBAY* results with the load cell signal for 4000-8000 interval (for TAP0160 – SHADOW Phase I)

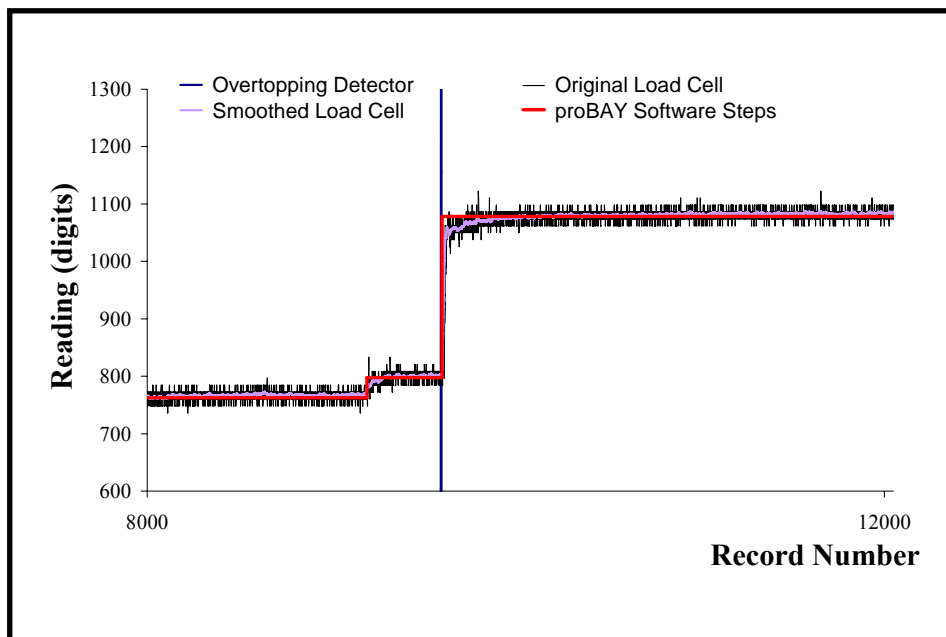


Figure B1-13 Visual check to compare *proBAY* results with the load cell signal for 8000-12000 interval (for TAP0160 – SHADOW Phase I)

Appendix B1 – Visual Check

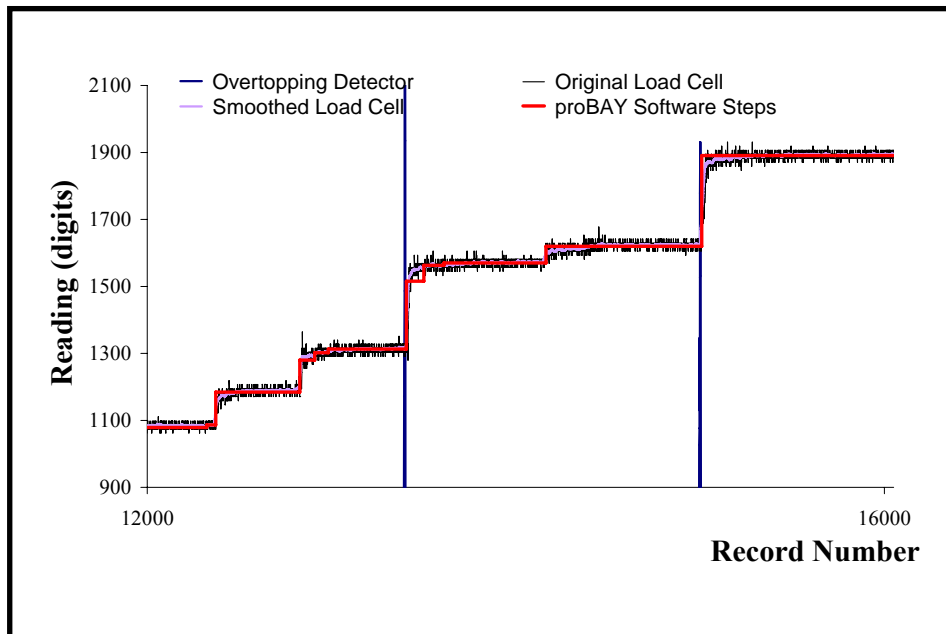


Figure B1-14 Visual check to compare *proBAY* results with the load cell signal for 12000-16000 interval (for TAP0160 – SHADOW Phase I)

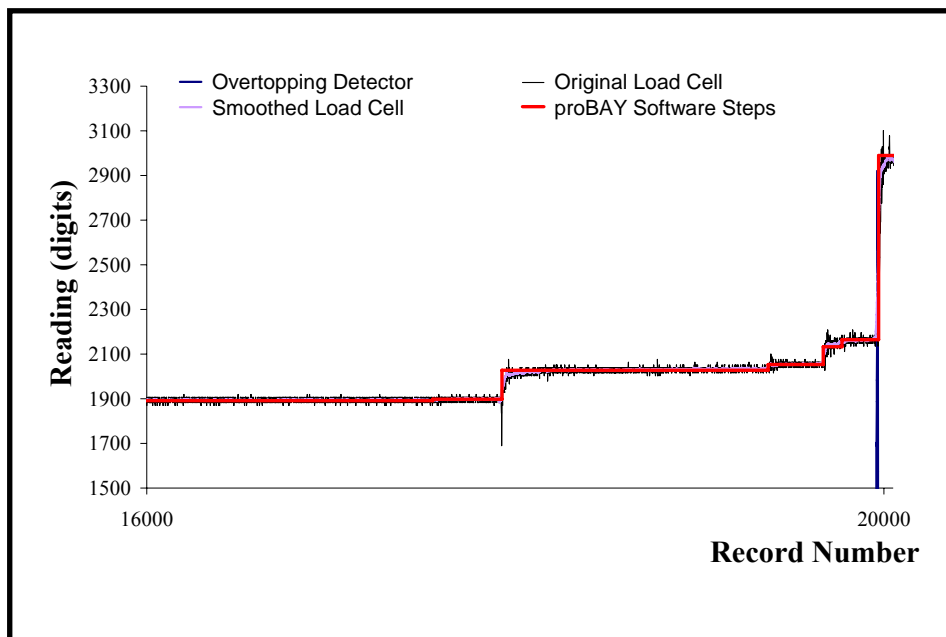


Figure B1-15 Visual check to compare *proBAY* results with the load cell signal for 16000-20000 interval (for TAP0160 – SHADOW Phase I)

Appendix B1 – Visual Check

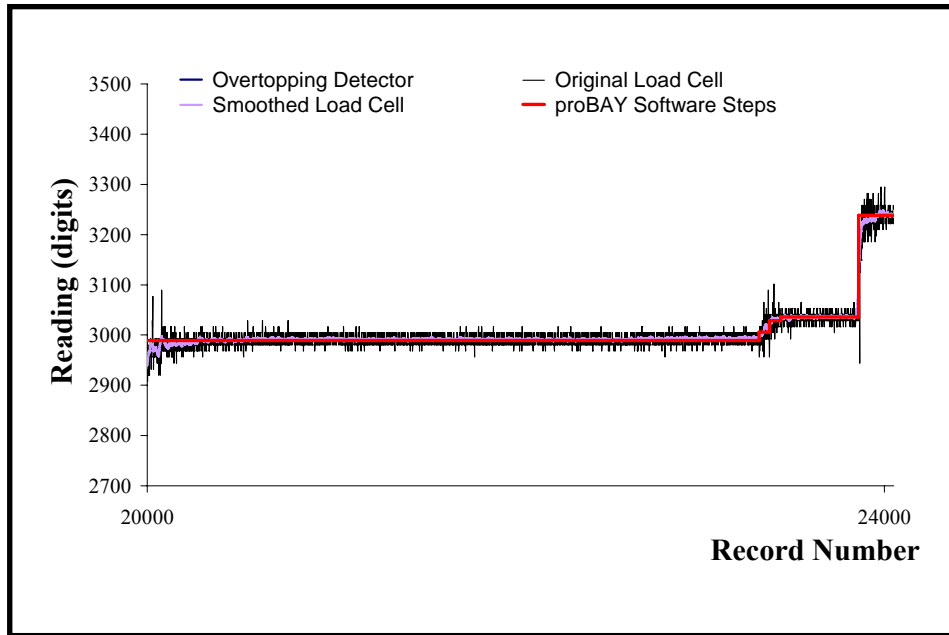


Figure B1-16 Visual check to compare *proBAY* results with the load cell signal for 20000-24000 interval (for TAP0160 – SHADOW Phase I)

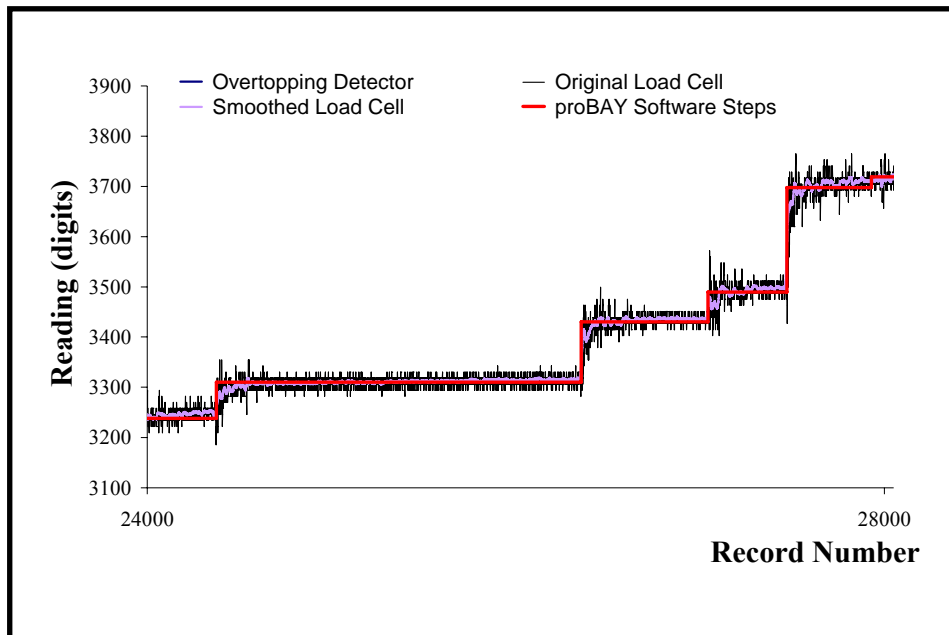


Figure B1-17 Visual check to compare *proBAY* results with the load cell signal for 24000-28000 interval (for TAP0160 – SHADOW Phase I)

Appendix B1 – Visual Check

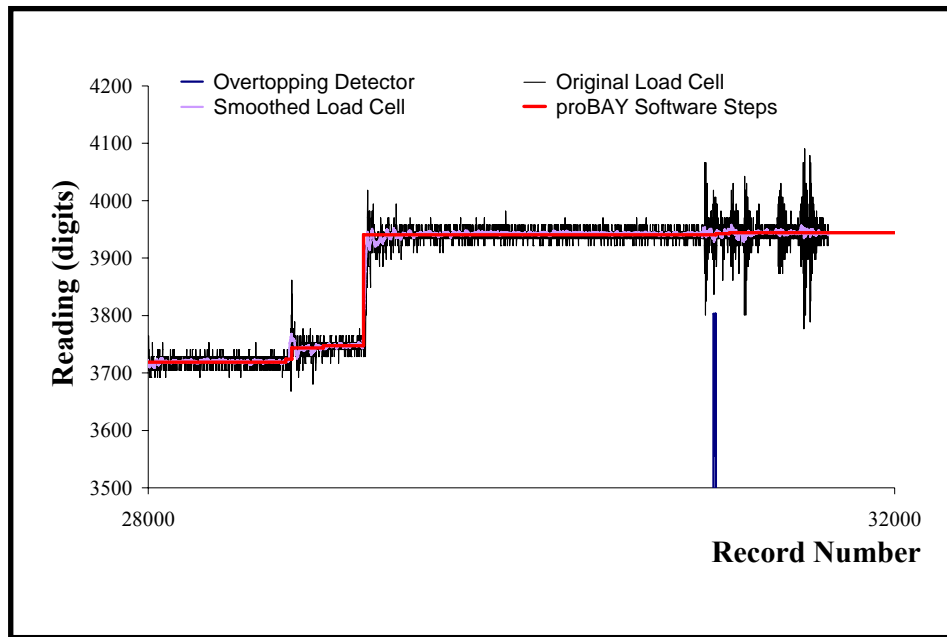


Figure B1-18 Visual check to compare *proBAY* results with the load cell signal for 28000-32000 interval (for TAP0160 – SHADOW Phase I)

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## Appendix - B2. Tables of *proBAY* results

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The tables below give *proBAY* results for all test conditions.

Table B2-1 *proBAY* results for SHADOW Phase I, 1:2 slope 600mm water depth tests

Test Number	File Name	H <sub>s</sub> (m)	T <sub>p</sub> (s)	Slope (1/x)	Water Depth (m)	Freeboard (m)
1	TAP0160	0.096	1.114	2	0.601	0.399
2	TAP0260	0.108	1.393	2	0.601	0.399
3	TAP0360	0.153	1.393	2	0.601	0.399
4	TAP0460	0.101	1.672	2	0.601	0.399
4a	TAP0460A	0.101	1.672	2	0.601	0.399
5	TAP0560	0.148	1.672	2	0.601	0.399
6X	TAP0660X	0.199	1.672	2	0.600	0.400
6Y	TAP0660Y	0.199	1.672	2	0.600	0.400
6Z	TAP0660Z	0.199	1.672	2	0.600	0.400
6	TAP0660ALL	0.199	1.672	2	0.600	0.400
7	TAP0760	0.104	2.076	2	0.600	0.400
7A	TAP0760A	0.104	2.076	2	0.600	0.400
8	TAP0860	0.149	2.076	2	0.600	0.400
9W	TAP0960W	0.199	2.076	2	0.600	0.400
9X	TAP0960X	0.199	2.076	2	0.600	0.400
9Y	TAP0960Y	0.199	2.076	2	0.600	0.400
9Z	TAP0960Z	0.199	2.076	2	0.600	0.400
9	TAP0960ALL	0.199	2.076	2	0.600	0.400
11	TAP1160	0.103	2.230	2	0.600	0.400
11A	TAP1160A	0.103	2.230	2	0.600	0.400
11B	TAP1160B	0.103	2.230	2	0.600	0.400
12Y	TAP1260Y	0.149	2.230	2	0.600	0.400
12Z	TAP1260Z	0.149	2.230	2	0.600	0.400
12	TAP1260ALL	0.149	2.230	2	0.600	0.400
13U	TAP1360U	0.199	2.230	2	0.600	0.400
13V	TAP1360V	0.199	2.230	2	0.600	0.400
13W	TAP1360W	0.199	2.230	2	0.600	0.400
13X	TAP1360X	0.199	2.230	2	0.600	0.400
13Y	TAP1360Y	0.199	2.230	2	0.600	0.400
13Z	TAP1360Z	0.199	2.230	2	0.600	0.400
13	TAP1360ALL	0.199	2.230	2	0.600	0.400
14	TAP1460	0.101	2.854	2	0.600	0.400
14A	TAP1460A	0.101	2.854	2	0.600	0.400
15Y	TAP1560Y	0.149	2.670	2	0.600	0.400
15Z	TAP1560Z	0.149	2.670	2	0.600	0.400

Appendix B2 – Tables of proBAY Results

15	TAP1560ALL	0.149	2.670	2	0.600	0.400
16	TAP1660	0.101	2.967	2	0.600	0.400
16A	TAP1660A	0.101	2.967	2	0.600	0.400

Table B2-1 continued

File Name	Detector File Name	Load Cell File Name	Chute Width (mm)	Total Sampling Time (s)	Analysis Start Time (s)
TAP0160	01AT02.ASC	01AT01.ASC	500	1058.41	30.01
TAP0260	02AT02.ASC	02AT01.ASC	500	1310.72	30.04
TAP0360	03AT02.ASC	03AT01.ASC	100	1310.72	30.04
TAP0460	04AT02.ASC	04AT01.ASC	100	1559.76	30.04
TAP0460A	04CT02.ASC	04CT01.ASC	500	1559.76	30.04
TAP0560	05AT02.ASC	05AT01.ASC	100	1559.76	30.04
TAP0660X	K06X00.ASC	K06X01.ASC	100	560.33	30.01
TAP0660Y	K06Y00.ASC	K06Y01.ASC	100	560.33	30.01
TAP0660Z	K06Z00.ASC	K06Z01.ASC	100	560.33	30.01
TAP0660ALL			100	1681.00	
TAP0760	07AT02.ASC	07AT01.ASC	100	1808.79	30.03
TAP0760A	07CT02.ASC	07CT01.ASC	500	1808.79	30.03
TAP0860	08AT02.ASC	08AT01.ASC	100	1808.79	30.03
TAP0960W	K09W00.ASC	K09W01.ASC	100	498.07	30.00
TAP0960X	K09X00.ASC	K09X01.ASC	100	498.07	30.00
TAP0960Y	K09Y00.ASC	K09Y01.ASC	100	498.07	30.00
TAP0960Z	K09Z00.ASC	K09Z01.ASC	100	498.07	30.00
TAP0960ALL			100	1992.30	
TAP1160	K11A00.ASC	K11A01.ASC	100	2057.83	30.02
TAP1160A	K11C00.ASC	K11C01.ASC	500	2057.83	30.02
TAP1160B	K11D00.ASC	K11D01.ASC	500	2057.83	30.02
TAP1260Y	K12Y00.ASC	K12Y01.ASC	100	1061.68	30.00
TAP1260Z	K12Z00.ASC	K12Z01.ASC	100	1061.68	30.00
TAP1260ALL			100	2123.36	
TAP1360U	K13U00.ASC	K13U01.ASC	100	393.22	30.00
TAP1360V	K13V00.ASC	K13V01.ASC	100	393.22	30.00
TAP1360W	K13W00.ASC	K13W01.ASC	100	393.22	30.00
TAP1360X	K13X00.ASC	K13X01.ASC	100	393.22	30.00
TAP1360Y	K13Y00.ASC	K13Y01.ASC	100	393.22	30.00
TAP1360Z	K13Z00.ASC	K13Z01.ASC	100	399.77	30.01
TAP1360ALL			100	2365.85	
TAP1460	K14A00.ASC	K14A01.ASC	100	2306.87	30.03
TAP1460A	K14C00.ASC	K14C01.ASC	500	2306.87	30.03
TAP1560Y	K15Y00.ASC	K15Y01.ASC	100	1186.20	30.01
TAP1560Z	K15Z00.ASC	K15Z01.ASC	100	1186.20	30.01
TAP1560ALL			100	2372.40	
TAP1660	K16A00.ASC	K16A01.ASC	500	2562.46	30.03
TAP1660A	K16C00.ASC	K16C01.ASC	500	2562.46	30.03

