Wind/swell seas and steep approach slopes

Technical report on wave flume studies

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February 1998

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Prepared by .... (name) Project Engineer (Title)

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Summary

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HR Wallingford was commissioned by the Ministry of Agriculture, Fisheries and Food to conduct a number of different research projects making use of similar physical model facilities. The projects were combined into a rolling programme of work using the Absorbing Wave Flume at HR Wallingford.

The three principle projects were:

(i) To study the effects of combined swell/storm (bi-modal) waves on wave overtopping on simple seawall structures (Sub-commission No. FD0202).

(ii) To investigate the cross-shore response of shingle beaches to bi-modal and wind sea waves (Sub-commission No. FD0705).

(iii) To study the importance of approach slope on the form of breaking waves and the subsequent effects on wave pressures on simple seawall structures (Sub-commission No. FD0201).

Information obtained during the execution of these projects was also used to validate a non-linear, surf-zone numerical model developed for MAFF under a separate commission (Sub-commission No. FD0204), and to provide data to a European Union PROVERBS project relating to wave loading on vertical structures.

This Technical Report documents the methods and results obtained from all of the studies within the rolling programme. Detailed discussions and conclusions drawn from the projects are presented in separate HR Wallingford reports.

Further information about the research projects can be obtained from the HR Wallingford Coastal Group.

Notation

A_c	Armour crest freeboard
A_e	Erosion area on cross-section
a	Empirical coefficient
B	Structure width, normal to face
b	Empirical coefficient
C_r	Coefficient of reflection
$C_r(f)$	Reflection coefficient function
D	Particle size or typical diameter
D_n	Nominal particle diameter, defined $(M/\rho_r)^{1/3}$ for rock and $(M/\rho_c)^{1/3}$ for concrete armour
D_{n50}	Nominal particle diameter calculated from the median particle mass M_{50}
d	Empirical coefficient, also used for water depth, but see h
E_i	Incident wave energy
E_r	Reflected wave energy
E_t	Transmitted wave energy
F_{Hmax}	Total backwards acting force on crown wall element
f_p	Frequency of peak of wave energy spectrum
g	Gravitational acceleration
H	Wave height, from trough to crest
H_{max}	Maximum wave height in a record
H_{m0}	Significant wave height from spectral analysis, defined $4.0m_0^{0.5}$
H_o	Offshore wave height, unaffected by shallow water processes
H_s	Significant wave height, average of highest one third of wave heights
$H_{2\%}$	Wave height exceeded by 2% of waves in a record
$H_{1/10}$	Mean height of highest 1/10 of waves in a record
h	Water depth
k	Wave number = $2\pi/L$
L	Wave length, in the direction of propagation
L_m	Offshore wave length of mean (T_m) period
L_o	Deep water or offshore wave length = $gT^2/2\pi$
L_p	Offshore wave length of peak (T_p) period
L_{ps}	Wave length of peak period at structure, given approximately by $(gT_p^2/2\pi)[\tanh(4\pi^2h/gT_p^2)]^{1/2}$
M	Mass of armour unit
M_{50}	Median mass of armour unit derived from the mass distribution curve
m_0	Zeroth moment of the wave energy density spectrum
N	Number of values
N_a	Total number of armour units in area considered
N_d	Number of armour units displaced, usually by more than D
N_r	Number of armour units rocking
N_s	Stability number, $H_s/\Delta D_n = (K_D \cot\alpha)^{1/3}$
N_{wo}	Number of waves overtopping expressed as proportion or % of total incident

Notation continued

$N_{\%d}$	Number of armour units displaced, expressed as % of total number of armour units
P	Notional permeability factor, used in calculation of armour stability, also encounter probability
Q	Overtopping discharge, per unit length of structure
Q^*	Dimensionless overtopping discharge, defined $Q^* = Q/(T_m g H_s)$
q_o	Volume of overtopping, per wave, per unit length of structure
R_c	Crest freeboard, level of crest less static water level
R_u	Run-up level, relative to static water level
R_{us}	Run-up level of significant wave
$R_{u2\%}$	Run-up level exceeded by 2% of run-up crests
R^*	Dimensionless freeboard, defined in terms of the steepness of the mean wave period, $R^*_m = (R_c/H_s)(s_m/2\pi)^{1/2}$
$R_{d98\%}$	Run-down level, below which only 2% pass
r	Roughness value, usually relative to smooth slopes
S	Damage number for (rock) armoured slopes = A_e/D_{n50}^2; also used as a general load or surcharge on the system in reliability analysis
$S(f)$	Spectral density
s_m	Steepness of mean wave period = $2\pi H/gT_m^2$
s_p	Steepness of peak wave period = $2\pi H/gT_p^2$
T	Structural, economic, or design lifetime (in years), also used as a (regular) wave period
T_m	Mean wave period
T_p	Spectral peak period, inverse of peak frequency
t	Tonne
u, v, w	Components of velocity along x, y, z axes
W	Armour unit weight
W_{50}	Median armour unit weight
α	Structure front slope angle to horizontal; also used as a coefficient; or a distribution parameter
γ	Partial coefficient; also used as peak factor of JONSWAP spectrum
γ_i	Partial coefficient related to characteristic value of X_i
ρ	Mass density, usually of fresh water; also used as correlation coefficient
ρ_w	Mass density of sea water
ρ_r, ρ_c, ρ_a	Mass density of rock, concrete, armour units
Δ	Reduced relative density, eg. (ρ_r/ρ_w)-1
λ	Model / prototype scale ratio; also used as the average number of H_s data values per year, H/T
ξ	Iribarren number or surf similarity parameter, = $\tan\alpha/s^{1/2}$
ξ_m, ξ_p	Iribarren number calculated in terms of s_m or s_p
ξ_c	Critical value of Iribarren number distinguishing plunging from surging waves

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1 Introduction

1.1 Background

HR Wallingford (HR) was commissioned by the Ministry of Agriculture, Fisheries and Food (MAFF) to conduct a number of different research projects during the financial year 1996-97, three of which used potentially similar physical model investigations. The approach to the modelling was to share the same test facility, thus sharing the initial set-up charges and other resources. The projects concerned were investigations of:

(i) the effects of combined wind/swell seas on wave overtopping of simple seawall structures (Sub-commission No. FD0202: Wave prediction at or near the coastline: Combined swell and storm waves);

(ii) the response of shingle beaches to combined wind/swell seas (Sub-commission No. FD0705: Beach management and design: Impact on bi-modal wave energy spectra on the response of shingle beaches);

(iii) the form of breaking waves on steep beaches and the effects on wave pressures on simple seawall structures (Sub-commission No. FD0201: Sea defence structures: Wave impact pressures on seawalls and sub-commission No. FD0705: Beach management and design: Effect of steep beach slopes on wave breaking, armour response and impacts).

During the course of the research an extension to the contract was authorised by MAFF (Sub-commission No. FD0705: Beach management and design: Extension of wave flume tests on bi-modal spectra, wave breaking and wave pressures). The extension allowed HR to make wave run-up and run-down measurements on crest freeboards for which there was no significant wave overtopping. Additional wave run up and overtopping velocities were determined using a photographic technique.

Following internal discussions on this joint approach two further projects were identified which benefited from the collaboration. The fifth project was the numerical model, constructed for MAFF, to study non-linear and surf zone processes (Sub-commission No. FD0204). Validation data required for this project was obtained from the observations taken during the execution of items (i) and (iii) above.

The final project was the PROVERBS-Project (Task 1: Hydrodynamics Aspects) conducted for the European Union under contract MAS3-CT95-0041. The form of breaking wind sea waves and bi-modal waves were used to study wave loadings on vertical structures obtained from observations made during the execution of items (i) and (iii) above.

The objective of this Technical Report is to document the wave calibrations, measurements obtained and the resources used during completion of the test programme for this collaborative research.