Appendix B2 – Tables of proBAY Results

Table B2-1 continued

File Name	Analysis Finish Time (s)	Total Analysis Time (s)	Number of Waves Analysed	Noise Filter Threshold	Number of Waves Overtopping
TAP0160	1052.11	1022.10	936	146.575	42
TAP0260	1302.56	1272.52	988	149.318	68
TAP0360	1302.96	1272.92	936	219.410	178
TAP0460	1550.95	1520.92	970	181.559	108
TAP0460A	1550.95	1520.92	970	215.997	83
TAP0560	1549.71	1519.68	954	254.161	186
TAP0660X	550.77	520.76	316	229.814	114
TAP0660Y	550.77	520.76	316	637.098	103
TAP0660Z	550.77	520.76	316	255.687	111
TAP0660ALL		1562.29	948		328
TAP0760	1797.09	1767.06	947	221.486	42
TAP0760A	1797.09	1767.06	947	221.590	48
TAP0860	1798.14	1768.11	938	256.230	177
TAP0960W	487.21	457.20	239	213.665	79
TAP0960X	487.21	457.20	239	1121.130	82
TAP0960Y	487.21	457.20	239	46.886	90
TAP0960Z	487.21	457.20	239	18.445	80
TAP0960ALL		1828.80	956		331
TAP1160	2044.77	2014.75	964	-11.490	28
TAP1160A	2044.77	2014.75	964	-10.030	32
TAP1160B	2044.77	2014.75	964	-18.257	48
TAP1260Y	1048.16	1018.15	483	-98.581	92
TAP1260Z	1048.16	1018.15	483	-104.894	103
TAP1260ALL		2036.30	966		195
TAP1360U	379.43	349.43	166	235.712	57
TAP1360V	379.43	349.43	166	85.634	50
TAP1360W	379.43	349.43	166	1212.410	54
TAP1360X	379.43	349.43	166	1668.020	57
TAP1360Y	379.43	349.43	166	1902.100	69
TAP1360Z	379.43	349.42	166	991.848	65
TAP1360ALL		2096.56	996		352
TAP1460	2291.59	2261.56	909	-66.080	19
TAP1460A	2291.59	2261.56	909	-6.699	26
TAP1560Y	1170.82	1140.81	472	-91.623	104
TAP1560Z	1170.82	1140.81	472	-91.456	133
TAP1560ALL		2281.62	944		237
TAP1660	2545.33	2515.30	915	-163.218	11
TAP1660A	2545.33	2515.30	915	-103.838	8

Appendix B2 – Tables of proBAY Results

Table B2-1 continued

<b>File Name</b>	<b>Total Overtopping Volume (lt)</b>	<b>Maximum Overtopping Volume (lt)</b>	<b>Mean Overtopping Volume (lt)</b>	<b>Mean Overtopping Rate (lt/s/m)</b>
TAP0160	3.292	0.825	0.078	6.442E-03
TAP0260	14.564	2.229	0.214	2.289E-02
TAP0360	26.467	1.057	0.149	2.079E-01
TAP0460	3.391	0.356	0.031	2.229E-02
TAP0460A	16.493	2.164	0.199	2.169E-02
TAP0560	31.287	2.136	0.168	2.059E-01
TAP0660X	23.521	1.304	0.206	4.517E-01
TAP0660Y	28.607	1.457	0.278	5.493E-01
TAP0660Z	28.934	2.675	0.261	5.556E-01
TAP0660ALL	81.062	2.675	0.247	5.189E-01
TAP0760	2.728	0.403	0.065	1.544E-02
TAP0760A	16.385	1.912	0.341	1.854E-02
TAP0860	39.259	1.793	0.222	2.220E-01
TAP0960W	23.528	2.239	0.298	5.146E-01
TAP0960X	32.458	1.848	0.396	7.099E-01
TAP0960Y	30.167	2.830	0.335	6.598E-01
TAP0960Z	28.895	4.943	0.361	6.320E-01
TAP0960ALL	115.048	4.943	0.348	6.291E-01
TAP1160	1.966	0.535	0.070	9.756E-03
TAP1160A	7.579	2.405	0.237	7.524E-03
TAP1160B	7.819	2.652	0.163	7.762E-03
TAP1260Y	28.981	3.814	0.315	2.846E-01
TAP1260Z	24.869	3.919	0.241	2.443E-01
TAP1260ALL	53.851	3.919	0.276	2.645E-01
TAP1360U	31.121	4.784	0.546	8.906E-01
TAP1360V	23.855	2.983	0.477	6.827E-01
TAP1360W	32.981	3.821	0.611	9.439E-01
TAP1360X	29.563	3.815	0.519	8.460E-01
TAP1360Y	34.617	2.954	0.502	9.907E-01
TAP1360Z	35.332	4.631	0.544	1.011E+00
TAP1360ALL	187.468	4.784	0.533	8.942E-01
TAP1460	3.329	1.321	0.175	1.472E-02
TAP1460A	18.187	5.732	0.699	1.608E-02
TAP1560Y	28.883	2.494	0.278	2.532E-01
TAP1560Z	31.162	2.930	0.234	2.732E-01
TAP1560ALL	60.044	2.930	0.253	2.632E-01
TAP1660	7.130	2.468	0.648	5.669E-03
TAP1660A	6.828	3.574	0.853	5.429E-03



Appendix B2 – Tables of proBAY Results

Table B2-2 proBAY results for SHADOW Phase I, 1:2 slope 750mm water depth tests

File Number	File Name	H <sub>s</sub> (m)	T <sub>p</sub> (s)	Slope (1/x)	Water Depth (m)	Freeboard (m)
1	TAP0175	0.075	1.039	2	0.750	0.250
1R	TAP0175R	0.075	1.039	2	0.750	0.250
2	TAP0275	0.075	1.254	2	0.750	0.250
2R	TAP0275R	0.075	1.254	2	0.750	0.250
3	TAP0375	0.075	1.532	2	0.750	0.250
3R	TAP0375R	0.075	1.532	2	0.750	0.250
3S	TAP0375S	0.075	1.532	2	0.750	0.250
4	TAP0475	0.077	1.988	2	0.750	0.250
5A	TAP0575A	0.094	1.268	2	0.750	0.250
5R	TAP0575R	0.094	1.268	2	0.750	0.250
6	TAP0675	0.104	1.393	2	0.750	0.250
7L	TAP0775L	0.136	1.254	2	0.750	0.250
7M	TAP0775M	0.136	1.254	2	0.750	0.250
7N	TAP0775N	0.136	1.254	2	0.750	0.250
7	TAP0775ALL	0.136	1.254	2	0.750	0.250
8K	TAP0875K	0.145	1.483	2	0.750	0.250
8L	TAP0875L	0.145	1.483	2	0.750	0.250
8M	TAP0875M	0.145	1.483	2	0.750	0.250
8N	TAP0875N	0.145	1.483	2	0.750	0.250
8	TAP0875ALL	0.145	1.483	2	0.750	0.250
9J	TAP0975J	0.146	1.532	2	0.750	0.250
9K	TAP0975K	0.146	1.532	2	0.750	0.250
9L	TAP0975L(CUT)	0.146	1.532	2	0.750	0.250
9M	TAP0975M	0.146	1.532	2	0.750	0.250
9N	TAP0975N	0.146	1.532	2	0.750	0.250
9	TAP0975ALL(CUT)	0.146	1.532	2	0.750	0.250
10I	TAP1075I	0.175	1.483	2	0.750	0.250
10J	TAP1075J	0.175	1.483	2	0.750	0.250
10K	TAP1075K(CUT)	0.175	1.483	2	0.750	0.250
10	TAP1075ALL(CUT)	0.175	1.483	2	0.750	0.250
11M	TAP1175M	0.095	1.672	2	0.750	0.250
11N	TAP1175N	0.095	1.672	2	0.750	0.250
11	TAP1175ALL	0.095	1.672	2	0.750	0.250
12L	TAP1275L	0.102	2.230	2	0.750	0.250
12M	TAP1275M	0.102	2.230	2	0.750	0.250
12N	TAP1275N	0.102	2.230	2	0.750	0.250
12	TAP1275ALL	0.102	2.230	2	0.750	0.250
13M	TAP1375M	0.103	2.966	2	0.750	0.250
13N	TAP1375N(CUT)	0.103	2.966	2	0.750	0.250
13	TAP1375ALL(CUT)	0.103	2.966	2	0.750	0.250
14J	TAP1475J	0.095	1.672	2	0.750	0.250
14K	TAP1475K	0.095	1.672	2	0.750	0.250
14L	TAP1475L(CUT)	0.095	1.672	2	0.750	0.250
14	TAP1475ALL(CUT)	0.095	1.672	2	0.750	0.250

Appendix B2 – Tables of proBAY Results

Table B2-2 continued

File Name	Detector File Name	Load Cell File Name	Chute Width (mm)	Total Sampling Time (s)	Analysis Start Time (s)
TAP0175	J01B00.ASC	J01B01.ASC	500	933.89	
TAP0175R	K01R00.ASC	K01R01.ASC	500	933.89	
TAP0275	J02B00.ASC	J02B01.ASC	500	1186.20	30.01
TAP0275R	K02R00.ASC	K02R01.ASC	500	1186.20	30.01
TAP0375	K03B00.ASC	K03B01.ASC	500	1435.24	30.00
TAP0375R	K03R00.ASC	K03R01.ASC	500	1435.24	30.00
TAP0375S	K03S00.ASC	K03S01.ASC	500	1435.24	30.00
TAP0475	J04B00.ASC	J04B01.ASC	100	1684.28	30.02
TAP0575A	K05F00.ASC	K05F01.ASC	100	1058.41	30.01
TAP0575R	05RT00.ASC	05RT01.ASC	100	1058.41	30.01
TAP0675	J06B00.ASC	J06B01.ASC	100	1310.72	30.04
TAP0775L	K07L00.ASC	K07L01.ASC	100	435.81	30.00
TAP0775M	K07M00.ASC	K07M01.ASC	100	435.81	30.00
TAP0775N	K07N00.ASC	K07N01.ASC	100	435.81	30.00
TAP0775ALL			100	1307.44	
TAP0875K	K08K00.ASC	K08K01.ASC	100	373.56	30.00
TAP0875L	K08L00.ASC	K08L01.ASC	100	373.56	30.00
TAP0875M	K08M00.ASC	K08M01.ASC	100	373.56	30.00
TAP0875N	K08N00.ASC	K08N01.ASC	100	373.56	30.00
TAP0875ALL			100	1494.22	
TAP0975J	K09J00.ASC	K09J01.ASC	100	334.23	30.01
TAP0975K	K09K00.ASC	K09K01.ASC	100	334.23	30.01
TAP0975L(CUT)	K09L00.ASC	K09L01.ASC	100	334.23	30.01
TAP0975M	K09M00.ASC	K09M01.ASC	100	334.23	30.01
TAP0975N	K09N00.ASC	K09N01.ASC	100	334.23	30.01
TAP0975ALL(CUT)			100	1671.17	
TAP1075I	10IT00.ASC	10IT01.ASC	100	268.70	30.00
TAP1075J	10JT00.ASC	10JT01.ASC	100	268.70	30.00
TAP1075K(CUT)	10KT00.ASC	10KT01.ASC	100	268.70	30.00
TAP1075ALL(CUT)			100	806.09	
TAP1175M	K11M00.ASC	K11M01.ASC	100	809.37	30.01
TAP1175N	K11N00.ASC	K11N01.ASC	100	809.37	30.01
TAP1175ALL			100	1618.74	
TAP1275L	K12L00.ASC	K12L01.ASC	100	727.45	30.01
TAP1275M	K12M00.ASC	K12M01.ASC	100	727.45	30.01
TAP1275N	K12N00.ASC	K12N01.ASC	100	727.45	30.01
TAP1275ALL			100	2182.35	
TAP1375M	K13M00.ASC	K13M01.ASC	100	1310.72	30.04
TAP1375N(CUT)	K13N00.ASC	K13N01.ASC	100	1310.72	30.04
TAP1375ALL(CUT)			100	2621.44	
TAP1475J	14JT00.ASC	14JT01.ASC	100	360.45	30.008
TAP1475K	14KT00.ASC	14KT01.ASC	100	360.45	30.008
TAP1475L(CUT)	14LT00.ASC	14LT01.ASC	100	360.45	30.008
TAP1475ALL(CUT)			100	1081.34	

Appendix B2 – Tables of proBAY Results

Table B2-2 continued

File Name	Analysis Finish Time (s)	Total Analysis Time (s)	Number of Waves Analysed	Noise Filter Threshold	Number of Waves Overtopping
TAP0175	928.42	898.41	931	-169.283	48
TAP0175R	928.42	898.41	931	-61.844	68
TAP0275	1158.98	1128.97	1000	-176.733	92
TAP0275R	1158.98	1128.97	1000	-51.289	104
TAP0375	1426.17	1396.17	998	-174.675	105
TAP0375R	1426.17	1396.17	998	-4.326	103
TAP0375S	1426.17	1396.17	998	-80.875	95
TAP0475	1674.41	1644.39	937	-87.945	92
TAP0575A	1051.46	1021.46	938	-60.125	112
TAP0575R	1051.46	1021.46	938	-0.014	102
TAP0675	1303.20	1273.16	997	161.783	237
TAP0775L	428.61	398.60	327	1842.520	86
TAP0775M	428.61	398.60	327	2678.170	110
TAP0775N	428.61	398.60	327	1661.710	81
TAP0775ALL		1195.80	981		277
TAP0875K	365.92	335.91	252	2311.520	101
TAP0875L	365.92	335.91	252	2834.360	104
TAP0875M	365.92	335.91	252	2712.260	105
TAP0875N	365.92	335.91	252	2804.900	86
TAP0875ALL		1343.65	1008		396
TAP0975J	325.36	295.35	208	1195.930	101
TAP0975K	325.36	295.35	208	2390.210	94
TAP0975L(CUT)	241.59	211.58	149	2744.000	64
TAP0975M	325.36	295.35	208	2836.050	95
TAP0975N	325.36	295.35	208	2605.420	92
TAP0975ALL(CUT)		1392.98	981		446
TAP1075I	259.74	229.74	166	0.382	70
TAP1075J	259.74	229.74	166	0.420	78
TAP1075K(CUT)	182.24	152.23	110	0.153	69
TAP1075ALL(CUT)		611.71	442		217
TAP1175M	800.50	770.49	500	333.380	133
TAP1175N	800.50	770.49	500	119.939	128
TAP1175ALL		1540.98	1000		261
TAP1275L	714.60	684.58	326	-69.105	81
TAP1275M	714.60	684.58	326	881.224	92
TAP1275N	714.60	684.58	326	196.943	105
TAP1275ALL		2053.74	978		278
TAP1375M	1292.720	1262.680	458	-109.357	83
TAP1375N(CUT)	1157.640	1127.600	409	-145.652	90
TAP1375ALL(CUT)		2390.280	867		173
TAP1475J	350.526	320.518	208	0.181	76
TAP1475K	350.526	320.518	208	0.362	97
TAP1475L(CUT)	304.304	274.296	178	0.245	77
TAP1475ALL(CUT)		915.332	594		250

Appendix B2 – Tables of *proBAY* Results

Table B2-2 continued

<b>File Name</b>	<b>Total Overtopping Volume (lt)</b>	<b>Maximum Overtopping Volume (lt)</b>	<b>Mean Overtopping Volume (lt)</b>	<b>Mean Overtopping Rate (lt/s/m)</b>
TAP0175	6.810	0.942	0.142	1.516E-02
TAP0175R	8.645	1.110	0.127	1.925E-02
TAP0275	26.658	2.451	0.290	4.722E-02
TAP0275R	23.839	2.100	0.229	4.223E-02
TAP0375	34.995	1.798	0.333	5.013E-02
TAP0375R	43.220	2.308	0.420	6.191E-02
TAP0375S	41.489	1.915	0.437	5.943E-02
TAP0475	12.376	1.016	0.135	7.526E-02
TAP0575A	9.505	0.610	0.085	9.306E-02
TAP0575R	8.874	0.403	0.087	8.687E-02
TAP0675	41.842	0.944	0.177	3.286E-01
TAP0775L	21.773	1.047	0.253	5.462E-01
TAP0775M	31.892	1.054	0.290	8.001E-01
TAP0775N	24.611	1.143	0.304	6.174E-01
TAP0775ALL	78.276	1.143	0.283	6.546E-01
TAP0875K	30.905	1.761	0.306	9.200E-01
TAP0875L	39.857	1.653	0.383	1.187E+00
TAP0875M	37.562	1.682	0.358	1.118E+00
TAP0875N	32.081	1.680	0.373	9.550E-01
TAP0875ALL	140.405	1.761	0.355	1.045E+00
TAP0975J	31.318	1.611	0.310	1.060E+00
TAP0975K	42.519	2.227	0.452	1.440E+00
TAP0975L(CUT)	40.418	1.842	0.632	1.910E+00
TAP0975M	41.255	1.573	0.434	1.397E+00
TAP0975N	41.328	2.398	0.449	1.399E+00
TAP0975ALL(CUT)	196.838	2.398	0.441	1.413E+00
TAP1075I	30.990	1.340	0.443	1.349E+00
TAP1075J	39.883	2.166	0.511	1.736E+00
TAP1075K(CUT)	39.773	2.401	0.576	2.613E+00
TAP1075ALL(CUT)	110.646	2.401	0.510	1.809E+00
TAP1175M	26.497	1.161	0.199	3.439E-01
TAP1175N	24.690	1.092	0.193	3.204E-01
TAP1175ALL	51.187	1.161	0.196	3.322E-01
TAP1275L	19.467	1.443	0.240	2.844E-01
TAP1275M	39.051	2.796	0.424	5.704E-01
TAP1275N	27.008	2.184	0.257	3.945E-01
TAP1275ALL	85.525	2.796	0.308	4.164E-01
TAP1375M	29.469	2.301	0.355	2.334E-01
TAP1375N(CUT)	41.283	2.689	0.459	3.661E-01
TAP1375ALL(CUT)	70.752	2.689	0.409	2.960E-01
TAP1475J	31.853	1.814	0.419	9.938E-01
TAP1475K	42.180	1.709	0.435	1.316E+00
TAP1475L(CUT)	41.078	2.434	0.533	1.498E+00
TAP1475ALL(CUT)	115.111	2.434	0.460	1.258E+00

Appendix B2 – Tables of proBAY Results

Table B2-3 proBAY results for SHADOW Phase I, Low Overtopping, 600mm water depth tests

Test Number	File Name	H <sub>s</sub> (m)	T <sub>p</sub> (s)	Slope (1/x)	Water Depth (m)	Freeboard (m)
1	KJO0160	0.051	1.103	2	0.607	0.393
2	KJO0260	0.063	1.117	2	0.607	0.393
3	KJO0360	0.074	1.160	2	0.607	0.393
4	KJO0460	0.086	1.202	2	0.607	0.393
5	KJO0560	0.078	1.438	2	0.607	0.393
6	KJO0660	0.065	1.452	2	0.607	0.393
7	KJO0760	0.057	1.693	2	0.607	0.393
8	KJO0860	0.082	1.699	2	0.607	0.393
9	KJO0960	0.070	2.036	2	0.607	0.393
10	KJO1060	0.082	2.030	2	0.607	0.393
11	KJO1160	0.106	2.032	2	0.607	0.393
12	KJO1260	0.089	2.020	2	0.607	0.393
13	KJO1360	0.086	2.322	2	0.607	0.393
14	KJO1460	0.096	2.320	2	0.607	0.393
15	KJO1560	0.100	2.651	2	0.607	0.393
16	KJO1660	0.089	2.652	2	0.607	0.393
17	KJO1760	0.076	2.606	2	0.607	0.393
18	KJO1860	0.065	2.614	2	0.607	0.393
19	KJO1960	0.083	3.005	2	0.607	0.393
20	KJO2060	0.106	2.970	2	0.607	0.393
21	KJO2160	0.094	2.985	2	0.607	0.393

Table B2-3 continued

File Name	Detector File Name	Load Cell File Name	Chute Width (mm)	Total Sampling Time (s)	Analysis Start Time (s)
KJO0160	NT0102.ASC	NT0101.ASC	500	1058.41	30.01
KJO0260	NT0202.ASC	NT0201.ASC	500	1058.41	30.01
KJO0360	NT0302.ASC	NT0301.ASC	500	1058.41	30.01
KJO0460	NT0402.ASC	NT0401.ASC	500	1058.41	30.01
KJO0560	NT0502.ASC	NT0501.ASC	500	1310.72	30.04
KJO0660	NT0602.ASC	NT0601.ASC	500	1310.72	30.04
KJO0760	NT0702.ASC	NT0701.ASC	500	1559.76	30.04
KJO0860	NT8602.ASC	NT8601.ASC	500	1559.76	30.04
KJO0960	6N0902.ASC	6N0901.ASC	500	1808.79	30.03
KJO1060	6N1002.ASC	6N1001.ASC	500	1808.79	30.03
KJO1160	6N1102.ASC	6N1101.ASC	500	1808.79	30.03
KJO1260	6N1202.ASC	6N1201.ASC	500	1808.79	30.03
KJO1360	6N1302.ASC	6N1301.ASC	500	2057.83	30.02
KJO1460	6N1402.ASC	6N1401.ASC	500	2057.83	30.02
KJO1560	6N1502.ASC	6N1501.ASC	500	2306.87	30.03
KJO1660	6N1602.ASC	6N1601.ASC	500	2306.87	30.03
KJO1760	6N1702.ASC	6N1701.ASC	500	2306.87	30.03

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KJO1860	6N1802.ASC	6N1801.ASC	500	2306.87	30.03
KJO1960	6N1902.ASC	6N1901.ASC	500	2562.46	30.03
KJO2060	6N2002.ASC	6N2001.ASC	500	2562.46	30.03
KJO2160	6N2102.ASC	6N2101.ASC	500	2562.46	30.03

Table B2-3 continued

File Name	Analysis Finish Time (s)	Total Analysis Time (s)	Number of Waves Analysed	Noise Filter Threshold	Number of Waves Overtopping
KJO0160	989.80	959.79	1000	32.890	0
KJO0260	1001.98	971.97	1000	45.389	2
KJO0360	1038.99	1008.99	1000	45.607	5
KJO0460	1051.95	1021.94	977	55.047	13
KJO0560	1281.04	1251.00	1000	27.725	6
KJO0660	1293.04	1263.00	1000	-0.815	2
KJO0760	1503.02	1472.98	1000	-40.631	0
KJO0860	1508.02	1477.98	1000	0.436	10
KJO0960	1797.48	1767.45	998	13.541	0
KJO1060	1795.99	1765.96	1000	-25.025	0
KJO1160	1796.21	1766.18	999	18.273	18
KJO1260	1786.99	1756.96	1000	9.043	4
KJO1360	2043.95	2013.93	997	-27.392	0
KJO1460	2041.94	2011.92	997	15.395	6
KJO1560	2292.19	2262.16	981	16.965	6
KJO1660	2293.17	2263.15	981	-3.670	1
KJO1760	2292.47	2262.44	998	-6.712	1
KJO1860	2292.65	2262.62	995	-28.698	0
KJO1960	2547.29	2517.26	963	-29.168	0
KJO2060	2546.35	2516.32	974	13.773	5
KJO2160	2546.50	2516.48	969	-20.389	0

Table B2-3 continued

File Name	Total Overtopping Volume (lt)	Maximum Overtopping Volume (lt)	Mean Overtopping Volume (lt)	Mean Overtopping Rate (lt/s/m)
KJO0160	0.000	0.000	0.000	0.000E+00
KJO0260	0.037	0.023	0.018	7.538E-05
KJO0360	0.124	0.033	0.025	2.467E-04
KJO0460	0.619	0.265	0.048	1.212E-03
KJO0560	1.173	0.525	0.196	1.876E-03
KJO0660	0.088	0.076	0.044	1.400E-04
KJO0760	0.000	0.000	0.000	0.000E+00
KJO0860	0.291	0.140	0.029	3.942E-04

Appendix B2 – Tables of proBAY Results

KJO0960	0.000	0.000	0.000	0.000E+00
KJO1060	0.000	0.000	0.000	0.000E+00
KJO1160	3.043	1.065	0.169	3.445E-03
KJO1260	0.463	0.413	0.116	5.273E-04
KJO1360	0.000	0.000	0.000	0.000E+00
KJO1460	1.668	0.908	0.278	1.658E-03
KJO1560	5.842	4.648	0.974	5.165E-03
KJO1660	2.162	2.162	2.162	1.910E-03
KJO1760	0.221	0.221	0.221	1.955E-04
KJO1860	0.000	0.000	0.000	0.000E+00
KJO1960	0.000	0.000	0.000	0.000E+00
KJO2060	4.126	2.775	0.825	3.279E-03
KJO2160	0.000	0.000	0.000	0.000E+00

Table B2-4 proBAY results for SHADOW Phase I, Low Overtopping, 750mm water depth tests

Test Number	File Name	H <sub>s</sub> (m)	T <sub>p</sub> (s)	Slope (1/x)	Water Depth (m)	Freeboard (m)
1	KJO0175	0.059	1.076	2	0.751	0.249
2	KJO0275	0.050	1.024	2	0.751	0.249
3	KJO0375	0.042	0.994	2	0.751	0.249
4	KJO0475	0.049	1.232	2	0.751	0.249
5	KJO0575	0.039	1.254	2	0.751	0.249
6	KJO0675	0.029	1.259	2	0.751	0.249
7	KJO0775	0.039	1.566	2	0.751	0.249
8	KJO0875	0.049	1.562	2	0.751	0.249
9	KJO0975	0.039	1.822	2	0.751	0.249
10	KJO1075	0.049	1.817	2	0.751	0.249
11	KJO1175	0.058	1.893	2	0.751	0.249
12	KJO1275	0.049	1.232	2	0.751	0.249

Table B2-4 continued

File Name	Detector File Name	Load Cell File Name	Chute Width (mm)	Total Sampling Time (s)	Analysis Start Time (s)
KJO0175	7N0102.ASC	7N0101.ASC	500	933.89	30.01
KJO0275	7N0202.ASC	7N0201.ASC	500	933.89	30.01
KJO0375	7N0302.ASC	7N0301.ASC	500	933.89	30.01
KJO0475	7N0402.ASC	7N0401.ASC	500	1186.20	30.01
KJO0575	7N0502.ASC	7N0501.ASC	500	1186.20	30.01
KJO0675	-	-	-	-	-
KJO0775	7N0702.ASC	7N0701.ASC	500	1435.24	30.00
KJO0875	7N0802.ASC	7N0801.ASC	500	1435.24	30.00
KJO0975	7N0902.ASC	7N0901.ASC	500	1684.28	30.02

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KJO1075	7N1002.ASC	7N1001.ASC	500	1684.28	30.02
KJO1175	7N1102.ASC	7N1101.ASC	500	1684.28	30.02
KJO1275	570402.ASC	570401.ASC	500	5747.51	30.08

Table B2-4 continued

File Name	Analysis Finish Time (s)	Total Analysis Time (s)	Number of Waves Analysed	Noise Filter Threshold	Number of Waves Overtopping
KJO0175	927.42	897.41	959	85.284	23
KJO0275	921.01	891.00	1000	1.805	11
KJO0375	895.10	865.09	1000	3.408	4
KJO0475	1102.00	1071.99	1000	0.676	30
KJO0575	1121.01	1091.00	1000	-8.637	3
KJO0675	-	-	-	-	-
KJO0775	1391.96	1361.96	1000	-15.807	0
KJO0875	1388.99	1358.98	1000	-16.318	3
KJO0975	1614.99	1584.97	1000	-21.986	0
KJO1075	1610.98	1580.96	1000	-27.986	1
KJO1175	1673.69	1643.67	998	-31.766	5
KJO1275	5390.04	5359.96	5000	4.628	22

Table B2-4 continued

File Name	Total Overtopping Volume (lt)	Maximum Overtopping Volume (lt)	Mean Overtopping Volume (lt)	Mean Overtopping Rate (lt/s/m)
KJO0175	1.769	0.315	0.077	3.942E-03
KJO0275	0.229	0.059	0.021	5.131E-04
KJO0375	0.030	0.015	0.007	6.883E-05
KJO0475	2.025	1.147	0.068	3.779E-03
KJO0575	0.272	0.228	0.091	4.983E-04
KJO0675	-	-	-	-
KJO0775	0.000	0.000	0.000	0.000E+00
KJO0875	0.391	0.247	0.130	5.758E-04
KJO0975	0.000	0.000	0.000	0.000E+00
KJO1075	0.076	0.076	0.076	9.627E-05
KJO1175	1.373	1.245	0.275	1.670E-03
KJO1275	1.926	0.659	0.088	7.186E-04



Appendix B2 – Tables of *proBAY* Results

Table B2-5 *proBAY* results for WSP tests

Test Number	File Name	H <sub>s</sub> (m)	T <sub>p</sub> (s)	Slope (1/x)	Water Depth (m)	Freeboard (m)
1	WSP01	0.032	0.899	2	0.842	0.158
2	WSP02	0.079	1.037	2	0.842	0.158
3	WSP03	0.055	1.220	2	0.754	0.246
4	WSP04	0.109	1.377	2	0.754	0.246
5	WSP05	0.078	1.589	2	0.647	0.353
6	WSP06	0.136	1.737	2	0.647	0.353
7	WSP07	0.103	1.159	2	0.647	0.353
8	WSP08	0.085	1.339	2	0.752	0.248
9	WSP09	0.060	1.444	2	0.847	0.153

Table B2-5 continued

File Name	Detector File Name	Load Cell File Name	Chute Width (mm)	Total Sampling Time (s)	Analysis Start Time (s)
WSP01	WS0102.ASC	WS0101.ASC	500	655.36	30.08
WSP02	WS0202.ASC	WS0201.ASC	500	993.69	30.08
WSP03	WS0302.ASC	WS0301.ASC	500	747.93	30.04
WSP04	WS0402.ASC	WS0401.ASC	500	1146.88	30.10
WSP05	WS0502.ASC	WS0501.ASC	500	880.64	30.10
WSP06	WS0602.ASC	WS0601.ASC	500	1259.93	30.14
WSP07	WS0702.ASC	WS0701.ASC	500	1044.48	30.09
WSP08	WS0802.ASC	WS0801.ASC	500	973.21	30.06
WSP09	WS0902.ASC	WS0901.ASC	500	839.68	30.03

Table B2-5 continued

File Name	Analysis Finish Time (s)	Total Analysis Time (s)	Number of Waves Analysed	Noise Filter Threshold	Number of Waves Overtopping
WSP01	550.08	520.00	1000	-14.859	1
WSP02	830.06	799.97	1000	1573.340	57
WSP03	629.97	599.93	1000	-20.087	1
WSP04	950.04	919.94	1000	119.613	62
WSP05	740.03	709.93	1000	19.034	1
WSP06	1040.00	1009.85	1000	89.723	38
WSP07	870.06	839.97	1000	77.369	3
WSP08	809.98	779.92	1000	110.103	20
WSP09	699.97	669.94	1000	145.414	36

Appendix B2 – Tables of *proBAY* Results

Table B2-5 continued

File Name	Total Overtopping Volume (lt)	Maximum Overtopping Volume (lt)	Mean Overtopping Volume (lt)	Mean Overtopping Rate (lt/s/m)
WSP01	0.001	0.001	0.001	2.460E-06
WSP02	2.831	0.222	0.050	7.078E-03
WSP03	0.002	0.002	0.002	6.039E-06
WSP04	16.071	1.176	0.259	3.494E-02
WSP05	0.011	0.011	0.011	2.974E-05
WSP06	9.984	2.014	0.263	1.977E-02
WSP07	0.257	0.137	0.086	6.116E-04
WSP08	2.514	0.600	0.126	6.447E-03
WSP09	3.498	0.466	0.097	1.044E-02

Table B2-6 *proBAY* results for SHADOW Phase II, 1:10 slope, 425mm water depth tests

Test Number	File Name	H <sub>s</sub> (m)	T <sub>p</sub> (s)	Slope (1/x)	Water Depth (m)	Freeboard (m)
1	ESI0104	0.039	0.836	10	0.425	0.225
2	ESI0204	0.037	1.393	10	0.425	0.225
3	ESI0304	0.076	1.393	10	0.425	0.225
4	ESI0404	0.112	1.393	10	0.425	0.225
5	ESI0504	0.035	1.951	10	0.425	0.225
6	ESI0604	0.074	1.951	10	0.425	0.225
7	ESI0704	0.111	1.951	10	0.425	0.225
8	ESI0804	0.145	1.951	10	0.425	0.225
9	ESI0904	0.035	2.506	10	0.425	0.225
10	ESI1004	0.072	2.506	10	0.425	0.225
11	ESI1104	0.108	2.506	10	0.423	0.227
12	ESI1204	0.139	2.506	10	0.422	0.228
13	ESI1304	0.035	3.069	10	0.425	0.225
14	ESI1404	0.072	3.069	10	0.424	0.226
15	ESI1504	0.105	3.069	10	0.423	0.227
16	ESI1604(CUT)	0.133	3.069	10	0.423	0.227
17	ESI1704	0.036	3.618	10	0.424	0.226
18	ESI1804	0.128	1.951	10	0.425	0.225
19	ESI1904	0.128	2.506	10	0.422	0.228
20	ESI2004	0.072	3.852	10	0.425	0.225
SB8	ESS0804	0.145	1.951	10	0.425	0.225
SB11	ESS1104	0.108	2.506	10	0.425	0.225
SB12	ESS1204	0.139	2.506	10	0.425	0.225
SB19	ESS1904	0.128	2.506	10	0.425	0.225

Appendix B2 – Tables of proBAY Results

Table B2-6 continued

File Name	Detector File Name	Load Cell File Name	Chute Width (mm)	Total Sampling Time (s)	Analysis Start Time (s)
ESI0104	-	-	-	-	-
ESI0204	-	-	-	-	-
ESI0304	-	-	-	-	-
ESI0404	-	-	-	-	-
ESI0504	-	-	-	-	-
ESI0604	-	-	-	-	-
ESI0704	-	-	-	-	-
ESI0804	BB0806.ASC	BB0807.ASC	500	1810.43	30.06
ESI0904	-	-	-	-	-
ESI1004	-	-	-	-	-
ESI1104	BB1106.ASC	BB1107.ASC	500	2310.14	30.03
ESI1204	BB1206.ASC	BB1207.ASC	500	2310.14	30.03
ESI1304	-	-	-	-	-
ESI1404	BB1406.ASC	BB1407.ASC	500	2811.49	30.03
ESI1504	BB1506.ASC	BB1507.ASC	500	2811.49	30.03
ESI1604(CUT)	BB1606.ASC	BB1607.ASC	500	2811.49	30.03
ESI1704	BB1706.ASC	BB1707.ASC	500	3309.57	30.10
ESI1804	BB1806.ASC	BB1807.ASC	500	1810.43	30.06
ESI1904	BB1906.ASC	BB1907.ASC	500	2310.14	30.03
ESI2004	BB2006.ASC	BB2007.ASC	500	3309.57	30.10
ESS0804	SB0806.ASC	SB0807.ASC	500	3558.60	30.08
ESS1104	SB1106.ASC	SB1107.ASC	500	11311.50	30.03
ESS1204	SB1206.ASC	SB1207.ASC	500	11311.50	30.03
ESS1904	SB1906.ASC	SB1907.ASC	500	4561.31	30.07

Table B2-6 continued

File Name	Analysis Finish Time (s)	Total Analysis Time (s)	Number of Waves Analysed	Noise Filter Threshold	Number of Waves Overtopping
ESI0104	-	-	-	-	-
ESI0204	-	-	-	-	-
ESI0304	-	-	-	-	-
ESI0404	-	-	-	-	-
ESI0504	-	-	-	-	-
ESI0604	-	-	-	-	-
ESI0704	-	-	-	-	-
ESI0804	1788.99	1758.94	1000	-54.031	1
ESI0904	-	-	-	-	-
ESI1004	-	-	-	-	-
ESI1104	2109.99	2079.96	1000	-100.933	0
ESI1204	2065.02	2034.98	1000	-128.441	11
ESI1304	-	-	-	-	-

Appendix B2 – Tables of proBAY Results

ESI1404	2667.01	2636.98	1000	0.393	1
ESI1504	2567.99	2537.96	1000	-46.760	14
ESI1604(CUT)	1531.79	1501.76	608	135.421	27
ESI1704	3277.05	3246.95	1000	147.812	0
ESI1804	1789.99	1759.93	1000	123.077	0
ESI1904	2072.98	2042.95	1000	-106.454	3
ESI2004	3288.16	3258.06	990	20.737	4
ESS0804	3548.07	3517.99	2000	149.879	3
ESS1104	10429.90	10399.80	5000	168.118	2
ESS1204	10205.00	10174.90	5000	265.422	38
ESS1904	4116.00	4085.94	2000	170.777	5

Table B2-6 continued

File Name	Total Overtopping Volume (lt)	Maximum Overtopping Volume (lt)	Mean Overtopping Volume (lt)	Mean Overtopping Rate (lt/s/m)
ESI0104	-	-	-	-
ESI0204	-	-	-	-
ESI0304	-	-	-	-
ESI0404	-	-	-	-
ESI0504	-	-	-	-
ESI0604	-	-	-	-
ESI0704	-	-	-	-
ESI0804	0.365	0.365	0.365	4.153E-04
ESI0904	-	-	-	-
ESI1004	-	-	-	-
ESI1104	0.000	0.000	0.000	0.000E+00
ESI1204	1.470	0.561	0.134	1.444E-03
ESI1304	-	-	-	-
ESI1404	0.004	0.004	0.004	2.820E-06
ESI1504	13.149	5.693	0.939	1.036E-02
ESI1604(CUT)	21.301	3.686	0.789	2.837E-02
ESI1704	0.000	0.000	0.000	0.000E+00
ESI1804	0.000	0.000	0.000	0.000E+00
ESI1904	0.240	0.139	0.080	2.352E-04
ESI2004	0.887	0.530	0.222	5.447E-04
ESS0804	2.230	1.195	0.743	1.268E-03
ESS1104	0.267	0.250	0.133	5.129E-05
ESS1204	17.281	1.474	0.455	3.397E-03
ESS1904	1.131	0.353	0.226	5.538E-04

Appendix B2 – Tables of proBAY Results

Table B2-7 proBAY results for SHADOW Phase II, 1:10 slope, 525mm water depth tests