The results of the projects are discussed further in several other HR Wallingford reports and papers. The effects of bi-modal seas (projects (i) and (ii)) are considered in Report SR 507 (Reference 1), while Reports SR 516 and SR 511 (References 2 and 3) discuss wave breaking and pressures on structures (project (iii)). Initial results have been incorporated into two papers presented at The Waves '97 Conference in Virginia, USA (References 4 and 5) and one paper has been submitted to a refereed journal (Reference 6). Wave pressures and forces experienced on the vertical structure have been reported to PROVERBS in SR 509 (Reference 7).

1.2 Outline of the study

1.2.1 Tests on structures

A series of wave flume tests were undertaken to investigate wave forces / pressures, run-up, overtopping and other responses on simple vertical and inclined walls. The work was completed in the HR Wallingford Absorbing Wave Flume at a scale of 1:20.

Three main structure types were studied: 1:2 and 1:4 smooth slope revetments, and a simple vertical wall. Later tests included a 1:2 slope incorporating a berm and a 1:2 rock armour slope. The responses of each structure were investigated using different foreshore slopes. The shallowest slope, 1:50, was taken as indicative of all shallower slope angles. An intermediate slope of 1:20 represented that used for many studies in the UK Coastal Research Facility at HR Wallingford (CRF), and was indicative of the steeper end of sand beaches. The steepest two slopes, 1:10 and 1:7, were indicative of shingle or mixed sediment beaches.

The responses measured included

- incident reflected waves, from which the reflection coefficient function, $C_r(f)$ and the overall reflection coefficient, C_r were calculated
- wave run-up and run-down levels
- mean overtopping discharges, distribution of overtopping volumes wave by wave
- wave pressures forces normal to the structure face.

Most conditions were tested using the 1:50 approach bed slope with the 1:2 and 1:4 structure slopes. Tests on the vertical wall followed the tests on these slopes. The bed slope was then changed to 1:20 and some of the previous tests were repeated. This test sequence was repeated for bed slopes of 1:10 and 1:7. A summary of the tests undertaken on the various structures is given in Appendix 1.

1.2.2 Tests on shingle beaches

Following the work on vertical and inclined walls, a series of tests was carried out on shingle beaches. They were designed to investigate the effect of combined swell / storm (bi-modal) waves on shingle beach response as a direct comparison with results from previous research at HR Wallingford by Powell (Reference 8). The results provide preliminary guidance to assist shoreline managers in the design of beach schemes in areas potentially affected by bi-modal wave conditions.

1.3 Outline of the report

This report describes the wave calibrations, measurements obtained and the resources used during the test programme of this collaborative research. This report should be read in conjunction with its companion reports SR 507 (Reference 1), SR 516 (Reference 2), and SR 511 (Reference 3). The study design and model facility is outlined in Chapter 2. The report is then broadly divided into two sections. In the first part (Chapters 3 and 4) the report describes the structure responses, while the second part (Chapters 5 and 6) describes beach responses. Chapters 3 and 5 describe the test procedures. In Chapters 4 and 6, the results from the testing of the different structures and shingle beaches are presented.

Appendices 1-4 present details of test methods for wave spectral analysis, scaling of rock for structures and wave reflection analysis. All test data have been stored on compact discs for future reference. Appendix 5 presents details.

All dimensions used in this report are prototype unless otherwise specified.

2 *Model facility*

2.1 Wave flume

The model tests described in this report were conducted in the Absorbing Wave Flume at HR Wallingford. The flume is 40m long, 1.5m wide and has an operating range of water depths at the wave paddle of 0.5-1.2m. The flume was equipped with a piston paddle, wave probes, an overhead camera, video equipment, a beach profiler, overtopping tanks and pressure sensors. Figure 2.1 indicates the model layout and the positions of the wave probes. The equipment is discussed in greater detail below.

The piston paddle is driven by an electro-hydraulic system. The paddle is controlled by a computer enabling either regular, random or solitary waves to be generated (Appendix 2). Two wave probes mounted on the front face of the paddle measure the water surface elevation continuously. This signal is then compared with that generated with the feedback loop adjusting the signal to the paddle to ensure that only the required incident wave train is generated, and that reflections from the structure are absorbed at the paddle.

2.2 Test conditions

2.2.1 Wave conditions

Tests on structures

The flume was calibrated to provide JONSWAP wind sea, swell conditions, bi-modal spectra and solitary waves. The complete set of wave conditions are given in Table 2.1. Each bi-modal spectrum consists of two superimposed JONSWAP spectra, each defined by its significant wave height (H_s) and peak period (T_p). The wind sea only conditions (Series 0) include sea steepnesses ($S_m = H_s/L_m$) of 0.02, 0.04 and 0.06. During calibration each wave condition was adjusted until the spectrum measured at the wave generator closely matched the target spectrum. Examples of the wind sea calibrations, with a foreshore slope of 1:50, are given in Figure 2.2. Example bi-modal wave calibrations are shown in Figure 2.3.

The bi-modal wave conditions were divided into six sequences of five tests each and one sequence of eight tests.

- Sequences 1-3 have wave conditions with equal energy, based on wind sea with a peak period at 7s coupled with swell at 11s, 14s and 19s. Sequence 2 was expanded to include three extra cases of wind sea with increasing traces of swell.

- Sequences 4-6 have wave conditions with an assumed equal return period (representative of twice per year conditions offshore of Yarmouth) based on wind sea with a maximum peak period of 8s coupled with swell at 11.5, 15 and 21s. Each sequence included: (a) wind sea only, (b) more wind sea than swell, (c) equal wind sea and swell, (d) more swell than wind sea and (e) swell only. The wind sea only conditions were the same for each of sequences 4-6.

At the end of the test programme a number of the seabed bathymetries were reinstated in the flume and calibrations repeated as a small procedural error had been detected. The error affected a number of the inshore wave probes on the 1:20, 1:10 and 1:7 seabed slopes. This error resulted in the loss of the original wave calibration on the inshore probes for these slopes. The wave calibration data obtained for the 1:50 seabed slope was not affected. All test data on the 1:50, 1:20, 1:10 and 1:7 slopes were collected satisfactorily. Wave breaking investigations reported by Durand, Allsop and Jones (Reference 2) were extended to include repeat data for the 1:20 and 1:10 seabed slopes. The (new) wave calibration data obtained both in flume and wave basin models, for slopes of 1:50, 1:30, 1:20 and 1:10, were compared with results obtained from numerical model investigations. Two numerical models, WENDIS and COSMOS, were used to predict wave breaking. New wave calibration data for the 1:20 and 1:10 seabed slopes, obtained from the wave flume, have been presented in Table 2.1 together with data for the 1:7 seabed slope which have been predicted using COSMOS.

Tests on shingle beaches
For this part of the study, some of the wave conditions calibrated for the tests on structures were re-used. These included the three sequences with equal energy wave conditions and one sequence with equal return period. To obtain a complete set of results additional wave conditions were calibrated to form three further sequences with equal energy. As for the tests on inclined and vertical structures, each sequence included five different conditions of varying wind sea and swell. The calibrated wave conditions did not include the wind sea only condition, since they had already been run in the previous sequences.

The test programme also included three wave conditions used by Powell (1990, Reference 8) in his work on shingle beaches. These conditions were run at the beginning of this part of the study to allow direct comparison with Powell's work.

All wave conditions run for the tests on shingle beaches are presented in Table 2.2.

2.2.2 Water levels

The depth of water in the flume varied according to the need to test broken or unbroken waves across the model approach slope. Depths at the paddle varied from 12m to 16m. Tables 2.1 and 2.2 set out the conditions for each test.

2.3 Design and construction of the model structures

2.3.1 Seabed bathymetry

The bathymetry was constructed in the working section of the flume at the model scale of 1:20, as shown in Figure 2.1. The 1:50, 1:20, 1:10 and 1:7 approach slopes were constructed in cement mortar. The flat area in the working section of the flume was defined as +8m relative to the flume floor. Test structures constructed from timber were bolted to this flat area. The overtopping tank was sited on the flat area behind the structures.