Test Number	File Name	H <sub>s</sub> (m)	T <sub>p</sub> (s)	Slope (1/x)	Water Depth (m)	Freeboard (m)
1	ESI0105	0.037	0.890	10	0.525	0.125
2	ESI0205	0.040	1.393	10	0.525	0.125
3	ESI0305	0.079	1.393	10	0.524	0.126
4	ESI0405	0.113	1.393	10	0.524	0.126
5	ESI0505	0.036	2.077	10	0.524	0.126
6	ESI0605	0.076	1.951	10	0.523	0.127
7	ESI0705	0.117	1.951	10	0.522	0.128
8	ESI0805(CUT)	0.155	1.951	10	0.522	0.128
9	ESI0905(CUT)	0.186	1.951	10	0.521	0.129
10	ESI1005	0.035	2.506	10	0.521	0.129
11	ESI1105	0.075	2.506	10	0.520	0.130
12	ESI1205(CUT)	0.115	2.506	10	0.523	0.127
13	ESI1305(CUT)	0.154	2.506	10	0.522	0.128
14	ESI1405	0.184	2.506	10	0.525	0.125
15	ESI1505	0.036	3.069	10	0.523	0.127
16	ESI1605(CUT)	0.073	3.267	10	0.524	0.126
17	ESI1705(CUT)	0.113	3.069	10	0.523	0.127
18	ESI1805	0.147	2.521	10	0.525	0.125
19	ESI1905	0.175	2.479	10	0.525	0.125
20	ESI2005	0.036	3.852	10	0.525	0.125
21	ESI2105	0.060	2.077	10	0.521	0.129
22	ESI2205	0.059	2.506	10	0.521	0.129
23	ESI2305	0.060	3.069	10	0.520	0.130
SA4	ESS0405	0.113	1.393	10	0.525	0.125
SA6	ESS0605	0.076	1.951	10	0.525	0.125
SA11	ESS1105	0.075	2.506	10	0.525	0.125

Table B2-7 continued

File Name	Detector File Name	Load Cell File Name	Chute Width (mm)	Total Sampling Time (s)	Analysis Start Time (s)
ESI0105	BA0106.ASC	BA0107.ASC	500	809.37	30.04
ESI0205	BA0206.ASC	BA0207.ASC	500	1310.72	30.08
ESI0305	BA0306.ASC	BA0307.ASC	500	1310.72	30.08
ESI0405	BA0406.ASC	BA0407.ASC	500	1310.72	30.08
ESI0505	BA0506.ASC	BA0507.ASC	500	1810.43	30.06
ESI0605	BA0606.ASC	BA0607.ASC	500	1810.43	30.06
ESI0705	BA0706.ASC	BA0707.ASC	500	1810.43	30.06
ESI0805(CUT)	BA0806.ASC	BA0807.ASC	100	1810.43	30.06
ESI0905(CUT)	BA0906.ASC	BA0907.ASC	100	1810.43	30.06
ESI1005	BA1006.ASC	BA1007.ASC	500	2310.14	30.03
ESI1105	BA1106.ASC	BA1107.ASC	500	2310.14	30.03
ESI1205(CUT)	BA1206.ASC	BA1207.ASC	500	2310.14	30.03

Appendix B2 – Tables of proBAY Results

ESI1305(CUT)	BA1306.ASC	BA1307.ASC	100	2310.14	30.03
ESI1405	-	-	-	-	-
ESI1505	BA1506.ASC	BA1507.ASC	500	2811.49	30.03
ESI1605(CUT)	BA1606.ASC	BA1607.ASC	500	2811.49	30.03
ESI1705(CUT)	BA1706.ASC	BA1707.ASC	100	2811.49	30.03
ESI1805	-	-	-	-	-
ESI1905	-	-	-	-	-
ESI2005	BA2006.ASC	BA2007.ASC	500	3309.57	30.10
ESI2105	BA2106.ASC	BA2107.ASC	500	1810.43	30.06
ESI2205	BA2206.ASC	BA2207.ASC	500	2310.14	30.03
ESI2305	BA2306.ASC	BA2307.ASC	500	2811.49	30.03
ESS0405	SA0406.ASC	SA0407.ASC	500	6311.12	30.05
ESS0605	SA0606.ASC	SA0607.ASC	500	8808.04	30.11
ESS1105	SA1106.ASC	SA1107.ASC	500	4561.31	30.07

Table B2-7 continued

File Name	Analysis Finish Time (s)	Total Analysis Time (s)	Number of Waves Analysed	Noise Filter Threshold	Number of Waves Overtopping
ESI0105	804.03	774.00	1000	0.953	0
ESI0205	1269.04	1238.96	1000	-2.515	0
ESI0305	1272.08	1242.00	1000	-6.874	0
ESI0405	1284.08	1254.00	1000	23.531	3
ESI0505	1770.98	1740.93	1000	1.965	0
ESI0605	1762.03	1731.98	1000	-39.287	3
ESI0705	1772.97	1742.92	1000	6.507	45
ESI0805(CUT)	357.80	327.74	187	191.600	18
ESI0905(CUT)	829.86	799.80	455	1034.390	58
ESI1005	2249.02	2218.99	1000	-28.689	0
ESI1105	2218.99	2188.95	1000	-28.828	19
ESI1205(CUT)	622.80	592.76	277	130.345	46
ESI1305(CUT)	669.54	639.51	306	1889.920	58
ESI1405	-	-	-	-	-
ESI1505	2752.98	2722.95	1000	-13.727	1
ESI1605(CUT)	1248.99	1218.96	442	106.696	52
ESI1705(CUT)	777.09	747.06	289	1440.430	63
ESI1805	-	-	-	-	-
ESI1905	-	-	-	-	-
ESI2005	3289.47	3259.37	991	78.168	7
ESI2105	1795.96	1765.90	1000	-24.194	1
ESI2205	2250.99	2220.96	1000	-19.747	3
ESI2305	2743.03	2713.00	1000	-3.038	40
ESS0405	6300.04	6270.00	5000	160.764	8
ESS0605	8690.04	8659.93	5000	-9.897	9
ESS1105	4408.05	4377.98	2000	-1.054	28

Appendix B2 – Tables of *proBAY* Results

Table B2-7 continued

File Name	Total Overtopping Volume (lt)	Maximum Overtopping Volume (lt)	Mean Overtopping Volume (lt)	Mean Overtopping Rate (lt/s/m)
ESI0105	0.000	0.000	0.000	0.000E+00
ESI0205	0.000	0.000	0.000	0.000E+00
ESI0305	0.000	0.000	0.000	0.000E+00
ESI0405	0.901	0.739	0.300	1.436E-03
ESI0505	0.000	0.000	0.000	0.000E+00
ESI0605	0.969	0.411	0.323	1.119E-03
ESI0705	15.591	4.052	0.346	1.789E-02
ESI0805(CUT)	21.303	5.008	1.184	6.500E-01
ESI0905(CUT)	18.608	1.971	0.321	2.327E-01
ESI1005	0.000	0.000	0.000	0.000E+00
ESI1105	3.644	0.919	0.192	3.329E-03
ESI1205(CUT)	21.632	4.133	0.470	7.299E-02
ESI1305(CUT)	20.179	1.707	0.348	3.155E-01
ESI1405	-	-	-	-
ESI1505	0.006	0.006	0.006	4.055E-06
ESI1605(CUT)	22.103	1.366	0.425	3.627E-02
ESI1705(CUT)	20.168	1.550	0.320	2.700E-01
ESI1805	-	-	-	-
ESI1905	-	-	-	-
ESI2005	1.096	0.680	0.157	6.723E-04
ESI2105	0.005	0.005	0.005	5.833E-06
ESI2205	0.070	0.056	0.023	6.277E-05
ESI2305	2.962	0.820	0.074	2.183E-03
ESS0405	0.706	0.343	0.088	2.252E-04
ESS0605	0.560	0.224	0.062	1.294E-04
ESS1105	6.120	0.907	0.219	2.796E-03

Table B2-8 *proBAY* results for SHADOW Phase II, 1:15 slope, 425mm water depth tests

Test Number	File Name	H <sub>s</sub> (m)	T <sub>p</sub> (s)	Slope (1/x)	Water Depth (m)	Freeboard (m)
1	ESB0104	0.039	0.836	15	0.424	0.161
2	ESB0204	0.037	1.393	15	0.424	0.161
3	ESB0304	0.076	1.393	15	0.424	0.161
4	ESB0404	0.112	1.393	15	0.424	0.161
5	ESB0504	0.035	1.951	15	0.423	0.162
6	ESB0604	0.074	1.951	15	0.425	0.160
7	ESB0704	0.111	1.951	15	0.423	0.162
8	ESB0804	0.145	1.951	15	0.423	0.162
9	ESB0904	0.035	2.506	15	0.425	0.160
10	ESB1004	0.072	2.506	15	0.424	0.161
11	ESB1104	0.108	2.506	15	0.422	0.163
12	ESB1204(CUT)	0.139	2.506	15	0.423	0.162

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13	ESB1304	0.035	3.069	15	0.424	0.161
14	ESB1404	0.072	3.069	15	0.423	0.162
15	ESB1504(CUT)	0.105	3.069	15	0.422	0.163
16	ESB1604(CUT)	0.133	3.069	15	0.422	0.163
17	ESB1704	0.036	3.618	15	0.424	0.161
18	ESB1804	0.128	1.951	15	0.425	0.160
19	ESB1904	0.128	2.506	15	0.425	0.160
20	ESB2004	0.072	3.852	15	0.425	0.160

Table B2-8 continued

File Name	Detector File Name	Load Cell File Name	Chute Width (mm)	Total Sampling Time (s)	Analysis Start Time (s)
ESB0104	AB0106.ASC	AB0107.ASC	500	809.37	30.04
ESB0204	AB0206.ASC	AB0207.ASC	500	1310.72	30.08
ESB0304	AB0306.ASC	AB0307.ASC	500	1310.72	30.08
ESB0404	AB0406.ASC	AB0407.ASC	500	1310.72	30.08
ESB0504	AB0506.ASC	AB0507.ASC	500	1810.43	30.06
ESB0604	AB0606.ASC	AB0607.ASC	500	1810.43	30.06
ESB0704	AB0706.ASC	AB0707.ASC	500	1810.43	30.06
ESB0804	AB0806.ASC	AB0807.ASC	500	1810.43	30.06
ESB0904	AB0906.ASC	AB0907.ASC	500	2310.14	30.03
ESB1004	AB1006.ASC	AB1007.ASC	500	2310.14	30.03
ESB1104	AB1106.ASC	AB1107.ASC	500	2310.14	30.03
ESB1204(CUT)	AB1206.ASC	AB1207.ASC	500	2310.14	30.03
ESB1304	AB1306.ASC	AB1307.ASC	500	2811.49	30.03
ESB1404	AB1406.ASC	AB1407.ASC	500	2811.49	30.03
ESB1504(CUT)	AB1506.ASC	AB1507.ASC	500	2811.49	30.03
ESB1604(CUT)	AB1606.ASC	AB1607.ASC	100	2811.49	30.03
ESB1704	AB1706.ASC	AB1707.ASC	500	3309.57	30.10
ESB1804	AB1806.ASC	AB1807.ASC	500	1810.43	30.06
ESB1904	AB1906.ASC	AB1907.ASC	500	2310.14	30.03
ESB2004	AB2006.ASC	AB2007.ASC	500	3309.57	30.10

Table B2-8 continued

File Name	Analysis Finish Time (s)	Total Analysis Time (s)	Number of Waves Analysed	Noise Filter Threshold	Number of Waves Overtopping
ESB0104	786.00	755.97	1000	-11.106	0
ESB0204	1265.04	1234.96	1000	6.428	0
ESB0304	1271.04	1240.96	1000	2.344	0
ESB0404	1284.08	1254.00	1000	-14.632	0
ESB0504	1750.98	1720.93	1000	3.268	0



Appendix B2 – Tables of proBAY Results

ESB0604	1765.02	1734.96	1000	40.765	0
ESB0704	1781.04	1750.98	1000	0.204	3
ESB0804	1788.99	1758.94	1000	-9.097	40
ESB0904	2234.99	2204.96	1000	-55.485	0
ESB1004	2180.00	2149.97	1000	-81.353	0
ESB1104	2109.99	2079.96	1000	-21.551	11
ESB1204(CUT)	974.24	944.21	464	-33.777	40
ESB1304	2752.98	2722.95	1000	-146.939	0
ESB1404	2667.01	2636.98	1000	-161.373	0
ESB1504(CUT)	1844.70	1814.67	715	22.493	35
ESB1604(CUT)	430.12	400.09	162	154.251	11
ESB1704	3277.05	3246.95	1000	-116.201	0
ESB1804	1789.99	1759.93	1000	85.560	16
ESB1904	2072.98	2042.95	1000	62.254	35
ESB2004	3288.16	3258.06	990	-9.276	1

Table B2-8 continued

File Name	Total Overtopping Volume (lt)	Maximum Overtopping Volume (lt)	Mean Overtopping Volume (lt)	Mean Overtopping Rate (lt/s/m)
ESB0104	0.000	0.000	0.000	0.000E+00
ESB0204	0.000	0.000	0.000	0.000E+00
ESB0304	0.000	0.000	0.000	0.000E+00
ESB0404	0.000	0.000	0.000	0.000E+00
ESB0504	0.000	0.000	0.000	0.000E+00
ESB0604	0.000	0.000	0.000	0.000E+00
ESB0704	1.749	1.172	0.583	1.998E-03
ESB0804	18.777	2.910	0.469	2.135E-02
ESB0904	0.000	0.000	0.000	0.000E+00
ESB1004	0.000	0.000	0.000	0.000E+00
ESB1104	3.121	1.373	0.284	3.001E-03
ESB1204(CUT)	21.957	2.397	0.549	4.651E-02
ESB1304	0.000	0.000	0.000	0.000E+00
ESB1404	0.000	0.000	0.000	0.000E+00
ESB1504(CUT)	19.978	4.712	0.571	2.202E-02
ESB1604(CUT)	21.996	4.939	2.000	5.498E-01
ESB1704	0.000	0.000	0.000	0.000E+00
ESB1804	10.543	3.907	0.659	1.198E-02
ESB1904	20.717	4.038	0.592	2.028E-02
ESB2004	0.123	0.123	0.123	7.526E-05

Appendix B2 – Tables of proBAY Results

Table B2-9 proBAY results for SHADOW Phase II, 1:15 slope, 525mm water depth tests

Test Number	File Name	H <sub>s</sub> (m)	T <sub>p</sub> (s)	Slope (1/x)	Water Depth (m)	Freeboard (m)
1	ESB0105	0.037	0.890	15	0.525	0.060
2	ESB0205	0.040	1.393	15	0.525	0.060
3	ESB0305	0.079	1.393	15	0.524	0.061
4	ESB0405	0.113	1.393	15	0.524	0.061
5	ESB0505	0.036	2.077	15	0.525	0.060
6	ESB0605(CUT)	0.076	1.951	15	0.525	0.060
7	ESB0705(CUT)	0.117	1.951	15	0.524	0.061
8	ESB0805	0.155	1.951	15	0.525	0.060
9	ESB0905	0.186	1.951	15	0.525	0.060
10	ESB1005	0.035	2.506	15	0.524	0.061
11	ESB1105	0.075	2.506	15	0.524	0.061
12	ESB1205	0.115	2.506	15	0.525	0.060
13	ESB1305	0.154	2.506	15	0.525	0.060
14	ESB1405	0.184	2.506	15	0.525	0.060
15	ESB1505	0.036	3.069	15	0.524	0.061
16	ESB1605(CUT)	0.073	3.267	15	0.524	0.061
17	ESB1705	0.113	3.069	15	0.525	0.060
18	ESB1805	0.147	3.069	15	0.525	0.060
19	ESB1905	0.175	3.069	15	0.525	0.060
20	ESB2005	0.036	3.852	15	0.525	0.060
21	ESB2105	0.060	2.077	15	0.525	0.060
22	ESB2205	0.059	2.506	15	0.525	0.060
23	ESB2305(CUT)	0.060	3.069	15	0.525	0.060

Table B2-9 continued

File Name	Detector File Name	Load Cell File Name	Chute Width (mm)	Total Sampling Time (s)	Analysis Start Time (s)
ESB0105	AA0106.ASC	AA0107.ASC	100	809.37	30.04
ESB0205	AA0206.ASC	AA0207.ASC	100	1310.72	30.08
ESB0305	AA0306.ASC	AA0307.ASC	500	1310.72	30.08
ESB0405	AA0406.ASC	AA0407.ASC	500	1310.72	30.08
ESB0505	AA0506.ASC	AA0507.ASC	500	1810.43	30.06
ESB0605(CUT)	AA0606.ASC	AA0607.ASC	500	1810.43	30.06
ESB0705(CUT)	AA0706.ASC	AA0707.ASC	500	1810.43	30.06
ESB0805	-	-	-	-	-
ESB0905	-	-	-	-	-
ESB1005	AA1006.ASC	AA1007.ASC	500	2310.14	30.03
ESB1105	AA1106.ASC	AA1107.ASC	500	2310.14	30.03
ESB1205	-	-	-	-	-
ESB1305	-	-	-	-	-
ESB1405	-	-	-	-	-
ESB1505	AA1506.ASC	AA1507.ASC	500	2811.49	30.03

*Appendix B2 – Tables of proBAY Results*

ESB1605(CUT)	AA1606.ASC	AA1607.ASC	100	2811.49	30.03
ESB1705	-	-	-	-	-
ESB1805	-	-	-	-	-
ESB1905	-	-	-	-	-
ESB2005	AA2006.ASC	AA2007.ASC	500	3309.57	30.10
ESB2105	AA2106.ASC	AA2107.ASC	500	1810.43	30.06
ESB2205	AA2206.ASC	AA2207.ASC	500	2310.14	30.03
ESB2305(CUT)	AA2306.ASC	AA2307.ASC	500	2844.26	30.03

Table B2-9 continued

<b>File Name</b>	<b>Analysis Finish Time (s)</b>	<b>Total Analysis Time (s)</b>	<b>Number of Waves Analysed</b>	<b>Noise Filter Threshold</b>	<b>Number of Waves Overtopping</b>
ESB0105	804.03	774.00	1000	-1634.42	0
ESB0205	1269.04	1238.96	1000	-1648.31	0
ESB0305	1272.08	1242.00	1000	-1584.12	30
ESB0405	1284.08	1254.00	1000	-1419.98	99
ESB0505	1770.98	1740.93	1000	-1452.92	0
ESB0605(CUT)	941.02	910.96	526	-1124.68	102
ESB0705(CUT)	620.90	590.84	339	1038.95	74
ESB0805	-	-	-	-	-
ESB0905	-	-	-	-	-
ESB1005	2249.02	2218.99	1000	-1706.34	8
ESB1105	2218.99	2188.95	1000	-860.969	132
ESB1205	-	-	-	-	-
ESB1305	-	-	-	-	-
ESB1405	-	-	-	-	-
ESB1505	2752.98	2722.95	1000	-1709.65	47
ESB1605(CUT)	964.91	934.88	339	422.824	96
ESB1705	-	-	-	-	-
ESB1805	-	-	-	-	-
ESB1905	-	-	-	-	-
ESB2005	3289.47	3259.37	991	-1585.52	185
ESB2105	1795.96	1765.90	1000	48.5243	75
ESB2205	2250.99	2220.96	1000	148.574	106
ESB2305(CUT)	705.51	675.48	249	771.502	57