2.3.2 Simple seawalls

The 1:2 or 1:4 seawalls were designed to allow wave overtopping during the bi-modal tests while minimising overtopping during the breaking wave tests. Run-up calculations (based on the criterion given in the CIRIA/CUR manual, Reference 9) using the calibrated wave conditions and water levels suggested that a seawall height of 18m should be used, giving crest freeboards of 2m and 4m during the bi-modal tests.

2.3.3 Vertical caisson

A vertical model caisson was used to study wave loadings. The crest of the caisson was equivalent to +21.8m.

2.3.4 Rubble structure

The rubble structure was constructed at a slope of 1:2. An armour mass of approximately 1-6 tonnes prototype was used. Density constraints apply to the model armour rock when modelled for stability. A prototype density of 2650 kg/m^3 was assumed for the armour rocks. Account was taken of the difference in the fluid density and the difference in density of the rocks between the model and prototype. The method for calculating the correct scaling of the rocks is outlined in Appendix 2. The armour rocks were individually weighed.

The core used in the model structure represented sizes in the range 10 to 500 kg prototype. Ordinary geometric scaling of the core and underlayer material would not have correctly reproduced prototype flow velocities in the model. The unit size of the model core and underlayer was made slightly larger in order to reproduce correctly the flow behaviour of the prototype. The procedure used for calculating the size of the model core and underlayer material is detailed in Appendix 3. The core material was prepared by sieving the material.

The rubble structure was constructed of two layers of armour stone and core, built upon an impermeable timber seawall of 1:2 slope. The frictional resistance between the timber and the core was increased using a layer of wire mesh attached to the timber slope.

2.4 Design and construction of the model beach

The model beach was designed to reproduce some of the work on shingle beaches by Powell (Reference 8).

The test beach was designed to represent a typical UK shingle beach at a scale of 1:20. It was defined by a D_{50} of 10mm and a ratio D_{85} / D_{15} of 2.6 in prototype. The model beach comprised crushed anthracite selected and mixed to achieve the required grading using accepted scaling procedures as set out in Reference 8. It was laid to a slope of 1:7, over a fill made of six parts of 10mm pea shingle with one part of Grade 1 anthracite. The cross-section of the model beach is represented in Figure 2.4.

The model beach was constructed in the working section of the wave flume. Its toe was located in deep water, directly on the horizontal flume floor. No approach slope was used between the wave generator and the model beach.

3 *Structures test procedures*

3.1 Overtopping

The method of measuring overtopping discharge was consistent for all tests and was based on standard procedures employed at Wallingford. Overtopping volume was measured in two tanks located behind the seawalls. Water reached the tank by means of a chute placed against the back wall of the seawalls. An electronic gauge in each tank enabled the difference in water level throughout the test, and hence the volume of water overtopping the seawalls, to be determined.

Overtopping volumes were collected for up to 1000 waves, from which the mean overtopping discharge, Q, was calculated. Measurements of Q were compared with predictions using Owen's (1980) prediction method (Reference 10). For tests with low mean overtopping discharges, Q<100l/s.m, the distribution of wave by wave overtopping volumes was also determined.

Model discharge rates were converted to prototype by using the following equation:

$$Q_p = (V_M/T_R{*}B_f){*}\lambda^{1.5}$$

where
Q_p = prototype discharge (l/s.m)
V_M = measured model discharge (l)
T_R = model run time (s)
B_f = model chute width (m)
λ = model scale

The number of waves overtopping the structure were measured using small electronic pulse counters. Signals from these overtopping instruments were logged at 20Hz on a PC.

3.2 Reflections

Reflection measurements were made using surface elevation measurements from three wave probes positioned approximately 2 wave lengths seaward of the seawalls. Wave data were collected at time step intervals of 1/8 f_p. The cross-spectral method based on the work of Kajima (Reference 11), interpreted by Gilbert and Thompson (Reference 12) (Appendix 4), was used to calculate $C_r(f)$ over 0.5 to 2.0 f_p, and then to determine the overall (energy weighted) value of C_r. Values of C_r calculated from these measurements were compared with the simple prediction method of Allsop (1990, Reference 13).

3.3 Run-up and run-down

Two capacitance gauges were installed approximately 3mm above the surface of the seawalls. Signals from these instruments were logged at 20Hz on a PC. Wave run-up and run-down levels were measured for those wave conditions and/or crest freeboards for which there was insignificant overtopping. The distribution of run-up, R_u, and run-down levels, R_d, were determined for each wave condition. Run-up levels at 2% and significant exceedance levels were compared with those predicted for smooth slopes in the CIRIA / CUR rock manual (Reference 9). These wave run-up and run-down measurements were taken for use during the wave breaking analysis.

3.4 Pressures

Wave pressures were measured using pressure transducers mounted in the face of the seawall / caisson. For the vertical caisson, pressures / forces were compared with the methods suggested in Allsop et al (1996, Reference 14). Pressure measurements were taken for use in the wave breaking and PROVERBS studies.

Nine pressure transducers were installed in the seawalls and the simple vertical caisson. These transducers were used to measure both wave impact and quasi-hydrostatic pressures at an acquisition rate of 1000Hz. Data were acquired continuously for all channels through each test for about 1000 waves to prevent the data loss which occurs with selective acquisition systems. The files generated were very large even in multiplexed binary format. The binary files were then processed through a FORTRAN analysis program, in which some data were selected for further analysis.

Within the analysis program, pressure measurements in volts were notionally converted to metres head of fresh water, and these values were then converted to pressures in kN/m^2 by multiplying the pressure head values by $\rho_w g$. Pressures were then integrated over the front face of the structure to provide horizontal force for the simple vertical wall and perpendicular force for the sloping seawalls.

The transducer centres were placed at the following levels (m) on the structure faces:

Sloping structures	Vertical structure 1:50 and 1:20 approach slopes	Vertical structure 1:10 and 1:7 approach slopes
9.0	10.12	10.12
10.0	12.12	12.12
11.0	13.12	13.12
12.0	14.12	14.12
13.0	15.12	15.12
14.0	17.12	16.12
15.0	18.12	17.12
16.0	19.12	18.12
17.0	21.12	21.12

3.5 Velocities

Three miniature wave probes were deployed in a line of small stilling wells on the crest of the 1:2 seawall, the 1:4 seawall and the 1:2 bermed structures during tests using a 1:50 approach slope. The structure crests were 3.2m wide, the front and rear probes were 0.6m from the crest edges, giving a total distance of 2.0m between the 3 probes. The middle probe was located in the centre of the crest.

A computer program was written, using Viewdac (a proprietary software), to monitor continuously the 3 wave probes throughout a test. A data collection rate of 1000Hz was used. Once a wave had been detected on the first probe, the detection time was recorded, together with the times taken to pass the second and third probes.

In addition to these velocity measurements a VHS video recorder was deployed adjacent to the structure crest. The camera provided an oblique view over the structure crest.

3.6 Flow visualisation

To provide validation data for the non-linear and surf zone numerical model, a time lapse photographic method captured solitary wave images running up and down the faces of the different structures. A 35mm camera was mounted outside the flume and viewed the structure through the glass window. The working area of the flume was covered in a plastic sheet, to act as a type of dark room, avoiding unwanted light entering the camera. A stroboscope mounted above the structure, and flashing at 500 cycles per minute, froze images of the wave front, which were photographed. An exposure time of 1 second was successfully employed to capture these images.

In an effort to increase the amount of light reflected by the water surface, and hence increase the picture quality, a fluorescent dye was added to the water. Results, however, were not enhanced by the addition of the dye. The majority of the tests were therefore completed without dye.

3.7 Armour

During testing, observations of armour rock movement were made through the flume windows. An overlay photographic technique was employed to monitor displacements during the test programme. Photographs were taken before and after each test. These were then analysed to detect movement of individual rocks in the following categories:

1- displaced between 0.5 and $1.0D_n$;
2- displaced more than $1.0D_n$.

where:

D_n is the nominal rock diameter equal to $(M/\rho_r)^{1/3}$;
M is the mass of the rock;
ρ_r is the density of the rock.