*Appendix B2 – Tables of proBAY Results*

Table B2-9 continued

<b>File Name</b>	<b>Total Overtopping Volume (lt)</b>	<b>Maximum Overtopping Volume (lt)</b>	<b>Mean Overtopping Volume (lt)</b>	<b>Mean Overtopping Rate (lt/s/m)</b>
ESB0105	0.000	0.000	0.000	0.000E+00
ESB0205	0.000	0.000	0.000	0.000E+00
ESB0305	3.753	0.738	0.125	6.043E-03
ESB0405	16.061	1.017	0.162	2.562E-02
ESB0505	0.000	0.000	0.000	0.000E+00
ESB0605(CUT)	22.682	1.969	0.222	4.980E-02
ESB0705(CUT)	20.477	2.458	0.277	6.931E-02
ESB0805	-	-	-	-
ESB0905	-	-	-	-
ESB1005	0.124	0.041	0.015	1.115E-04
ESB1105	18.028	0.736	0.137	1.647E-02
ESB1205	-	-	-	-
ESB1305	-	-	-	-
ESB1405	-	-	-	-
ESB1505	5.050	1.237	0.107	3.709E-03
ESB1605(CUT)	20.912	0.829	0.218	2.237E-01
ESB1705	-	-	-	-
ESB1805	-	-	-	-
ESB1905	-	-	-	-
ESB2005	24.929	1.205	0.135	1.530E-02
ESB2105	7.070	0.962	0.094	8.007E-03
ESB2205	18.928	1.077	0.179	1.704E-02
ESB2305(CUT)	21.516	1.554	0.377	6.370E-02

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## Appendix - B3. Summary sheets

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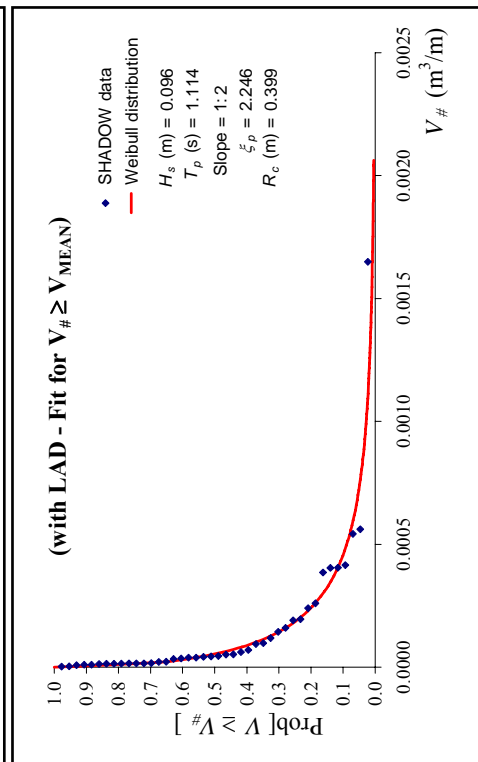
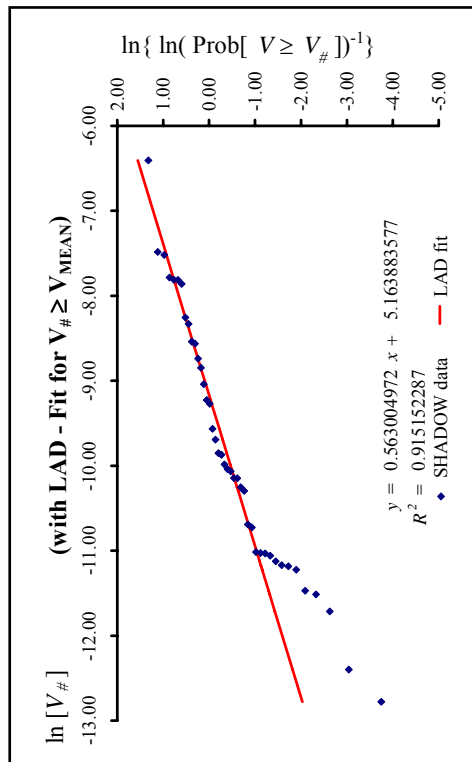
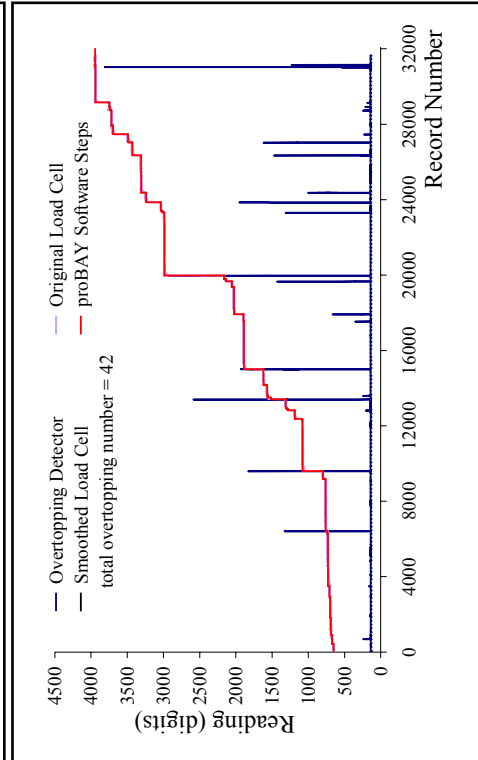
A summary sheet has prepared for each test condition. Besides 3 graphs, the *proBAY* results are presented in a tabular form. The first graph shows the overtopping detector signal, the original and smoothed load cell signals and the *proBAY* steps to show volume changes in the overtopping tank. The second graph shows individual overtopping volumes with an LAD fit to the data. The third graph illustrates the probability distribution of individual overtopping volumes together with the theoretical Weibull distribution.

A sample of the summary sheets is given below. Six WORD documents summarize all results and relevant files are provided on the enclosed DVD.

*root: DVD:\Summary Sheets*

Test Name: TAP0160

Test Number =	1
Test Name =	TAP0160
H <sub>s</sub> (m) =	0.096
T <sub>p</sub> (s) =	1.114
Slope (1/x) =	2
Water depth (m) =	0.601
Freeboard, R <sub>c</sub> (m) =	0.399
Detector File Name =	01AT02.ASC
Load Cell File Name =	01AT01.ASC
Chute Width (mm) =	500
Total Sampling Time (s) =	1058.41
Analysis Start Time (s) =	30.01
Analysis Finish Time (s) =	1052.11
Total Analysis Time (s) =	1022.10
Number of Waves Analysed =	936.00
Noise Filter Threshold =	146.58
Number of Waves Overtopping =	42
Total Overtopping Volume (m <sup>3</sup> ) =	0.006585
Maximum Overtopping Volume (m <sup>3</sup> ) =	0.001650
Mean Overtopping Volume (m <sup>3</sup> ) =	0.000157
Mean Overtopping Rate (m <sup>3</sup> /s.m) =	0.000013



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## Appendix - B4. Examining the wave spectra

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Spectra of the measured wave conditions were investigated and compared with the theoretical JONSWAP spectrum. All figures are gathered in "SS 4 Wave Spectra.doc" and separate EXCEL files for each group of tests are also provided on the enclosed DVD. An example of the figures is given below.

root: DVD:\Other Files

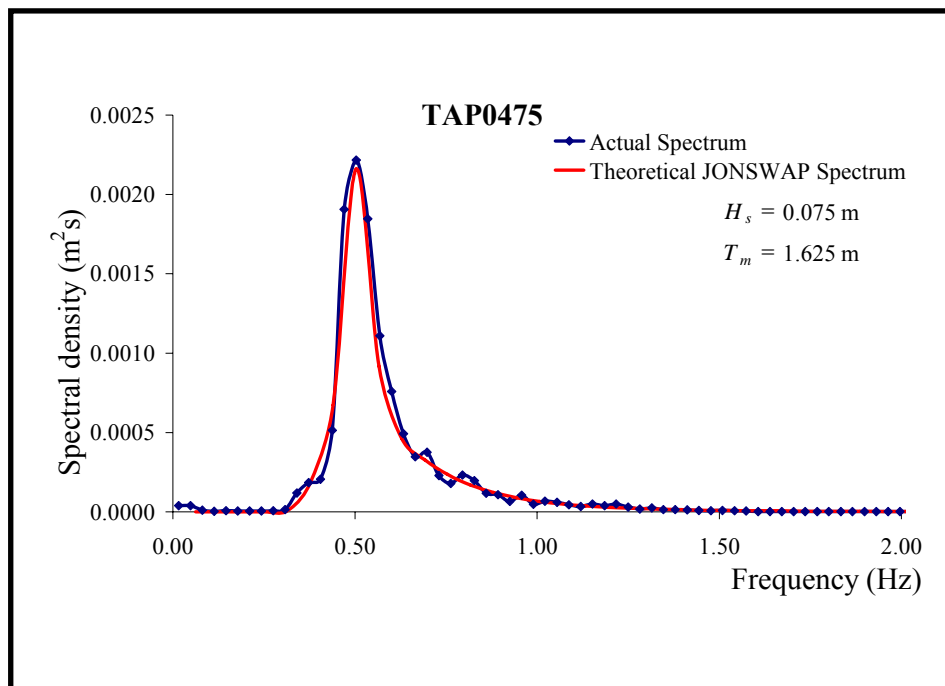


Figure B4-1 Comparison of the measured wave spectrum with the theoretical JONSWAP spectrum

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## Appendix - B5. Application of the divided tests

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Since the repeatability was good, those wave conditions delivering more overtopping water than the capacity of the collecting tank were divided into smaller runs. Initially, tests were run for their normal lengths but if the overtopping tank overflowed, then, depending on the time when overflowing occurred, wave trains were divided into 2, 3, 4, 5 or even into 6 parts. The first wave condition to be split was TAP0660 ( $H_s = 0.2m$  and  $T_m = 1.5s$ ): it was divided into three runs. The first two runs contained 333 waves and the last one had 334 waves. The time schedule for the first run was set as for a normal test but for 333 waves. The total test duration was calculated as  $333 * T_m$  and the test performed accordingly. The time schedule was changed for the second run. Waves were started, together with the stopwatch, and ran for  $90 + 333 * T_m$  (s) to the start of recording. The chute was placed at  $120 + 333 * T_m$  (this corresponded to the time when the chute was removed in the previous run) and removed at  $120 + 666 * T_m$ . Data collection stopped when the stopwatch read  $150 + 666 * T_m$ . Recording data for the last run started after  $90 + 666 * T_m$  (s). The chute was placed at  $120 + 666 * T_m$  and removed at  $120 + 1000 * T_m$ . Figure 3-36 illustrates the time schedule for TAP0660. In another words, the overtopping performance of the structure was tested in such a way that the combination of overtopping volumes for the shortened runs provided the same amount of overtopping volume as if the test had run for 1000 continuous waves.

Table B5-1 gives the time schedules for all divided conditions.



Table B5-1 Time schedule for divided test conditions

File Name	T <sub>m</sub> (s)	Number of Waves	Total Time (s)	Paddle Starts	Data Collection Starts	Chute Placed	Chute Removed	Data Collection Stops
tap0660	x	333	499.500	0	( 1 : 30.00 )	( 2 : 0.00 )	( 10 : 19.50 )	( 10 : 49.50 )
	y	333	499.500	0	( 9 : 49.50 )	( 10 : 19.50 )	( 18 : 39.00 )	( 19 : 9.00 )
	z	334	501.000	0	( 18 : 9.00 )	( 18 : 39.00 )	( 27 : 0.00 )	( 27 : 30.00 )
tap0960	w	250	437.500	0	( 1 : 30.00 )	( 2 : 0.00 )	( 9 : 17.50 )	( 9 : 47.50 )
	x	250	437.500	0	( 8 : 47.50 )	( 9 : 17.50 )	( 16 : 35.00 )	( 17 : 5.00 )
	y	250	437.500	0	( 16 : 5.00 )	( 16 : 35.00 )	( 23 : 52.50 )	( 24 : 22.50 )
	z	250	437.500	0	( 23 : 22.50 )	( 23 : 52.50 )	( 31 : 10.00 )	( 31 : 40.00 )
tap1260	y	500	1000.000	0	( 1 : 30.00 )	( 2 : 0.00 )	( 18 : 40.00 )	( 19 : 10.00 )
	z	500	1000.000	0	( 18 : 10.00 )	( 18 : 40.00 )	( 35 : 20.00 )	( 35 : 50.00 )
	u	166	332.000	0	( 1 : 30.00 )	( 2 : 0.00 )	( 7 : 32.00 )	( 8 : 2.00 )
tap1360	v	166	332.000	0	( 7 : 2.00 )	( 7 : 32.00 )	( 13 : 4.00 )	( 13 : 34.00 )
	w	166	332.000	0	( 12 : 34.00 )	( 13 : 4.00 )	( 18 : 36.00 )	( 19 : 6.00 )
	x	166	332.000	0	( 18 : 6.00 )	( 18 : 36.00 )	( 24 : 8.00 )	( 24 : 38.00 )
	y	166	332.000	0	( 23 : 38.00 )	( 24 : 8.00 )	( 29 : 40.00 )	( 30 : 10.00 )
	z	170	340.000	0	( 29 : 10.00 )	( 29 : 40.00 )	( 35 : 20.00 )	( 35 : 50.00 )
	y	500	1125.000	0	( 1 : 30.00 )	( 2 : 0.00 )	( 20 : 45.00 )	( 21 : 15.00 )
tap1560	z	500	1125.000	0	( 20 : 15.00 )	( 20 : 45.00 )	( 39 : 30.00 )	( 40 : 0.00 )
	l	333	374.625	0	( 1 : 30.00 )	( 2 : 0.00 )	( 8 : 14.63 )	( 8 : 44.63 )
	m	333	374.625	0	( 7 : 44.63 )	( 8 : 14.63 )	( 14 : 29.25 )	( 14 : 59.25 )
	n	334	375.750	0	( 13 : 59.25 )	( 14 : 29.25 )	( 20 : 45.00 )	( 21 : 15.00 )

Table B5-1 continued

File Name	T <sub>m</sub> (s)	Number of Waves	Total Time (s)	Paddle Starts	Data Collection Starts	Chute Placed	Chute Removed	Data Collection Stops
tap0875	k	250	312.500	0	( 1 : 30.00 )	( 2 : 0.00 )	( 7 : 12.50 )	( 7 : 42.50 )
	l	250	312.500	0	( 6 : 42.50 )	( 7 : 12.50 )	( 12 : 25.00 )	( 12 : 55.00 )
	m	250	312.500	0	( 11 : 55.00 )	( 12 : 25.00 )	( 17 : 37.50 )	( 18 : 7.50 )
	n	250	312.500	0	( 17 : 7.50 )	( 17 : 37.50 )	( 22 : 50.00 )	( 23 : 20.00 )
tap0975	j	200	275.000	0	( 1 : 30.00 )	( 2 : 0.00 )	( 6 : 35.00 )	( 7 : 5.00 )
	k	200	275.000	0	( 6 : 5.00 )	( 6 : 35.00 )	( 11 : 10.00 )	( 11 : 40.00 )
	l	200	275.000	0	( 10 : 40.00 )	( 11 : 10.00 )	( 15 : 45.00 )	( 16 : 15.00 )
	m	200	275.000	0	( 15 : 15.00 )	( 15 : 45.00 )	( 20 : 20.00 )	( 20 : 50.00 )
tap1075	n	200	275.000	0	( 19 : 50.00 )	( 20 : 20.00 )	( 24 : 55.00 )	( 25 : 25.00 )
	i	166	207.500	0	( 1 : 30.00 )	( 2 : 0.00 )	( 5 : 27.50 )	( 5 : 57.50 )
	j	166	207.500	0	( 4 : 57.50 )	( 5 : 27.50 )	( 8 : 55.00 )	( 9 : 25.00 )
	k	166	207.500	0	( 8 : 25.00 )	( 8 : 55.00 )	( 12 : 22.50 )	( 12 : 52.50 )
tap1175	l	166	207.500	0	( 11 : 52.50 )	( 12 : 22.50 )	( 15 : 50.00 )	( 16 : 20.00 )
	m	166	207.500	0	( 15 : 20.00 )	( 15 : 50.00 )	( 19 : 17.50 )	( 19 : 47.50 )
	n	170	212.500	0	( 18 : 47.50 )	( 19 : 17.50 )	( 22 : 50.00 )	( 23 : 20.00 )
	m	500	750.000	0	( 1 : 30.00 )	( 2 : 0.00 )	( 14 : 30.00 )	( 15 : 0.00 )
tap1275	n	500	750.000	0	( 14 : 0.00 )	( 14 : 30.00 )	( 27 : 0.00 )	( 27 : 30.00 )
	j	333	666.000	0	( 1 : 30.00 )	( 2 : 0.00 )	( 13 : 6.00 )	( 13 : 36.00 )
	m	333	666.000	0	( 12 : 36.00 )	( 13 : 6.00 )	( 24 : 12.00 )	( 24 : 42.00 )
	n	334	668.000	0	( 23 : 42.00 )	( 24 : 12.00 )	( 35 : 20.00 )	( 35 : 50.00 )

Table B5-1 continued

File Name	T <sub>m</sub> (s)	Number of Waves	Total Time (s)	Paddle Starts	Data Collection Starts	Chute Placed	Chute Removed	Data Collection Stops
tap1275	j	333	666.000	0	( 1 : 30.00 )	( 2 : 0.00 )	( 13 : 6.00 )	( 13 : 36.00 )
	m	333	666.000	0	( 12 : 36.00 )	( 13 : 6.00 )	( 24 : 12.00 )	( 24 : 42.00 )
	n	334	668.000	0	( 23 : 42.00 )	( 24 : 12.00 )	( 35 : 20.00 )	( 35 : 50.00 )
tap1375	m	500	1250.000	0	( 1 : 30.00 )	( 2 : 0.00 )	( 22 : 50.00 )	( 23 : 20.00 )
	n	500	1250.000	0	( 22 : 20.00 )	( 22 : 50.00 )	( 43 : 40.00 )	( 44 : 10.00 )
tap1475	j	200	300.000	0	( 1 : 30.00 )	( 2 : 0.00 )	( 7 : 0.00 )	( 7 : 30.00 )
	k	200	300.000	0	( 6 : 30.00 )	( 7 : 0.00 )	( 12 : 0.00 )	( 12 : 30.00 )
	l	200	300.000	0	( 11 : 30.00 )	( 12 : 0.00 )	( 17 : 0.00 )	( 17 : 30.00 )
	m	200	300.000	0	( 16 : 30.00 )	( 17 : 0.00 )	( 22 : 0.00 )	( 22 : 30.00 )
n	1.500	200	300.000	0	( 21 : 30.00 )	( 22 : 0.00 )	( 27 : 0.00 )	( 27 : 30.00 )

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## Appendix - B6. Digital Versatile Disc (DVD)

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Analysis files, created using “LS – LAD Comparison.xls”, and results files created using “*proBAY* Results - Graphical Expression.xls” are provided on the enclosed DVD.

The folders tree of the DVD is as follows:

DVD:\	
— Analysis Files	(contains one EXCEL workbook for each test)
— <i>proBAY</i> Results	(contains seven EXCEL workbooks for the <i>proBAY</i> results and three subfolders for each slope)
— 1 on 2 Slope	(contains four subfolders)
— 600mm Tests	(contains one EXCEL workbook for each test and an additional EXCEL workbook for divided test conditions)
— 750mm Tests	(contains one EXCEL workbook for each test and an additional EXCEL workbook for divided test conditions)
— Low Overtopping Tests	(contains one EXCEL workbook for each test)
— WSP Tests	(contains one EXCEL workbook for each test)
— 1 on 10 Slope	(contains one EXCEL workbook for each test and an additional EXCEL workbook for partly damaged test conditions)
— 1 on 15 Slope	(contains one EXCEL workbook for each test and an additional EXCEL workbook for partly damaged test conditions)
— <i>proBAY</i> Software	(contains the <i>proBAY</i> software, paraBAY.txt, sample data file for TAP0160, FORTRAN dynamic library file “salflibc.dll”)
— <i>proBAY</i> Sub-Software	(contains EXCEL workbooks used to assist the <i>proBAY</i> software with macros)
— Summary Sheets	(contains WORD documents to give summary sheets only)
— Others	(contains calibrated wave spectra files)

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# APPENDIX C

## Publications

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## Appendix - C1. Publications

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- Bay, I, 2003, “Wave overtopping of coastal structures”, Poster presentation in The University of Liverpool, Engineering Faculty Poster Presentation Day, 3<sup>rd</sup> April, Liverpool, UK.
- Bay, I, 2005, “Wave overtopping of coastal structures”, 1st UK Young Coastal Scientists’ and Engineers’ Conference (YCSEC), 6-7<sup>th</sup> January 2005, University of Nottingham, UK.
- Bay, I., Hedges, T.S., Shareef, M. and Pullen, T., 2005, “Wave overtopping of shallow sloping seawalls: extension and refinement of empirical prediction methods”, Proceedings of the Twenty-ninth International Conference on Coastal Engineering, Volume 4, pp.4417-4429, Lisbon, Portugal, World Scientific, London, UK.

### *Reports to be published:*

- Pullen, T. and Bay, I., “Two-dimensional physical model studies of wave overtopping”, Report TR 127, DEFRA/EA Project Code: FD2410, HR Wallingford Ltd., Wallingford, UK.
- Pullen, T., Bay, I. and Napp, N., “Three-dimensional physical model studies of wave overtopping”, Report TR 128, DEFRA / EA Project Code: FD2410, HR Wallingford Ltd., Wallingford, UK.

# SHADOW

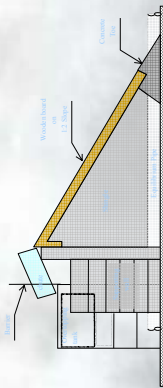
Ibrahim BAY, BSc(Eng), MSc(Eng)  
Research Student, Department of Civil Engineering, The University of Liverpool

## PROBLEM

- At a time of rising sea levels and threats from coastal flooding, society is increasingly concerned about the safety and reliability of coastal defences.
- Seawalls must be designed to allow only acceptable overtopping rates.
- Some empirical methods (formulae or simple computer programs) are available to assist the design process, but they are limited to relatively simple structural shapes and to certain ranges of those shapes.
- The prediction methods are often inconsistent and it is not known which of them is most reliable?

## INTRODUCTION

- DEFRA / EA commissioned HR Wallingford to study Coastal Flooding Hazard by Wave Overtopping (COFLOW) under project code FD2410. This project is known within HR Wallingford and amongst collaborating partners as Sea Hazard Defences against Overtopping by Waves (SHADOW).
- An associated PhD study was proposed at the University of Liverpool as one of the collaborating institutions. Ibrahim Bay was to carry out the physical modelling at HR Wallingford under the general supervision of Terry Hedges and with day-to-day technical supervision from the HR Wallingford project team (William Allsop, Tim Pullen).



## OBJECTIVES

- Over-designing seawalls is a waste of money. Defences should be designed for acceptable amounts of overtopping.
- The safety of pedestrians, vehicles and buildings is the most important criterion in designing these structures.
- Therefore, the particular aims of this PhD study are:
  - to fill gaps in existing data sets;
  - to improve existing methods for predicting wave overtopping; and
  - if necessary, to develop a new prediction method.

## PHYSICAL MODELLING

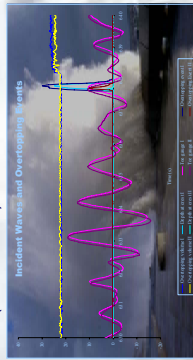
- Four well-known empirical methods (Owen<sup>10</sup>, van der Meer<sup>11</sup>, Hedges & Rees<sup>12</sup> and Bealey<sup>13</sup>) have been selected for initial study.
- They provide widely-varying predictions of overtopping volumes:

$R_1$	$T_p$	Owen (1990)	Bealey (1999)	Hedges & Rees (1988)	van der Meer (1995)	SHADOW (2005)
0.15	5.29	48	170	150	190	190
0.15	5.30	24	270	150	440	334
0.20	5.30	804	678	1311	1145	811
0.15	5.30	10	10	10	10	10
0.15	5.30	85	85	85	85	85
0.20	5.30	2093	1663	1342	288	1155
0.20	5.30	4904	3372	1330	2722	1807
0.10	2.25	1584	981	0	6729	36

- Physical model tests were undertaken in the Absorbing Flume of HR Wallingford. They started with a 1:2 smooth sloping structure.

- Data were collected during the tests using: a series of wave gauges, an overtopping detector, a lead cell, an overtopping height detector, an overtopping velocity detector and a pair of computers.
- Structures were tested for previously-calibrated wave conditions using two different water depths. Chutes were used to catch the overtopping volumes.

- Phase One measurements were compared with the predicted values and it was then decided to collect further data covering a wider range of conditions (this was Phase Two).



- In Phase Two, the new data covered:
  - 2-dimensional, 1:10 and 1:15 smooth impermeable slopes.
  - 2-dimensional, 1:2 slopes with 50%, 75% and 90% of their surface covered with rock over an impermeable core.
  - 2-dimensional, 1:2 slopes with rock armour over a permeable core.
  - 3-dimensional, 1:2 smooth slopes fronted by 1:10 beaches and with wave attack from 0°, 15°, 30° and 60° from normal. Some cases incorporated a 120° elbow.

## CONCLUDING REMARKS

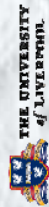
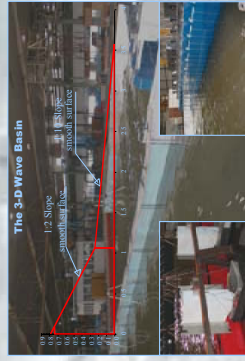
- A series of 2-D and 3-D physical model tests have been completed.
- Results provide new data on wave overtopping and on the associated behaviour of coastal defences under attack from waves.
- Careful analysis is now needed to improve the existing prediction methods. Alternatively, a new prediction method may be derived.

## ACKNOWLEDGEMENTS

- The following are acknowledged: DEFRA for its funding, HR Wallingford for their technical support to SHADOW 2-D and 3-D, and Terry Hedges for his supervision.

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HR Wallingford

# Wave Overtopping *of* Coastal Structures

by

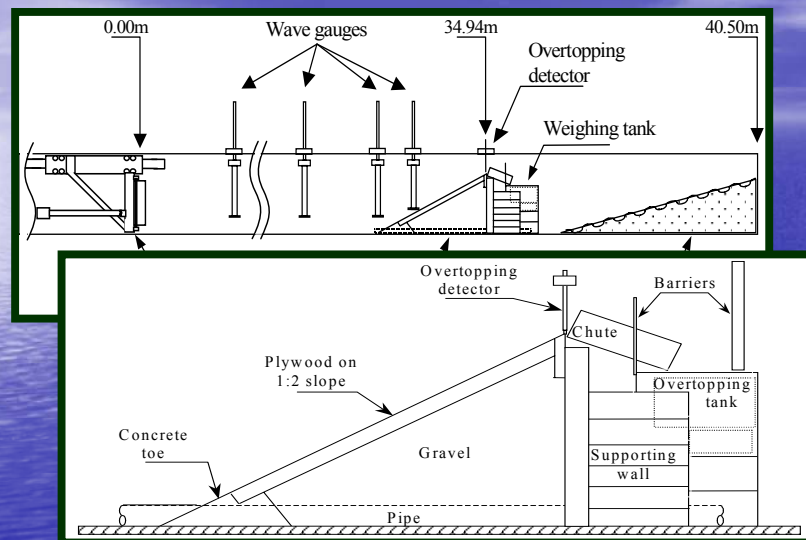
**Ibrahim Bay**

University of Liverpool

- ✦ A primary concern in designing any seawall is identifying the desired overtopping performance and then relating this required performance to suitable structure geometries.
- ✦ The most-widely used tools for predicting wave overtopping are empirical formulae based on hydraulic model tests of simplified cross-sections.
- ✦ Owen (1980), van der Meer & Janssen (1995), Hedges & Reis (1998) and Besley (1999) have developed the principal overtopping methods currently in use in Europe.
- ✦ However, even for simple structures, there are gaps in data, particularly at low overtopping discharges, the level for which many seawalls are designed.



- ✦ The paper describes the design, execution and results of a new series of 2-dimensional physical model tests designed to fill some of the gaps in current knowledge.
- ✦ Wave-by-wave and mean overtopping volumes were measured for simple seawalls having uniform seaward slopes of 1:2, 1:10 and 1:15.
- ✦ Random waves, conforming to the mean JONSWAP spectral form, were employed in the study. Each test lasted for between 500 and 5000 waves, with the bulk of the tests lasting for about 1000 waves.
- ✦ In total, 105 wave conditions were employed.





Microsoft Excel - proBAY Full List.xls

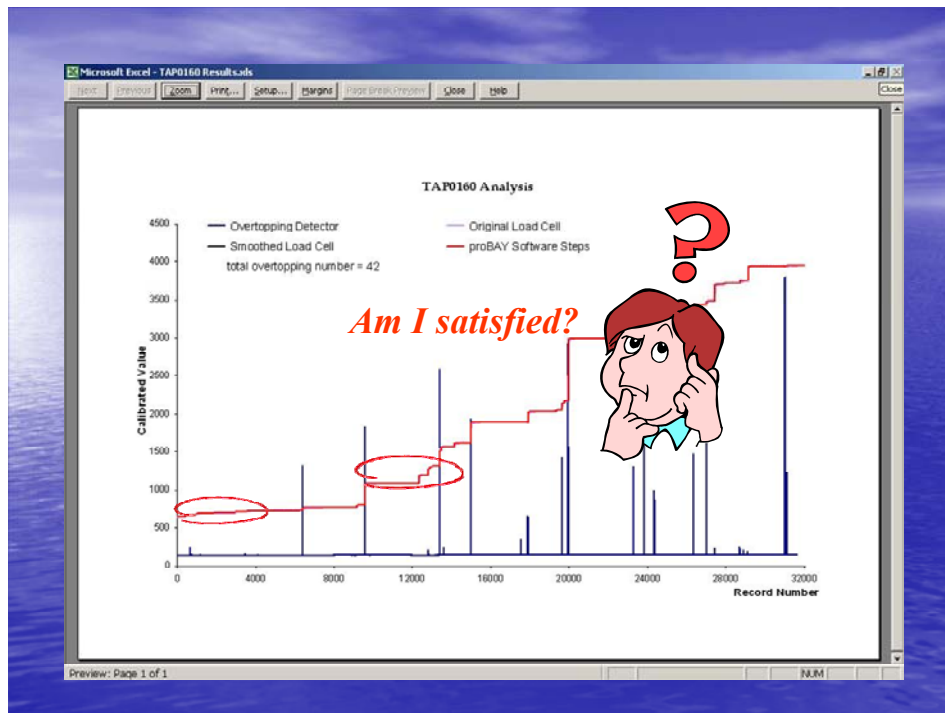
File Edit View Insert Format Tools Data Window Help AutoCAD

Arial 10

Test Number =

	A	F	G	H	I	J	K	L	M	N	O	P
1	Test Number =	1				2				3		
2	View	Test Name =	TAF0160			TAF0260				TAF0360		
3	Summary	H <sub>s</sub> (m) =	0.096			0.108				0.153		
4		T <sub>p</sub> (s) =	1.114			1.393				1.393		
5		Slope (1:s) =	2			2				2		
6		Water depth (m) =	0.6006			0.6006				0.6006		
7		Foreward (m) =	0.3994			0.3994				0.3994		
8		Detector File Name =	AT02.ASC			02AT02.ASC				03AT02.ASC		
9		Load Cell File Name =	AT01.ASC			02AT01.ASC				03AT01.ASC		
10		Chute Width (mm) =	500			500				100		
11		Total Sampling Time (s) =	1050.41			1310.72				1310.72		
12		Analysis Start Time (s) =	30.01			30.04				30.04		
13		Analysis Finish Time (s) =	1052.11			1302.56				1302.96		
14		Total Analysis Time (s) =	1022.10			1272.52				1272.92		
15		Number of Waves Analysed =	936.00			988.00				936.00		
16		Noise Filter Threshold =	146.58			149.32				219.41		
17		Number of Waves Overtopping =	42			68				178		
18		Total Overtopping Volume (l) =	3.292			14.564				26.467		
19		Maximum Overtopping Volume (l) =	0.825			2.229				1.057		
20		Mean Overtopping Volume (l) =	0.078			0.214				0.148		
21		Mean Overtopping Rate (l/s.m) =	6.44E-03			2.289E-02				2.079E-01		
22		Ranked Individual Overtopping Volumes	Ovtp No	Time (s)	Volume (l)	Ovtp No	Time (s)	Volume (l)	Ovtp No	Time (s)	Volume (l)	
23			1	644.611	0.82489	1	287.36	2.22925	1	306.36	1.05652	
24		Transfer Data	2	309.628	0.28037	2	1124.96	1.55293	2	910.48	0.850357	
25			3	484.306	0.27117	3	641.48	0.981278	3	512.04	0.772678	
26		Close proBAY files	4	886.809	0.20794	4	1210.56	0.713664	4	1443.48	0.753191	
27			5	432.562	0.20264	5	777.24	0.634212	5	807.52	0.721936	
28		Summarize	6	770.193	0.20224	6	433.64	0.632604	6	954.76	0.707703	
29			7	941.222	0.19294	7	808.24	0.626349	7	282.04	0.657444	
30		Save	8	578.59	0.12999	8	83.36	0.479599	8	562.96	0.651304	
31			9	890.814	0.12042	9	410.52	0.477823	9	687.04	0.64888	
32			10	399.163	0.09776	10	743.64	0.454799	10	363.64	0.647079	
33			11	413.892	0.09541	11	1176.08	0.437376	11	601.24	0.600473	
34			12	634.889	0.08013	12	171.88	0.351462	12	568.72	0.587812	
35			13	706.06	0.07108	13	900.72	0.324430	13	357.60	0.532504	

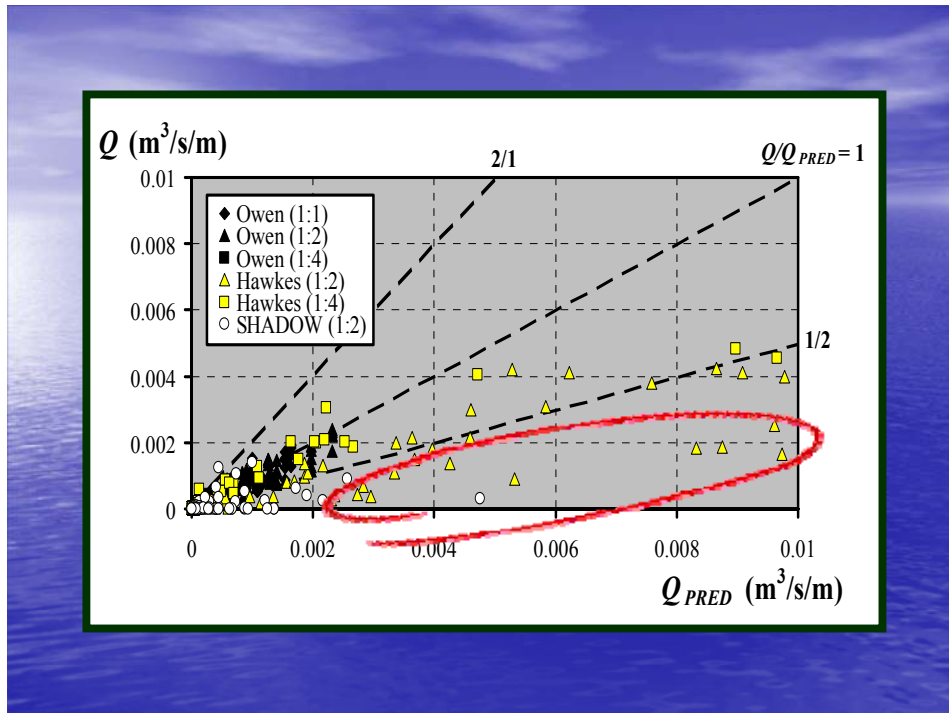
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⊕ Owen's model:

$$\frac{Q}{T_m g H_s} = A \exp\left(-B \frac{R_c}{T_m \sqrt{g H_s}}\right)$$

⊕ A comparison between measurements and predictions for slopes in the range 1:1 to 1:4 are shown in the following slide (using Owen's original values for empirical coefficients A and B). Note that agreement is good with Owen's original data. However, Owen's relationship tends to overestimate overtopping rates for swell conditions (Hawkes 1999).



⊕ The Hedges & Reis model

$$\frac{Q}{\sqrt{gR_{max}^3}} = A \left( 1 - \frac{R_c}{R_{max}} \right)^B \quad \text{for } 0 \leq \frac{R_c}{R_{max}} < 1$$

$$= 0 \quad \text{for } \frac{R_c}{R_{max}} \geq 1$$

⊕  $R_{max}$  must be estimated. The estimate should ensure that, if any overtopping occurs, the mean overtopping discharge remains negligible. Note that as the estimate of  $R_{max}$  changes, so also must the values of coefficients A and B. However, values have been determined for a standard case (see next slide).

- ⊕ The most probable maximum run-up in 100 waves (the value exceeded in 37% of cases for a Rayleigh distribution of run-ups) is:

$$(R_{max})_{37\%,100} = 1.52 R_s$$

- ⊕ Note that:

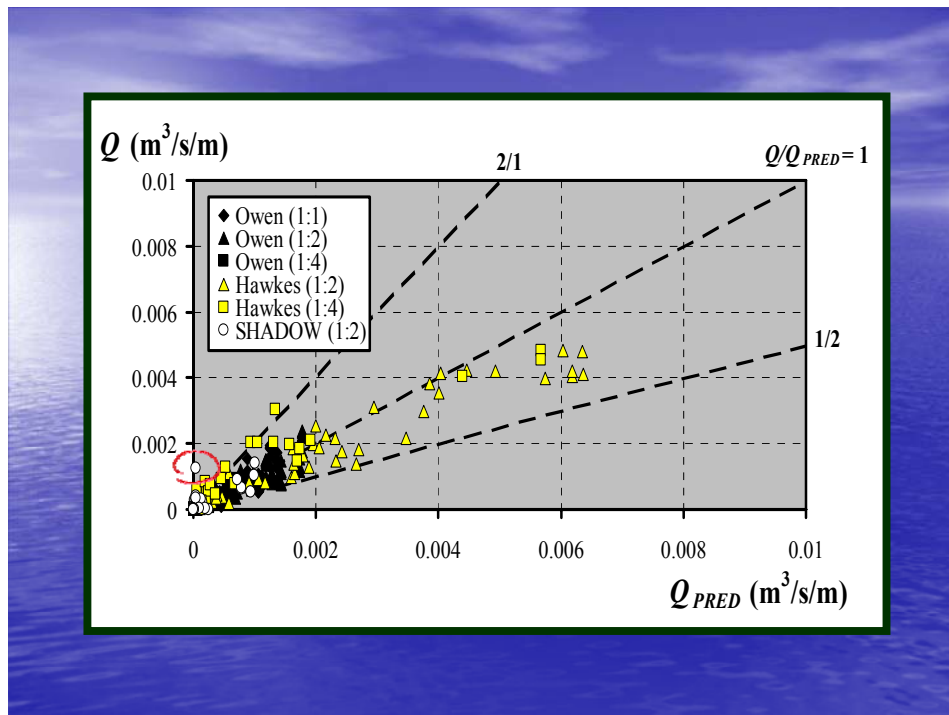
$$(R_{max})_{37\%,100} = R_{1\%}$$

- ⊕ Sea defences in continental Europe are often planned with a freeboard equal to  $R_{2\%}$  under design wave conditions.  $(R_{max})_{37\%,100}$  is about 8.5% greater than  $R_{2\%}$ , according to the Rayleigh distribution.