Translucent A4 size prints were prepared which precisely overlayed each other against fixed marks on the structure slope. By overlying subsequent photographs, the movement of individual armour rocks on the structure was identified and categorised.

Armour movements were determined for the 1:2 seawall tested with both the 1:50 and the 1:20 seabed slopes.

Movements were compared to the standard van der Meer (1988, Reference 15) prediction method. The relative effects of wind waves and bi-modal waves were investigated together with the relative influence of changing the approach slope. Armour movements were used in the wave breaking study.

3.8 Wave transmission

The coefficient of total wave transmission, C_t, produced by waves overtopping the structure was studied during tests on the vertical wall and selected tests on some of the simple seawall structures (1:4, 1:2 and bermed). During calibration, wave conditions were measured at a point behind the test structures. Wave measurements were then repeated at this point during the model test programme. An overall coefficient of wave transmission, C_t, was determined by comparing the statistically derived test wave heights against those obtained during the wave calibration exercise. The coefficient of wave transmission was defined as:

$C_t = H_{st}/H_{si}$,

where

H_{si} = significant wave height determined during wave calibration
H_{st} = significant wave height obtained during testing.

4 Structures test results

4.1 Wave overtopping measurements

Summaries of the prototype overtopping discharges are presented in Table 4.1. Overtopping data for both uni-modal and bi-modal wave conditions are presented for simple 1:2 and 1:4

seawall slopes, tested using 1:50, 1:20, 1:10 and 1:7 seabed slopes and different static water levels.

Indications from an initial analysis are that the foreshore slope influences the volume of wave overtopping. In some instances the influence is less pronounced than others, but a general increase in volume was observed. The wave overtopping volumes for a number of example wave conditions using a simple seawall slope of 1:2 are presented in Figure 4.1. Three different seabed approach slopes have been included in the analysis, 1:50, 1:20 and 1:10. The influence of bi-modal wave conditions on the volume of wave overtopping has also been studied in an early analysis. The initial analysis suggests that bi-modal wave conditions may lead to significant increases in wave overtopping discharges. The influence upon both 1:2 and 1:4 simple seawall structures is considered in Figure 4.2. Different wave energy distributions are presented in the figure, ranging from a wind generated spectrum through to swell generated only, and including three combinations of swell and wind generated wave conditions.

A more detailed analysis of the wave overtopping has been undertaken by Hawkes, Coates and Jones (1997, Reference 1).

4.2 Wave reflection measurements

The reflection performances of the 1:2 and 1:4 simple seawalls were investigated for the different approach slopes and types of wave conditions studied in this project. The wave reflection measurements are summarised in Table 4.2 and Figures 4.3 – 4.5. Investigations by Allsop (1990, Reference 13) used a simple empirical relationship between the reflection coefficient C_r, and the mean Iribarren number ξ_m in the form:

$$C_r = a\ \xi_m^2 / b+\xi_m^2$$

where a and b are empirically derived constants, and ξ_m is defined by:

$$\xi_m = \tan \alpha / (2\pi\ H_s / gT_m^2)^{1/2}$$

The results of tests at HR Wallingford suggest values for coefficients a = 0.96 and b = 4.8 for a smooth structure. The empirical relationship is shown as a prediction line in Figures 4.3 – 4.5.

Two types of structures, overtopping and non-overtopping, were investigated using an approach bathymetry of 1:50. The results of the analysis using data obtained from uni-modal wave conditions are shown in Figure 4.3. As might be expected, at higher values of mean Iribarren number the overtopping structure had reflections below those predicted by the empirical relationship.

The reflection performance of bi-modal waves is compared to uni-modal waves, using an approach bathymetry of 1:50, in Figure 4.4. Both uni-modal and bi-modal waves had similar reflection performances, although there was less data scatter with the bi-modal waves, and they appeared to provide a better fit to the empirical relationship.

The influence of changing approach slope is summarised for uni-modal wave conditions in Figure 4.5. The reflection analysis is considered in more detail in Report SR 507 (Reference 1).

4.3 Wave run-up and run-down measurements

Run-up and run-down measurements were obtained for 1:2 and 1:4 simple seawalls using an approach bathymetry of 1:50. The statistics of the wave excursions were determined using software written at HR Wallingford. Summaries of the results are presented in Tables 4.3 and 4.4. Bi-modal and uni-modal wave conditions are compared in the Figures 4.6 and 4.7.

The level exceeded by only 2% of wave run-up events is summarised in Figure 4.6 and a summary of the corresponding run-down level is presented in Figure 4.7. Investigations by

Allsop et al and Ahrens (see CIRIA/CUR Manual, Reference 9) used simple empirical relationships between the 2% run-up levels and the Iribarren number in the form:

$0< \xi_m < 2.18$	$R_{u2\%} / H_s = 1.84\ \xi_m$	Eq 5.12 from Ahrens
$\xi_m > 2.18$	$R_{u2\%} / H_s = 4.5\text{-}0.23\ \xi_m$	Eq 5.13 from Ahrens
$2.44 < \xi_m < 5.22$	$R_{u2\%} / H_s = 3.39\text{-}0.24\ \xi_m$	Eq 5.16 from Allsop et al

These empirical relationships for run-up levels are given on Figure 4.6.

An initial analysis of these results indicates that bi-modal wave conditions produce higher run-up/run-down levels than corresponding uni-modal wave conditions.

4.4 Wave pressure measurements

An analysis of the wave pressure measurements recorded during this study is reported fully by McConnell and Allsop (1998, References 3 and 7). A simple analysis has been presented in this report.

Nine pressure transducers were located, at different vertical levels (Section 3), on the front faces of the simple seawall and vertical structures. Data were recorded using fast digitisation rates, example extracts of the pressure time series have been reproduced as Figures 4.8 and 4.9.

Data from tests on the 1:4 seawall built with an approach slope of 1:10 are given in Figure 4.8, while data from the vertical wall tests using the same approach slope are given in Figure 4.9. Both figures represent a 54 second extract from tests using the same test wave conditions, and taken at precisely the same time in the test wave sequence (after 3707 seconds). In the figures, each transducer has been plotted in relation to its relative slope position, with the lowest transducer at the bottom of the figure. The example reproduced is a uni-modal wave condition (0f6) conducted with a water level of 14m and a nominal wave height, H_s=4m, and wave period, T_m=6.5s. The pressures, in kN/m^2, are given in prototype terms in the figures. For the 1:4 seawall example, the pressure transducer situated at static water level is the sixth plot from the bottom of Figure 4.8. The transducer situated at static water level for the vertical structure test is the fourth plot from the bottom of Figure 4.9.

A number of interesting comparisons can be drawn between tests on the 1:4 slope and the vertical structure by considering Figures 4.8 and 4.9. It should be noted that the top transducer in Figure 4.8 was not functioning correctly in this example and has not been included.

Pressure time signals recorded on the vertical structure occur (almost) instantaneously on all of the transducers. Whereas the pressure time signals recorded on the sloping structure were displaced both in time and space.

Pressures on the vertical structure are higher than those recorded on the sloping structure. In this example, a maximum pressure of 1500kN/m^2, (150m) was recorded on the vertical structure (although the peak is not shown fully due to scaling restraints), while only 80kN/m^2, (8m) was measured on the 1:4 structure.

Impact events were clearly visible on the vertical structure. These impacts exhibit a classic "church roof" pressure event possessing a very short duration high impact pressure, followed by a much longer, lower, quasi-hydrostatic pressure. Impact pressure events on the sloping structure, however, were more confused. The pressures still exhibited a short duration high pressure (although much lower than those of the vertical structure), followed by a longer duration quasi-hydrostatic pressure event. The quasi-hydrostatic event was less clearly defined on the sloping structure.

The principal result of this part of the study is the determination of wave forces/pressures experienced by structures for different incident wave conditions. The analysis of these pressure measurements made at laboratory scale using fresh water has unusually used a Froude scaling relationship to convert to prototype scale. The use of other parameters scaled by Froude scale has therefore implicitly assumed that forces/pressures measured in the model can be so scaled.