- ⊕ The original Hedges & Reis model estimated the significant wave run-up,  $R_s$ , using:

$$\begin{aligned} \frac{R_s}{H_s} &= 1.35 \xi_p && \text{for } 0 < \xi_p \leq 2 \\ &= 3.00 - 0.15 \xi_p && \text{for } 2 < \xi_p \leq 12 \end{aligned}$$

- ⊕ Results for slopes in the range 1:1 to 1:4, employing Hedges and Reis's original values for empirical coefficients A and B, are shown in the following slide.



✦ The Hedges & Reis model has now been extended to account for shallower slopes.

$$\frac{R_s}{H_s} = 0.25 + 1.10 \xi_p \quad \text{for } 0 < \xi_p \leq 2.2$$

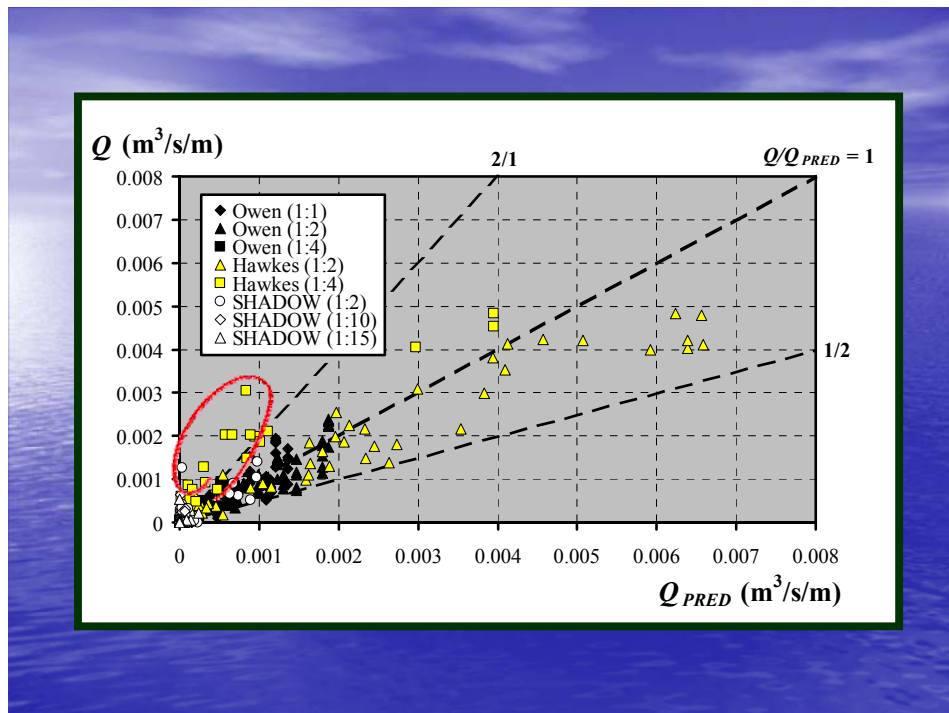
$$= 3.00 - 0.15 \xi_p \quad \text{for } 2.2 < \xi_p \leq 9.0$$

$$= 1.65 \quad \text{for } 9.0 < \xi_p$$

$$A = 0.0046 + 0.0018 \cot \alpha \quad \text{for } 1.0 \leq \cot \alpha \leq 20.0$$

$$B = 1.83 + 1.27 \cot \alpha \quad \text{for } 1.0 \leq \cot \alpha \leq 5.3$$

$$= 9.86 - 0.25 \cot \alpha \quad \text{for } 5.3 \leq \cot \alpha \leq 20.0$$



✦ Assuming that the run-ups of random waves approximately follow a Rayleigh distribution, then:

$$\text{Prob}[R > R_c] \approx \exp\left[-2\left(\frac{R_c}{R_s}\right)^2\right]$$

✦ Obviously, the number of run-ups exceeding the seawall crest level is equal to the number of overtoppings. If  $N_o$  is the number of overtoppings and  $N_R$  is the number of run-ups, then:

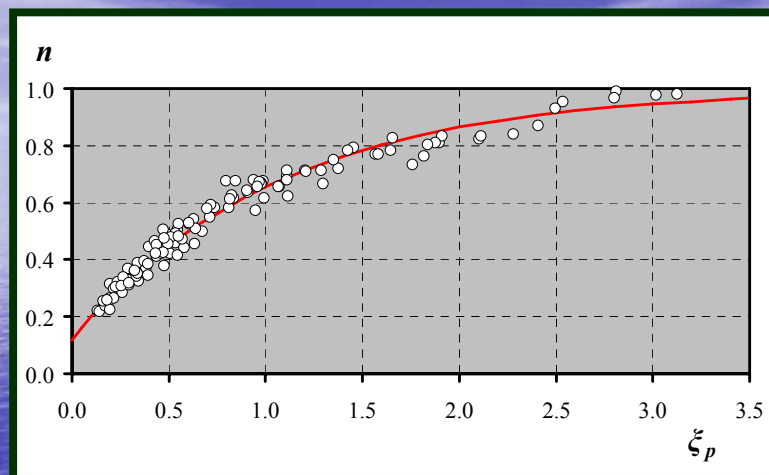
$$\text{Prob}[R > R_c] = \frac{N_o}{N_R}$$

- ✦ Note that the number of run-ups,  $N_R$ , is not necessarily the same as the number of incident waves,  $N$ . The difference is especially marked for gentle slopes. Therefore:

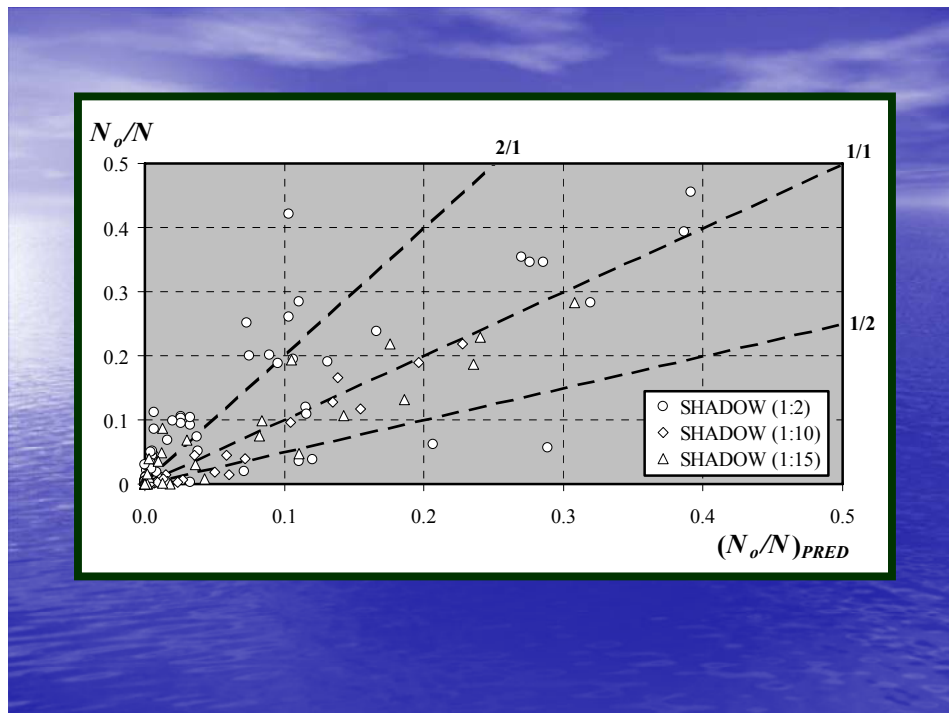
$$N_R = nN$$

- ✦ Values of coefficient  $n$  have been established by Mase & Iwagaki (1984). An equation fitted to their data gives:

$$n = \frac{N_R}{N} \approx \tanh\left(0.07 + \frac{\xi_p}{1.5}\right)^{0.8}$$





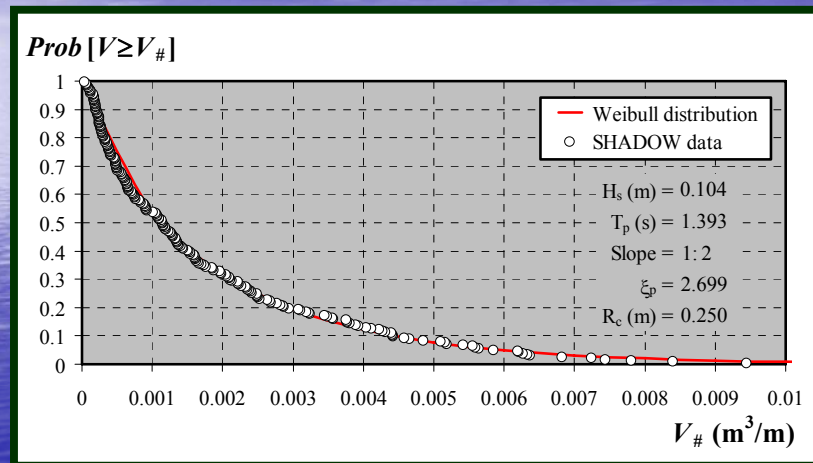


✦ The 2-parameter Weibull probability distribution may be used to represent the distribution of individual overtopping volumes,  $V$ :

$$Prob[V \geq V_{\#}] \approx \exp \left[ - \left( \frac{V_{\#}}{V_{char}} \right)^{\beta} \right]$$

✦ Ongoing research is aimed at establishing whether coefficient  $\beta$  varies systematically with the physical parameters of the tests over the wide range of front slopes for which overtopping data are now available. Besley (1999) reports  $\beta = 0.75$  for vertical walls, increasing to about 0.85 for sloping structures.

- ⊕ Here is an example of a fit of the Weibull distribution to the SHADOW data ( $\beta = 0.88$ ).



## CONCLUDING REMARKS

- ⊕ The outputs from two empirical prediction models have been compared with data from new physical model studies (the SHADOW project).
- ⊕ Modified values of the coefficients employed in the models are suggested for use with shallow-sloping structures.
- ⊕ Brief details are also reported of the wave-by-wave overtopping volumes recorded during the tests.

## ACKNOWLEDGEMENTS

- ✦ Supervision of Terry Hedges and contributions of Tim Pullen (HRW) and Mohamed Shareef (University of Liverpool) are acknowledged.
- ✦ Special thanks to Associate Professor Hajime Mase of the Disaster Prevention Research Institute, Kyoto University, for providing the data on numbers of run-ups compared with numbers of incident waves is.
- ✦ The tests at HR Wallingford (HRW) were commissioned by the UK Department for Environment, Food and Rural Affairs (Defra) under contracts FD2410 and 2412.
- ✦ Last but not the least, provided opportunity by the COZONE and The Marine Studies Group is appreciated.

## AND FINALLY...

- ✦ Thank you for your attention.
- ✦ Are there any questions?



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**WAVE OVERTOPPING OF SHALLOW SLOPING SEAWALLS:  
EXTENSION AND REFINEMENT OF EMPIRICAL  
PREDICTION METHODS**

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Currently available empirical methods often provide poor predictions of the overtopping discharges from waves on shallow sloping seawalls. As part of UK Government-funded research on Sea Hazard Defences against Overtopping by Waves (the SHADOW project), physical model studies have been undertaken on structures with 1:2, 1:10 and 1:15 front slopes. The outputs from two empirical prediction models have been compared with the measurements, and modified values of the coefficients employed in the models are suggested for use with shallow-sloping structures. Brief details are also reported of the wave-by-wave overtopping volumes recorded during the tests.

**1. Introduction**

The most-widely used tools for predicting wave overtopping of seawalls are empirical formulae based on hydraulic model tests of simplified cross-sections. Owen (1980), van der Meer & Janssen (1995), Hedges & Reis (1998) and Besley (1999) have developed the principal overtopping methods currently in use in Europe. However, even for simple structures, there are gaps in data, particularly at low overtopping discharges, the level for which many seawalls are designed.

The paper describes the design, execution and results of a new series of 2-dimensional physical model tests designed to fill some of the gaps in current knowledge. The tests formed part of UK Government-funded research on Sea Hazard Defences against Overtopping by Waves (the SHADOW project). Wave-by-wave and mean overtopping volumes were measured for simple seawalls having uniform seaward slopes of 1:2, 1:10 and 1:15. One purpose of the tests was to extend the range of Owen's (1980) prediction method; another was to further develop the Hedges & Reis (1998) approach, which recognizes that there will be many conditions resulting in zero overtopping. Empirical formulae of exponential form, such as Owen's expression, cannot represent cases of zero overtopping.

## 2. Physical Model Tests

The first stage tests were performed in a 40m long, 1.5m wide channel (Figure 1). The model structure had a 1:2 smooth plywood front slope spanning the full width, with a supporting toe of concrete (Figure 2) and with its crest at 1.0m above the horizontal bed. The channel was equipped with an absorbing wave paddle, wave gauges, an overtopping detector, and a tank supported on a load cell to trap and weigh overtopping water. A computer collected and stored the data in digital format at frequencies in the range 20Hz to 90Hz.

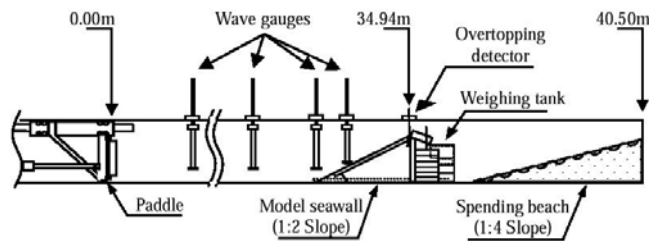


Figure 1: Wave flume and model seawall

Random waves, conforming to the mean JONSWAP spectral form, were employed in the study and each test lasted for between 500 and 5000 waves, with the overtopping detector sending a pulse to the recording equipment whenever water reached it. Overtopping water was directed to the weighing tank by means of a chute with a width of either 100mm or 500mm, depending upon the expected total volume. The load cell beneath the tank could measure up to 45kg of overtopping water. Total volumes were checked manually using a measuring cylinder.

The model seawall was tested for freeboards,  $R_c$ , of 0.25m and 0.40m (i.e. in water depths of 0.75m and 0.60m, respectively). In total, 62 wave conditions were employed, with significant wave heights,  $H_s$ , at the toe of the seawall ranging from 0.075m to 0.199m and spectral peak periods,  $T_p$ , ranging from 1.039s to 2.967s.

The second stage tests used a channel 50m long and 1m wide. Two similar models were employed in this work: a seawall with a 1:10 smooth plywood front slope having a crest at 0.65m above the horizontal bed, and a second structure with a 1:15 front slope and a crest at 0.575m above the bed. Operating water depths of 0.425m and 0.525m provided different freeboards. Both models were tested using the same 43 wave conditions in which  $H_s$  varied between 0.035m and 0.186m, with  $T_p$  ranging from 0.836s to 3.852s. Again, the tests lasted for between 500 and 5000 times the mean zero-crossing wave period,  $T_m$ , with the bulk of the tests lasting for about 1000 waves.

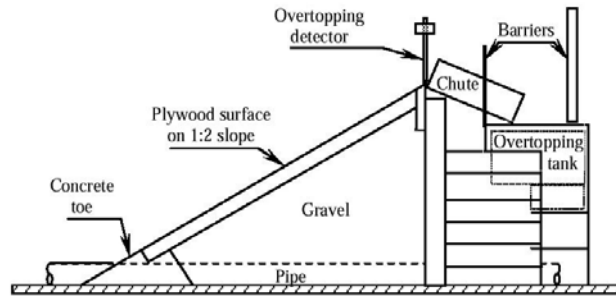


Figure 2: Model seawall details

### 3. Theoretical Considerations

#### 3.1. Mean Overtopping Discharge

Various overtopping models have been proposed over the last 25 years for predicting the mean discharge when random waves overtop seawalls. In this paper, the formulae of Owen (1980) and Hedges & Reis (1998) are considered. The following sub-sections summarize the two models.

##### 3.1.1. Owen's (1980) Model:

Owen's model was developed from physical model tests representing storm wave conditions in the Severn Estuary, UK (Owen 1980). Owen abandoned the awkward approaches to estimating overtopping rates which involved the use of design curves, overtopping coefficients which were functions of wave conditions, and potential run-up, as in the Shore Protection Manual (CERC 1984). Potential run-up is the run-up which would occur if the structure was high enough to prevent overtopping.

Owen's model may be expressed as:

$$Q/(T_m g H_s) = A \exp \left[ -B R_c / (T_m \sqrt{g H_s}) \right] \quad (1)$$

in which  $g$  is the acceleration due to gravity, and  $A$  and  $B$  are empirical coefficients which depend principally on the angle of the front slope of the structure.

Owen used model seawalls with uniform seaward slopes of 1:1, 1:2 and 1:4 to evaluate coefficients  $A$  and  $B$ . Note that, for fixed values of  $R_c$  and  $H_s$ , Eq. (1) indicates that the overtopping discharge always increases with an increase in  $T_m$ . However, this is not the case and Owen's relationship tends to overestimate overtopping rates for swell conditions (Hawkes 1999). According to Owen (1980), coefficients  $A$  and  $B$  are valid for the following range of conditions:

$$0.05 < R_c / (T_m \sqrt{gH_s}) < 0.30; 10^{-6} < Q / (T_m g H_s) < 10^{-2};$$

$$1.5 < d_s / H_s < 5.5; 0.035 < H_s / L_{om} < 0.055;$$

in which  $L_{om} = gT_m^2 / 2\pi$ .

3.1.2. *The Hedges & Reis (1998) Model:*

The Hedges & Reis (1998) overtopping model may be written:

$$\begin{aligned} Q / \sqrt{gR_{max}^3} &= A [1 - (R_c / R_{max})]^B && \text{for } 0 \leq R_c / R_{max} < 1 \\ &= 0 && \text{for } R_c / R_{max} \geq 1 \end{aligned} \quad (2)$$

Eqs. (2) give zero discharge when the crest of the seawall is above the maximum run-up,  $R_{max}$ . Unless  $R_{max}$  exceeds the freeboard,  $R_c$ , there is no overtopping apart from wind-blown spray.