In the case of pulsating wave pressures where the relationships between wave momentum, pressure impulse, and horizontal force are relatively simple, the assumption of Froude scaling is realistic. For wave impact pressure, scaling is less simple. It has long been argued and is well accepted that wave impacts in small scale hydraulic model tests will be greater in magnitude, but shorter in duration than their equivalents at full scale in (aerated) sea water. It is very probable therefore that the higher impact pressures measured in these model tests can be scaled to lower values, but that the impulse durations must be scaled to larger values. It may be noted that the largest pressures may occur when there is least air entrained or trapped, and these impact pressures may therefore actually be less influenced by scale effects on air compression.

Scaling aspects are discussed further in Reports SR 511 and SR 509 (References 3 and 7).

4.5 Wave velocity measurements

Variable success was experienced recording wave overtopping velocity data. On occasions a wave was observed passing the seaward facing probe, mounted on the breakwater crest, but then not on one of the remaining probes. This lack of observation was probably due to water "jetting" past / over the remaining probe(s). Upon initialisation by a wave, the recording program waited until an event was observed on the middle, or rear probe, before the program re-set itself to wait for another overtopping event. A number of events were therefore lost, or a number of extremely long events were recorded in-accurately.

One of the test records, using the uni-modal wave condition 0c2, is summarised in Table 4.5. The spurious records have been deleted from Table 4.5. In this example, velocity observations are for the 1:4 simple seawall structure constructed with an approach of slope of 1:50. The structure crest was set at 18m and the configuration was tested with a water level of 14m. The velocity of the overtopping wave between the middle and seaward measurement points varied between about 2 and 10m/s. Between the middle and rear measurement positions the velocity generally reduced by approximately 30%. Data collected during this study has not been used or analysed fully, but have been stored (CD number 19) for future reference (Appendix 5).

4.6 Flow visualisation measurements

The flow visualisation photographs, detailing water surface elevations recorded on the various structures studied in this research, have been used by Waller and Allsop (1997, Reference 16) to provide supporting data for the calibration of their wave dynamics numerical model. Example photographs have been reproduced in this report as Plates 1 and 2.

An example of the wave front flowing up the non-overtopping 1:2 simple seawall is given in Plate 1. The example shown in Plate 1 was for a seabed slope of 1:50, a water depth of 14m and a solitary wave height of 2m. An example of the wave front passing over the 1:2 bermed structure has been given in Plate 2. The example in Plate 2 had the same environmental conditions except that the solitary wave height was increased to 2.4m. The flow visualisation photographs have been retained for future reference.

4.7 Armour

Summaries of the armour displacements have been presented in Table 4.6. Armour movements were determined for a 1:2 structure using uni-modal and bi-modal wave conditions. Seabed slopes of 1:50 and 1:20 were studied. The cumulative percentages of armour displacements were determined using a detailed photographic method described previously in Section 3. In addition, the corresponding armour damage levels, S, have been estimated according to the method described by van der Meer (1988, Reference 15). Armour damage, S, has also been included in Table 4.6.

Indications from an initial analysis are that the foreshore slope influences armour stability. A general increase in armour movement was observed with the steeper seabed slope. A review of the armour damage photographs did not indicate any spatial difference in levels of damage between the two slopes studied. The armour displacements for a number of example uni-modal wave conditions using a simple seawall slope of 1:2 are presented in Figure 4.10. Armour movements of approximately 30% represent localised areas of failure on the structure.

The influence of bi-modal wave conditions on armour movements has been examined in an initial analysis in Figure 4.11. In this instance the influence is less pronounced than with the uni-modal wave conditions, but is still present. The results from 2 different groups of bi-modal spectra are presented in Figure 4.11. The group of spectra on the left of the figure have equal overall energy levels, starting with wind sea waves only on the left; increasing amounts of swell sea are added until the final spectrum is swell sea waves only. The group of spectra on the right were constructed in the same manner, but instead have the same overall return period. Armour movements increase with increasing amounts of swell sea in the case of equal overall energy levels. With equal return period there appears to be no clear trend becoming visible in this early analysis.

4.8 Wave transmission measurements

Wave transmission measurements were obtained for 1:4, 1:2, 1:2 bermed and vertical structures. The simple seawall structures incorporated a small crest and a 1:2 rear slope. The transmission coefficient, C_t, was determined using the method described in Section 3.8. The measurements for the sloping seawall structures have been summarised in Table 4.7 and for the vertical structure in Table 4.8. Two wave transmission probe positions were used during the seawall tests. During testing, probe 15 was positioned part way down the rear face of the seawall, while probe 16 was located clear of the structure in the same position used during wave calibration.

To date, no wave transmission analysis has been undertaken.

5 Shingle beach test procedures

5.1 Initial tests for comparison with Powell (1990)

A series of initial tests (Tests 0a to 0c) were carried out using a procedure similar to that used by Powell (Reference 8). This was done to allow direct comparison between the two studies.

In both studies the model beach was mixed and screeded to a slope of 1:7, then compacted for 3 hours (prototype) using large waves (H_s = 3m and T_m = 5.7s). The compaction phase was used to put the beach in a more natural state than that obtained by screeding. Powell used a range of sediment distributions, one of which was used for the present study.

In Powell's work, testing was based on various sequences of wave heights (H_s) with the same wave steepness. The sequences started with the smallest waves and built up to the largest. In this way sets of beach profiles were built on top of each other.

In the present study three wave conditions were used with wave steepnesses (s_m) of 0.02, 0.04 and 0.06 respectively. The same conditions were run by Powell, but they were part of a test sequence. In Powell's work these conditions occupied respectively the first, third and second position in their sequence. The condition with a steepness of 0.02 was, therefore, the only one to exactly replicate Powell's work.

For both studies each condition tested was run for a duration of 3000 waves following which the beach profile was recorded using an automated bed profiler.

5.2 Tests 1 to 32

The test sequences for Tests 1 to 32 are described in Section 1.2.2 and Table 2.2.

Before each test sequence the beach was mixed and screeded to a slope of 1:7. For each wave condition tested, the following procedure was then applied:

(i) Compaction of the beach for 30 minutes (model) with condition 0g6 (H_s = 4.4m, T_m = 8s).

(ii) Testing for a duration of 1000 waves.

(iii) Video recording of the beach development near the end of the test.

(iv) Profiling of the model beach using the bed profiler.

The first phase was used to compact and re-distribute the beach material to a more natural state than that obtained by screeding, and to ensure a consistent initial profile.

6 Tests results for shingle beaches

6.1 Initial tests for comparison with Powell (1990)

The beach profiles resulting from tests 0a to 0c are presented in Figure 6.1. These results show good agreement for the crest position between this study and Powell's work but some discrepancies for the crest elevation. As the same model beach, wave conditions and test procedure were used in both studies, the difference in crest elevation could be explained by the use of slightly different scales (1:17 and 1:20), the use of different wave generators or an error in the preparation of the beach material leading to an unintended difference in sediment size or distribution. Sediment analysis and the measured wave spectra from the original study are not available for comparison, but it is possible that either, or both, were different from those used in the flume for the present study. The lack of similarity between the two sets of profiles restricts the value of the study in producing design guidelines for beach management schemes, but does not affect the importance of the work in assessing the importance of bi-modal spectra on beach response.

6.2 Tests 1 to 32

The test programme consisted of one sequence with constant return period (Tests 1-5) and 5 sequences with constant energy (Tests 6-10, 11-15, 16-20, 21-24, 25-28 and 29-32).

Beach profiles resulting from tests in the same sequence were plotted together to see the effect of increasing swell energy. From the five beach profiles recorded in each sequence, the values of crest elevation and crest position were derived.

Figure 6.2 presents the profiles for wave conditions of constant return period. Wind sea only conditions produced the greatest cut back of the beach crest. As for the crest elevation, the combination of swell and storm waves led to higher elevations than wind sea only or swell only waves.

Figures 6.3 to 6.7 present the results of tests run with wave conditions of constant energy. These all show that bi-modal waves and swell only waves produce a higher crest elevation and a beach crest further inshore than wind sea only conditions.

From tests run within sequences of constant energy, 6 plots were produced, showing the effect of varying the distribution of spectral energy (% swell energy and swell peak period on crest elevation and crest position (Figures 6.8 – 6.13).

The beach crest elevations are presented as percentage increases in freeboard (height of crest above SWL) for each bi-modal or swell wave condition relative to the freeboard measured for the wind sea only condition. The crest cut-back values are presented as percentage increases in cross-shore distances relative to the position of the still water line on the wind sea only profile. The crest of each profile is taken as the highest point built up by the waves.

Freeboard and cut-back values were not derived for Tests 1-5. The concept of constant return period of wave energy distribution is site dependent, so the results are only of general use as an indicator of possible beach responses under a hypothetical range of predicted conditions.

A full discussion of the results is presented in the companion report SR 507 (Reference 1), including guidance for the application of the results to beach management operations. In brief, the results show that varying spectral distributions have several important effects on beach response:

- increasing swell wave period ($T_{p(swell)}$) and swell energy relative to total energy gives higher beach crests and greater cut-back.

- beach response is non-linear relative to both the swell wave peak period and the percentage of swell energy, with greatest change occurring up to $T_{p(swell)}$ = 14 seconds and 18%-50 % of total energy.

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Tables

Table 2.1 Calibrated wave conditions

1:50 seabed slope uni-modal waves

Condition	SWL (m)	s_{mo}	Nominal conditions					Statistically determined			
			Wind waves			Swell waves					
			H_{so} (m)	T_{mo} (s)	T_{po} (s)	H_{so} (m)	T_{po} (s)	H_{so} (m)	T_{mo} (s)	H_{si} (m)	T_{mi} (s)
0a2	12	0.02	1.5	6.9	7.9	*	*	1.58	7.17	1.76	7.3
0b2	12	0.02	2	8	9.2	*	*	2.06	8.08	2.28	8.4
0c2	12	0.02	2.5	8.9	10.2	*	*	2.5	8.73	2.75	8.57
0d2/4e	12	0.02	2.76	10.0	11.5	*	*	2.91	10.16	2.98	9.5
0e2	12	0.02	3.5	10.6	12.2	*	*	3.52	10.33	2.98	9.41
0f2	12	0.02	4	11.3	13.0	*	*	4.18	10.62	2.9	9.56
0g2	12	0.02	4.5	12	13.8	*	*	5.17	11.07	2.86	10.43
0a4	12	0.04	1.5	4.9	5.6	*	*	1.58	4.88	1.54	5.1
0b4/3a	12	0.04	2.12	6.1	7.0	*	*	2.26	6.18	2.26	6.47
0c4	12	0.04	2.5	6.3	7.2	*	*	2.66	6.28	2.43	6.7
0d4	12	0.04	3	6.9	7.9	*	*	3.14	7.05	2.64	7.36
0e4	12	0.04	3.5	7.5	8.6	*	*	3.66	7.61	2.73	7.86
0f4	12	0.04	4	8	9.2	*	*	4.03	8.15	2.71	8.22
0g4	12	0.04	4.5	8.5	9.8	*	*	4.6	8.45	2.73	8.78
0a6	12	0.06	1.5	4	4.6	*	*	1.54	4.12	1.33	4.45
0b6	12	0.06	2	4.6	5.3	*	*	2.12	4.73	1.84	5.22
0c6	12	0.06	2.5	5.2	6.0	*	*	2.66	5.4	2.21	5.81
0d6/2a	12	0.06	2.83	6.1	7.0	*	*	2.98	6.17	2.43	6.64
0e6/1a	12	0.06	3.53	6.1	7.0	*	*	3.71	6.25	2.5	6.75
0f6	12	0.06	4	6.5	7.5	*	*	4.23	6.72	2.53	7.23
0g6/4a	12	0.06	4.4	7.0	8.0	*	*	4.63	7.2	2.61	7.68
0a2	14	0.02	1.5	6.9	7.9	*	*	1.49	7.04	1.5	7.16
0b2	14	0.02	2	8	9.2	*	*	1.88	8.1	2.08	8.36
0c2	14	0.02	2.5	8.9	10.2	*	*	2.36	8.88	2.76	9.09
0d2/4e	14	0.02	2.76	10.0	11.5	*	*	2.73	10.17	3.12	9.84
0e2	14	0.02	3.5	10.6	12.2	*	*	3.38	10.57	3.74	10.17
0f2	14	0.02	4	11.3	13.0	*	*	3.99	11.1	4.06	10.2
0g2	14	0.02	4.5	12	13.8	*	*	4.8	11.35	4.06	10.12
0a4	14	0.04	1.5	4.9	5.6	*	*	1.53	4.82	1.4	5.03
0b4/3a	14	0.04	2.12	6.1	7.0	*	*	2.21	6.11	2.2	6.34
0c4	14	0.04	2.5	6.3	7.2	*	*	2.47	6.24	2.51	6.64
0d4	14	0.04	3	6.9	7.9	*	*	3.03	7.1	3.04	7.33
0e4	14	0.04	3.5	7.5	8.6	*	*	3.53	7.75	3.44	8.09
0f4	14	0.04	4	8	9.2	*	*	3.82	8.09	3.76	8.36
0g4	14	0.04	4.5	8.5	9.8	*	*	4.38	8.58	3.85	8.8
0a6	14	0.06	1.5	4	4.6	*	*	1.48	4.05	1.28	4.31
0b6	14	0.06	2	4.6	5.3	*	*	2.04	4.13	1.79	4.98
0c6	14	0.06	2.5	5.2	6.0	*	*	2.51	5.35	2.28	5.66
0d6/2a	14	0.06	2.83	6.1	7.0	*	*	2.77	6.09	2.64	6.56
0e6/1a	14	0.06	3.53	6.1	7.0	*	*	3.53	6.22	3.05	6.83
0f6	14	0.06	4	6.5	7.5	*	*	4.01	6.71	3.29	7.33
0g6/4a	14	0.06	4.4	7.0	8.0	*	*	4.46	7.28	3.62	7.73