To evaluate coefficients A and B in Eqs. (2), Hedges & Reis (1998) used Owen's data in which overtopping had been evaluated for runs of 100 waves. In this case, the most probable maximum run-up during each run, i.e. the modal value of the probability density function of maximum run-up, or the value not exceeded in 37% of the cases for a Rayleigh distribution of run-ups, was:

$$(R_{max})_{37\%,100} = 1.52 R_s \quad (3)$$

in which  $R_s$ , the significant wave run-up, was evaluated using the equations given in the CIRIA/CUR (1991) manual:

$$\begin{aligned} R_s / H_s &= 1.35 \xi_p && \text{for } 0 < \xi_p \leq 2 \\ &= 3.00 - 0.15 \xi_p && \text{for } 2 < \xi_p \leq 12 \end{aligned} \quad (4)$$

Here,  $\xi_p$  is the surf similarity parameter calculated using the wave period,  $T_p$ , corresponding to the peak of the incident wave spectrum ( $\xi_p = \tan \alpha / \sqrt{H_s / L_{op}}$ , in which  $\alpha$  is the angle of the seawall front slope measured from the horizontal, and  $L_{op} = gT_p^2 / 2\pi$ ). Combining Eqs. (3) and (4) then gives:

$$\begin{aligned} (R_{max})_{37\%,100} / H_s &= 1.52 (1.35 \xi_p) \approx 2.05 \xi_p && \text{for } 0 < \xi_p \leq 2 \\ &= 1.52 (3.00 - 0.15 \xi_p) \approx 4.56 - 0.23 \xi_p && \text{for } 2 < \xi_p \leq 12 \end{aligned} \quad (5)$$

A value such as  $(R_{max})_{37\%,100}$  simply provides an estimate of the actual maximum run-up during a storm (i.e. an estimate of the minimum freeboard needed to ensure zero overtopping). However, this estimate should guarantee, at the very least, that any overtopping which does occur remains negligible. In this connection, it is worth noting that Eqs. (5) estimate the most probable maximum run-up as  $4.1H_s$ , regardless of the structure slope or incident wave steepness, and



van der Meer & Janssen (1995) record no overtopping discharges for cases in which  $R_c > 4.1H_s$ , even for tests involving many more than 100 waves. Furthermore, if the Rayleigh distribution applies to run-ups, then:

$$(R_{\max})_{37\%,100} = R_{1\%} \tag{6}$$

in which  $R_{n\%}$  denotes the value exceeded by  $n\%$  of all the individual run-ups. It is worth noting that sea defences in continental Europe are often planned with a freeboard equal to  $R_{2\%}$  under design wave conditions.  $(R_{\max})_{37\%,100}$  is about 8.5% greater than  $R_{2\%}$ , according to the Rayleigh distribution.

Table 1 contains the values of coefficients A and B established by Owen (1980) for seawalls with uniform front slopes of 1:1, 1:2 and 1:4, together with Besley's (1999) recommended values for Owen's model, and the Hedges & Reis (1998) values for their model.

Table 1. Coefficients for use in the models of Owen (1980) and Hedges & Reis (1998)

		Owen's model		Hedges & Reis model (1998) [ using $(R_{\max})_{37\%,100}$ ]
		Owen (1980)	Besley (1999)	
Slope 1:1	A	0.00794	0.00794	0.00703
	B	20.12	20.1	3.42
Slope 1:2	A	0.0125	0.00939	0.00753
	B	22.06	21.6	4.17
Slope 1:4	A	0.0192	0.0116	0.0104
	B	46.96	41.0	6.27

### 3.2. Wave-by-Wave Overtopping

#### 3.2.1. Number of Overtoppings:

Assuming that the run-ups,  $R$ , of random waves approximately follow a Rayleigh distribution, then:

$$\text{Prob}[ R > R_c ] \approx \exp[-2(R_c/R_s)^2] \tag{7}$$

Obviously, the number of run-ups exceeding the seawall crest level is equal to the number of overtoppings,  $N_o$ . Thus:

$$\text{Prob}[ R > R_c ] = N_o/N_R \tag{8}$$

in which  $N_R$  is the number of run-ups. Note that the number of run-ups is not necessarily the same as the number of incident waves,  $N$  (Mase & Iwagaki 1984). The difference is especially marked for gentle slopes. Therefore:

$$N_R = nN \tag{9}$$

in which  $0 < n \leq 1$ , giving:

$$N_o/N \approx n \exp[-2(R_c/R_s)^2] \tag{10}$$

Eq. (10) is an approximation: it predicts that some proportion of the waves will always cause overtopping of the seawall regardless of the freeboard:  $N_o/N$  is zero only when  $R_c/R_s$  is infinite. Note that the Hedges & Reis (1998) mean overtopping model predicts that there is no overtopping once  $R_c \geq R_{max}$ .

Values of coefficient  $n$  have been established by Mase & Iwagaki (1984). Figure 3 shows the relationship between  $n$  and  $\xi_p$ . The line fitted to the data is:

$$n = N_R/N \approx \tanh[0.07 + (\xi_p/1.5)]^{0.8} \tag{11}$$

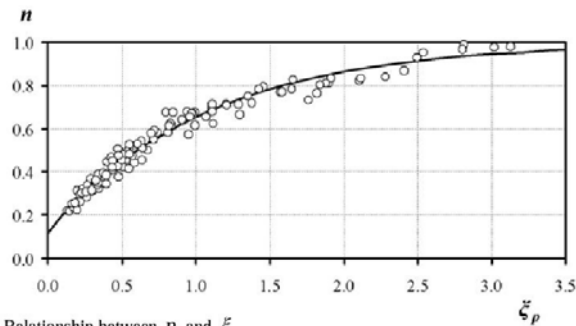


Figure 3: Relationship between  $n$  and  $\xi_p$

3.2.2. Individual Overtopping Volumes:

The 2-parameter Weibull probability distribution may be used to represent the distribution of individual overtopping volumes,  $V$ :

$$\text{Prob}[V \geq V_\#] \approx \exp[-(V_\#/V_{char})^\beta] \tag{12}$$

in which  $V_{char}$  characterizes the scale of the overtopping and  $\beta$  is the shape parameter (a pure number). Again, note that Eq. (12) is an approximation. It correctly predicts that  $\text{Prob}[V \geq 0] = 1$ . However, just as the Rayleigh distribution predicts the possibility of an infinite run-up, the Weibull distribution predicts the possibility of an infinitely large overtopping volume.

Clearly, the value of  $V_{char}$  in Eq. (12) depends upon the incident wave conditions and the seawall details (front slope, freeboard, etc). It may be evaluated,

together with coefficient  $\beta$ , by twice taking natural logarithms of both sides of Eq. (12):

$$\left\{ \ln \left( \text{Prob}[V \geq V_{\#}] \right)^{-1} \right\}^{1/\beta} = V_{\#} / V_{\text{char}} \quad (13)$$

$$\ln \left\{ \ln \left( \text{Prob}[V \geq V_{\#}] \right)^{-1} \right\} = \beta \ln V_{\#} - \beta \ln V_{\text{char}} \quad (14)$$

If the Weibull distribution properly characterizes the individual overtopping volumes, then a plot of  $\ln \{ \ln (\text{Prob}[V \geq V_{\#}]^{-1}) \}$  against  $\ln V_{\#}$  should produce a straight line from which  $\beta$  and  $V_{\text{char}}$  may be evaluated.

Exceedance probabilities may be estimated using the concept of plotting positions. There are various plotting positions, but two are commonly used. The measured overtopping volumes are firstly ranked in order of descending magnitude from the biggest ( $i = 1$ ) to the smallest ( $i = N_o$ ). Then:

$$\text{Prob}[V \geq (V_{\#})_i] \approx i / N_o \quad (15)$$

or, alternatively,  $\text{Prob}[V \geq (V_{\#})_i] \approx i / (N_o + 1)$  (16)

The first expression gives the probabilities observed in the sample. However, it implies that all overtopping volumes are greater than or equal to the minimum value recorded in the sample. Adding 1 to the denominator allows the possibility of an overtopping volume which is smaller than the smallest measured value. The difference between the two probability estimates is small if  $N_o$  is reasonably large. As noted above,  $\text{Prob}[V \geq 0] = 1$ .

Assuming a Weibull distribution of individual overtopping volumes, the mean volume is given by:

$$V_{\text{bar}} = V_{\text{char}} \Gamma[1 + (1/\beta)] \quad (17)$$

in which  $\Gamma[ ]$  denotes the gamma function. However, the mean overtopping volume may also be established directly from knowledge of the mean overtopping discharge,  $Q$ , the number of incident waves,  $N$ , their mean period,  $T_m$ , and the number of overtoppings,  $N_o$ :

$$V_{\text{mean}} = Q(N T_m) / N_o = Q T_m / (N_o / N) \quad (18)$$

$V_{\text{bar}} = V_{\text{mean}}$  if Eq. (12) properly describes the individual overtopping volumes and if the probability estimate from Eq. (16) is reliable. Eqs. (17) and (18) then provide a link between the mean overtopping discharge,  $Q$ , and information on the distribution of the individual overtopping volumes (Franco & Franco 1999).

4. Results

Owen's (1980) model and the Hedges & Reis (1998) model were originally calibrated using data only for front slopes of 1:1, 1:2 and 1:4 (see Table 1). As a result, new coefficients A and B have had to be established to cover the shallower slopes considered in the present tests. But, firstly, results from the SHADOW tests on the 1:2 slope are compared with predictions provided by the two original models.

4.1. Mean Overtopping Discharges for Steep Front Slopes (1:1, 1:2 and 1:4)

Figure 4 compares the mean overtopping discharges measured in the present experiments (Q) with predictions (Q<sub>PRED</sub>) provided by Owen's (1980) model.

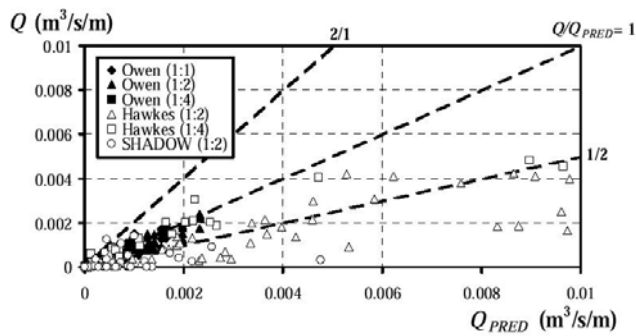


Figure 4: Comparison of measured and predicted overtopping discharges for 1:1, 1:2 and 1:4 slopes: Owen's (1980) model

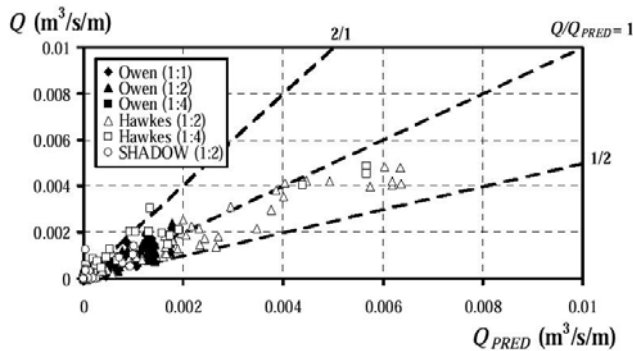


Figure 5: Comparison of measured and predicted overtopping discharges for 1:1, 1:2 and 1:4 slopes: Hedges & Reis (1998) model

The figure also shows Owen's original data and the data of Hawkes et al (1998). As noted earlier, Owen's model tends to overestimate overtopping for swell conditions (Hawkes 1999). Figure 5 shows the same data, this time compared with predictions provided by the Hedges & Reis (1998) model. It may be seen that there is improved agreement. Note that all measured and predicted overtopping discharges are reported at model scale. If the prototype/model length ratio is  $L_r$ , then discharges (in  $m^3/s/m$ ) scale by  $L_r^{3/2}$ .

**4.2. Extensions to Owen's Model for Shallow Front Slopes**

Following completion of the SHADOW tests, Allsop & Pullen (2003) provided interim guidance on new values of A and B for use in Owen's model, extending the range of front slopes for which the model may be applied; see Table 2.

Table 2: New coefficients for use in Owen's model (Allsop & Pullen 2003)

	Slope 1:2	Slope 1:4	Slope 1:6	Slope 1:8	Slope 1:10	Slope 1:15
A	0.01	0.01	0.01	0.01	0.01	0.01
B	21.6	43	65	86	108	162

Figure 6 again compares the mean overtopping discharges measured in the present experiments with the predictions provided by Owen's model, in this instance for slopes of 1:10 and 1:15. It can be seen that agreement is reasonable for these very low overtopping discharges, particularly in view of the expected degree of scatter in the data. The presence of even a single extreme event has a large influence on the mean value when the total number of overtoppings is small.

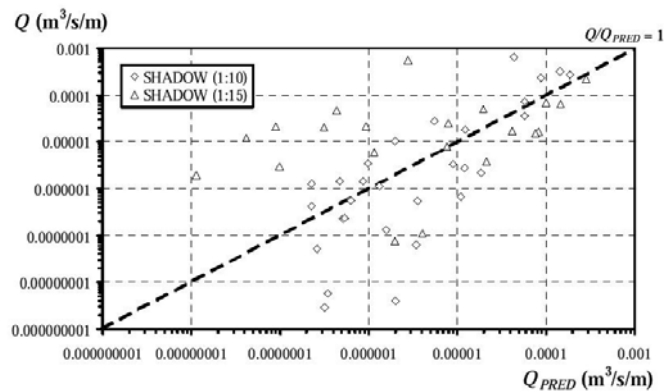


Figure 6: Comparison of measured and predicted overtopping discharges for 1:10 and 1:15 slopes: Owen's (1980) model

#### 4.3. Extensions to the Hedges & Reis Model for Shallow Front Slopes

Mase et al (2003) modified and extended the Hedges & Reis (1998) model to account for Japanese data on run-up and overtopping not considered originally. The new data covered front slopes as shallow as 1:20.

Instead of using the expressions for  $R_s$  given in the CIRIA/CUR (1991) manual (Eqs. (4), above), Mase et al (2003) used the following relationships, which provide improved agreement with run-up data, particularly for small values of  $\xi_p$  (see Hedges & Mase 2004):

$$\begin{aligned} R_s/H_s &= 0.25 + 1.10\xi_p && \text{for } 0 < \xi_p \leq 2.2 \\ &= 3.00 - 0.15\xi_p && \text{for } 2.2 < \xi_p \leq 9.0 \\ &= 1.65 && \text{for } 9.0 < \xi_p \end{aligned} \quad (19)$$

Combining Eqs. (3) and (19) then gives:

$$\begin{aligned} (R_{\max})_{37\%,100}/H_s &= 1.52(0.25 + 1.10\xi_p) \approx 0.38 + 1.67\xi_p && \text{for } 0 < \xi_p \leq 2.2 \\ &= 1.52(3.00 - 0.15\xi_p) \approx 4.56 - 0.23\xi_p && \text{for } 2.2 < \xi_p \leq 9.0 \\ &= 1.52(1.65) \approx 2.51 && \text{for } 9.0 < \xi_p \end{aligned} \quad (20)$$

Revised values of coefficients A and B were then established to cover a much wider range of slopes than was considered originally. The values are described by the following expressions (Mase et al 2003):

$$A = 0.0046 + 0.0018 \cot \alpha \quad \text{for } 1.0 \leq \cot \alpha \leq 20.0 \quad (21)$$

$$\begin{aligned} B &= 1.83 + 1.27 \cot \alpha && \text{for } 1.0 \leq \cot \alpha \leq 5.3 \\ &= 9.86 - 0.25 \cot \alpha && \text{for } 5.3 \leq \cot \alpha \leq 20.0 \end{aligned} \quad (22)$$

Figure 7 compares all the measured mean overtopping discharges of Owen (1980) and Hawkes et al (1998), together with the SHADOW data for the 1:2, 1:10 and 1:15 slopes, with the predictions provided by the extended Hedges & Reis model. As can be seen, predictions are generally good, although agreement with the data of Hawkes et al (1998) is somewhat poorer than in Figure 5.

#### 4.4. Number of Overtoppings

Figure 8 plots the numbers of overtoppings divided by the corresponding numbers of incident waves,  $N_o/N$ , measured during the SHADOW tests against the predictions provided by Eqs. (10) and (11),  $(N_o/N)_{\text{PRED}}$ , with  $R_s$  determined from Eqs. (19). It can be seen that the agreement is reasonable. The greatest scatter occurs in the case of the 1:2 slope, for which there would have

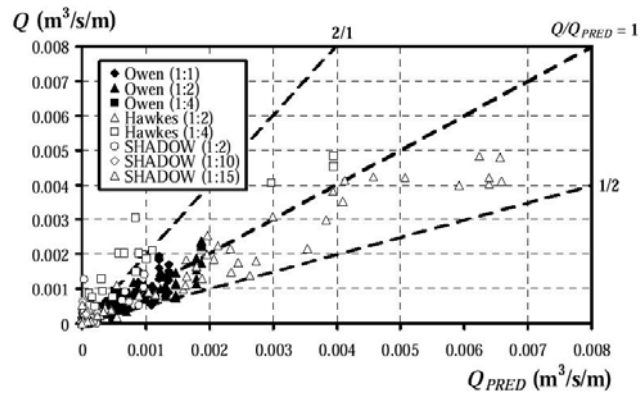


Figure 7: Comparison of measured and predicted overtopping discharges for all slopes: Hedges & Reis (1998) model

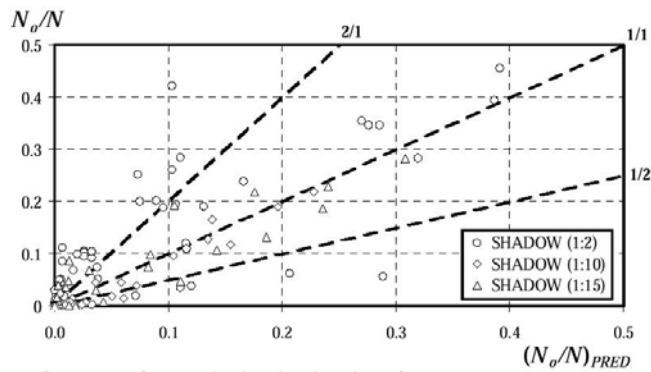


Figure 8: Comparison of measured and predicted numbers of overtoppings

been the greatest reflection of the incident wave energy, possibly causing some sloshing within the wave flume, despite the use of the absorbing wave paddle. Agreement also generally improves as the expected number of overtoppings increases.

#### 4.5. Individual Overtopping Volumes

Figure 9 is an example of a Weibull distribution fitted to the measured individual overtopping volumes. In this case, the distribution gives values of  $\beta = 0.88$  and  $V_{char} = 0.00171 \text{ m}^3/\text{m}$ , from which  $V_{bar} = 0.00182 \text{ m}^3/\text{m}$ , according to Eq. (17).

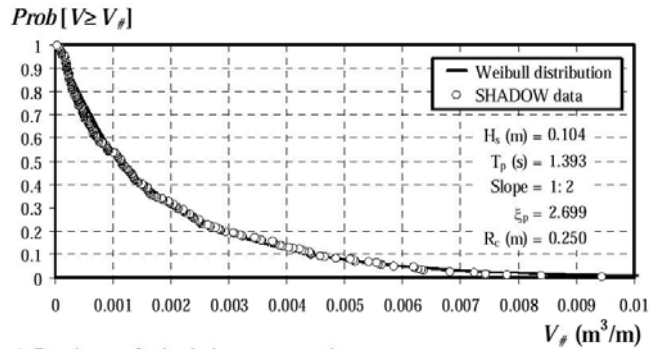


Figure 9: Distribution of individual overtopping volumes

This latter value is in close agreement with the measured mean overtopping volume from Eq. (18),  $V_{mean} = 0.00177 m^3/m$ . Ongoing research is aimed at establishing whether coefficient  $\beta$  varies systematically with the physical parameters of the tests over the wide range of front slopes for which data are now available. Besley (1999) reports  $\beta = 0.75$  for vertical walls, increasing to about 0.85 for sloping structures.

### 5. Concluding Remarks

The outputs from two empirical prediction models have been compared with data from new physical model studies (the SHADOW project). Modified values of the coefficients employed in the models are suggested for use with shallow-sloping structures. Brief details are also reported of the wave-by-wave overtopping volumes recorded during the tests.

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