Table 2.1 continued

1:50 seabed slope bi-modal waves

Condition	SWL (m)	s_{mo}	Nominal conditions					Statistically determined			
			Wind waves			Swell waves					
			H_{so} (m)	T_{mo} (s)	T_{po} (s)	H_{so} (m)	T_{po} (s)	H_{so} (m)	T_{mo} (s)	H_{si} (m)	T_{mi} (s)
1a	14	0.06	3.53	6.1	7			3.53	6.22	3.05	6.83
1b	14		3.12	6.1	7	1.67	11	3.41	6.8	3.11	7.27
1c	14		2.5	6.1	7	2.5	11	3.45	7.45	3.38	8.17
1d	14		1.67	6.1	7	3.12	11	3.43	8.27	3.52	8.81
1e	14					3.53	11	3.52	9.49	3.84	9.64
2a	14	0.05	2.83	6.1	7			2.77	6.09	2.64	6.56
2a1	14		2.8	6.1	7	0.4	14	2.87	6.22	2.64	6.54
2a2	14		2.71	6.1	7	0.8	14	2.79	6.51	2.65	6.83
2b	14		2.56	6.1	7	1.2	14	2.65	6.81	2.7	7.27
2b3	14		2.34	6.1	7	1.6	14	2.57	7.44	2.76	7.65
2c	14		2	6.1	7	2	14	2.64	8.57	3.03	8.49
2d	14		1.2	6.1	7	2.56	14	2.68	10.1	3.2	9.53
2e	14					2.83	14	2.86	11.61	3.58	10.77
3a	14	0.04	2.12	6.1	7			2.21	6.11	2.2	6.34
3b	14		1.91	6.1	7	0.94	19	1.85	7.24	2.05	7.62
3c	14		1.5	6.1	7	1.5	19	1.87	9.2	2.3	9.33
3d	14		0.94	6.1	7	1.91	19	1.84	11.9	2.35	11.46
3e	14					2.12	19	2.08	15.13	2.71	12.3
4a	14	0.06	4.4	7.0	8			4.46	7.28	3.62	7.73
4b	14		3.68	6.4	7.32	1.93	11.5	4.21	7.15	3.5	7.9
4c	14		2.99	5.7	6.6	2.4	11.5	3.71	6.95	3.3	7.54
4d	14		2.3	5.0	5.79	2.62	11.5	3.62	7.2	3.45	7.86
4e	14					2.76	11.5	2.73	10.17	3.12	9.84
5b	14		4	6.6	7.63	1.08	15	4	7.05	3.5	7.86
5c	14		3.4	6.1	7.03	1.27	15	3.55	6.7	3.2	7.43
5d	14		2.6	5.4	6.15	1.39	15	2.8	6.25	2.61	6.73
5e	14					1.5	15	1.37	12.55	1.73	12.3
6b	14		4	6.6	7.63	0.5	21	3.88	6.84	3.31	7.46
6c	14		3.4	6.1	7.03	0.59	21	3.35	6.3	2.91	6.9
6d	14		2.6	5.4	6.15	0.65	21	2.61	5.72	2.86	6.21
6e	14					0.7	21	0.7	17.2	0.95	19.33
1a	16	0.06	3.53	6.1	7			3.76	6.23	3.2	6.8
1b	16		3.12	6.1	7	1.67	11	3.3	6.79	3.22	7.4
1c	16		2.5	6.1	7	2.5	11	3.35	7.74	3.46	8.03
1d	16		1.67	6.1	7	3.12	11	3.34	8.68	3.53	8.8
1e	16					3.53	11	3.78	9.55	3.8	9.79
2a	16	0.05	2.83	6.1	7			3	6.15	2.36	6.5
2a1	16		2.8	6.1	7	0.4	14	2.76	6.34	2.64	6.54
2a2	16		2.71	6.1	7	0.8	14	2.64	6.44	2.62	6.89
2b	16		2.56	6.1	7	1.2	14	2.54	6.84	2.58	7.25
2b3	16		2.34	6.1	7	1.6	14	2.47	7.42	2.62	7.86
2c	16		2	6.1	7	2	14	2.55	8.64	2.87	9.14
2d	16		1.2	6.1	7	2.56	14	2.6	10.45	3.02	10.8
2e	16					2.83	14	3.09	11.86	3.43	11.82

Table 2.1 continued

3a	16	0.04	2.12	6.1	7			2.36	6.1	1.85	6.3
3b	16		1.91	6.1	7	0.94	19	1.73	7.38	1.82	7.78
3c	16		1.5	6.1	7	1.5	19	1.81	9.38	2.04	9.94
3d	16		0.94	6.1	7	1.91	19	1.8	12.37	2.16	12.44
3e	16					2.12	19	2.32	16	2.46	14.26
4a	16	0.06	4.4	7.0	8			4.84	7.3	4	7.7
4b	16		3.68	6.4	7.32	1.93	11.5	4.04	7.15	3.8	7.85
4c	16		2.99	5.7	6.6	2.4	11.5	3.53	7	3.38	7.36
4d	16		2.3	5.0	5.79	2.62	11.5	3.61	7.6	3.55	8
4e	16					2.76	11.5	2.9	10.4	2.65	10.6
5b	16		4	6.6	7.63	1.08	15	3.78	6.98	3.63	7.53
5c	16		3.4	6.1	7.03	1.27	15	3.35	6.64	3.23	7.25
5d	16		2.6	5.4	6.15	1.39	15	2.65	6.41	2.57	6.68
5e	16					1.5	15	1.45	12.95	1.75	12.82
6b	16		4	6.6	7.63	0.5	21	3.66	6.81	3.5	7.2
6c	16		3.4	6.1	7.03	0.59	21	3.14	6.62	2.95	6.81
6d	16		2.6	5.4	6.15	0.65	21	2.41	5.7	2.22	5.95
6e	16					0.7	21	0.59	17.61	0.68	17.63

Table 2.1 continued

1:20 seabed slope uni-modal waves

Condition	SWL (m)	s_{mo}	Nominal conditions					Statistically determined			
			Wind waves			Swell waves					
			H_{so} (m)	T_{mo} (s)	T_{po} (s)	H_{so} (m)	T_{po} (s)	H_{so} (m)	T_{mo} (s)	H_{si} (m)	T_{mi} (s)
0f2	12	0.02	4	11.3	13.0	*	*	3.56	10.91	3.54	10.01
0c4	12	0.04	2.5	6.3	7.2	*	*	2.44	6.29	2.53	6.67
0f4	12	0.04	4	8	9.2	*	*	3.85	8.12	3.12	8.22
0b2	14	0.02	2	8	9.2	*	*	1.94	8.10	2.23	8.36
0d2/4e	14	0.02	2.76	10.0	11.5	*	*	2.69	10.02	3.30	9.65
0f2	14	0.02	4	11.3	13.0	*	*	3.76	11.19	4.64	11.15
0a4	14	0.04	1.5	4.9	5.6	*	*	1.53	4.84	1.40	4.99
0d4	14	0.04	3	6.9	7.9	*	*	3.00	6.96	3.18	7.31
0f4	14	0.04	4	8	9.2	*	*	3.74	8.34	3.93	8.52
0d6/2a	14	0.06	2.83	6.1	7.0	*	*	2.73	6.15	2.84	6.43
0f6	14	0.06	4	6.5	7.5	*	*	3.95	6.65	3.62	7.22

1:20 seabed slope bi-modal waves

Condition	SWL (m)	s_{mo}	Nominal conditions					Statistically determined			
			Wind waves			Swell waves					
			H_{so} (m)	T_{mo} (s)	T_{po} (s)	H_{so} (m)	T_{po} (s)	H_{so} (m)	T_{mo} (s)	H_{si} (m)	T_{mi} (s)
1a	14	0.06	3.53	6.1	7			3.47	6.26	3.20	6.67
1b	14		3.12	6.1	7	1.67	11	3.33	6.81	3.31	7.39
1c	14		2.5	6.1	7	2.5	11	3.06	7.68	3.56	8.09
1d	14		1.67	6.1	7	3.12	11	3.34	8.53	3.76	8.77
1e	14					3.53	11	3.47	9.47	4.13	9.49
2a	14	0.05	2.83	6.1	7			2.73	6.15	2.84	6.43
2b	14		2.56	6.1	7	1.2	14	2.65	6.92	2.89	7.40
5d	14		2.6	5.4	6.15	1.39	15	2.79	6.53	2.92	6.89
6d	14		2.6	5.4	6.15	0.65	21	2.53	5.82	2.54	6.20

Table 2.1 continued

1:10 seabed slope uni-modal waves

Condition	SWL (m)	s_{mo}	Nominal conditions					Statistically determined			
			Wind waves			Swell waves					
			H_{so} (m)	T_{mo} (s)	T_{po} (s)	H_{so} (m)	T_{po} (s)	H_{so} (m)	T_{mo} (s)	H_{si} (m)	T_{mi} (s)
0a2	12	0.02	1.5	6.9	7.9	*	*	1.538	7.042	1.823	7.339
0b2	12	0.02	2	8	9.2	*	*	1.942	8.011	2.35	8.142
0d2/4e	12	0.02	2.76	10.0	11.5	*	*	2.795	10.09	3.356	10.02
0f2	12	0.02	4	11.3	13.0	*	*	4.113	10.67	4.205	10.96
0a4	12	0.04	1.5	4.9	5.6	*	*	1.546	4.859	1.451	5.034
0c4	12	0.04	2.5	6.3	7.2	*	*	2.465	6.385	2.735	6.654
0d4	12	0.04	3	6.9	7.9	*	*	3.099	7.12	3.311	7.269
0f4	12	0.04	4	8	9.2	*	*	3.997	7.985	3.786	8.447
0d4	12	0.04	3	6.9	7.9	*	*	2.841	6.145	2.806	6.533
0f4	12	0.04	4	8	9.2	*	*	4.05	6.698	3.439	7.005
0a2	14	0.02	1.5	6.9	7.9	*	*	1.504	6.957	1.666	7.225
0b2	14	0.02	2	8	9.2	*	*	1.799	8.013	2.226	8.405
0d2/4e	14	0.02	2.76	10.0	11.5	*	*	2.52	9.966	3.192	10.3
0f2	14	0.02	4	11.3	13.0	*	*	3.81	11.49	4.646	11.39
0a4	14	0.04	1.5	4.9	5.6	*	*	1.49	4.784	1.427	4.877
0d4	14	0.04	3	6.9	7.9	*	*	2.803	7.068	3.562	7.287
0f4	14	0.04	4	8	9.2	*	*	3.993	8.129	4.334	8.439
0d6/2a	14	0.06	2.83	6.1	7.0	*	*	2.559	6.168	2.958	6.537
0f6	14	0.06	4	6.5	7.5	*	*	3.757	6.637	4.295	7.133

Table 2.1 continued

1:10 seabed slope bi-modal waves

Condition	SWL (m)	s_{mo}	Nominal conditions					Statistically determined			
			Wind waves			Swell waves					
			H_{so} (m)	T_{mo} (s)	T_{po} (s)	H_{so} (m)	T_{po} (s)	H_{so} (m)	T_{mo} (s)	H_{si} (m)	T_{mi} (s)
1a	14	0.06	3.53	6.1	7			3.427	6.218	3.307	6.631
1b	14		3.12	6.1	7	1.67	11	3.353	6.702	3.435	7.308
1c	14		2.5	6.1	7	2.5	11	3.393	7.513	3.786	7.941
1d	14		1.67	6.1	7	3.12	11	3.294	8.349	4.667	8.961
1e	14					3.53	11	3.482	9.532	4.919	9.662
2a	14	0.05	2.83	6.1	7			2.612	6.139	3.103	6.285
2b	14		2.56	6.1	7	1.2	14	2.508	6.821	3.362	7.401
3a	14	0.04	2.12	6.1	7			2.246	6.154	2.37	6.461
3b	14		1.91	6.1	7	0.94	19	1.932	7.451	2.068	7.724
3c	14		1.5	6.1	7	1.5	19	1.894	8.995	2.019	9.059
3d	14		0.94	6.1	7	1.91	19	1.942	11.77	2.108	11.47
3e	14					2.12	19	2.274	14.9	2.408	13.75
5b	14		4	6.6	7.63	1.08	15	3.808	6.997	4.093	7.394
5c	14		3.4	6.1	7.03	1.27	15	3.348	6.686	3.677	7.116
5d	14		2.6	5.4	6.15	1.39	15	2.781	6.511	3.453	6.925
5e	14					1.5	15	1.48	12.36	1.688	12.61
6d	14		2.6	5.4	6.15	0.65	21	2.467	5.853	2.954	6.264

Table 2.1 continued

1:7 seabed slope uni-modal waves

Condition	SWL (m)	s_{mo}	Nominal conditions					Statistically determined				
			Wind waves			Swell waves						
			H_{so} (m)	T_{mo} (s)	T_{po} (s)	H_{so} (m)	T_{po} (s)	H_{so} (m)	T_{mo} (s)	H_{si} (m)		T_{mi} (s)
0f2	12.00	0.02	4.00	11.30	13.00	*	*	4.18	10.69	4.27	i	11.37
0c4	12.00	0.04	2.50	6.30	7.25	*	*	2.66	6.30	2.80	i	6.62
0f4	12.00	0.04	4.00	8.00	9.20	*	*	4.00	7.99	4.20	i	8.46
0b2	14.00	0.02	2.00	8.00	9.20	*	*	1.94	8.13	2.10	i	8.37
0d2/4e	14.00	0.02	2.76	10.01	11.50	*	*	1.72	9.99	1.94	i	10.18
0f2	14.00	0.02	4.00	11.30	13.00	*	*	4.14	11.38	4.68	i	11.60
0a4	14.00	0.04	1.50	4.90	5.64	*	*	1.55	4.75	1.45	i	5.04
0d4	14.00	0.04	3.00	6.90	7.94	*	*	3.07	7.02	3.18	i	7.29
0f4	14.00	0.04	4.00	8.00	9.20	*	*	4.01	8.18	4.26	i	8.44
0d6/2a	14.00	0.06	2.83	6.09	7.00	*	*	2.88	6.15	2.86	i	6.40
0f6	14.00	0.06	4.00	6.50	7.48	*	*	4.20	6.60	3.94	i	7.14

1:7 seabed slope bi-modal waves

Condition	SWL (m)	s_{mo}	Nominal conditions					Statistically determined				
			Wind waves			Swell waves						
			H_{so} (m)	T_{mo} (s)	T_{po} (s)	H_{so} (m)	T_{po} (s)	H_{so} (m)	T_{mo} (s)	H_{si} (m)		T_{mi} (s)
1a	14.00	0.06	3.53	6.09	7.00			3.56	6.30	3.47	i	6.56
1b	14.00		3.12	6.09	7.00	1.67	11.00	3.46	6.78	3.52	i	7.24
1c	14.00		2.50	6.09	7.00	2.50	11.00	3.55	7.52	3.73	i	8.02
1d	14.00		1.67	6.09	7.00	3.12	11.00	3.59	8.45	3.89	i	9.06
1e	14.00					3.53	11.00	3.71	9.41	4.10	i	9.74
2a	14.00	0.05	2.83	6.09	7.00			2.85	6.13	2.83	i	6.28
2b	14.00		2.56	6.09	7.00	1.20	14.00	2.73	6.86	2.81	i	7.32
5d	14.00		2.60	5.35	6.15	1.39	15.00	2.86	6.38	2.88	i	6.85
6d	14.00		2.60	5.35	6.15	0.65	21.00	2.60	5.83	2.55	i	6.16

i = H_{si} interpolated

Table 2.2 Wave conditions used in the shingle beach tests

Test number	Condition reference	Wave conditions					Depth of water (m)
		Wind sea		Swell			
		Hs1 (m)	Tp1 (s)	Hs2 (m)	Tp2 (s)	Percentage swell energy	
Tests for comparison with SR219							
0a	Keith02	0.75	5	----	----	0	14
0b	Keith04	1.5	5	----	----	0	14
0c	keith06	2.4	5	----	----	0	14
0a1	keith02	0.75	5	----	----	0	14
0a2	keith02	0.75	5	----	----	0	14
0b1	keith04	1.5	5	----	----	0	14
Tests with constant return period (1 in 6 months)							
1	0g6	4.4	8	----	----	0	14
2	5b	4	7.63	1.08	15	18	14
3	5c	3.4	7.03	1.27	15	50	14
4	5d	2.6	6.15	1.39	15	82	14
5	5e	----	----	1.5	15	100	14
1a	0g6	4.4	8	----	----	0	14
Tests with constant total spectral energy Hs = 3.53m and Tp2 = 11s							
6	0e6	3.53	7	----	----	0	14
7	1b	3.12	7	1.67	11	22	14
8	1c	2.5	7	2.5	11	50	14
9	1d	1.67	7	3.12	11	78	14
10	1e	----	----	3.53	11	100	14
6 repeat	0e6	3.53	7	----	----	0	14
7 repeat	1b	3.12	7	1.67	11	22	14
9 repeat	1d	1.67	7	3.12	11	78	14
Tests with constant total spectral energy Hs = 2.12m and Tp2 = 19s							
11	0b4	2.12	7	----	----	0	14
12	3b	1.91	7	0.94	19	18	14
13	3c	1.5	7	1.5	19	50	14
14	3d	0.94	7	1.91	19	82	14
15	3e	----	----	2.12	19	100	14
14 repeat	3d	0.94	7	1.91	19	82	14
Tests with constant total spectral energy Hs = 2.83m and Tp2 = 14s							
16	0d6	2.83	7	----	----	0	14
17	2b	2.56	7	1.2	14	18	14
18	2c	2	7	2	14	50	14
19	2d	1.2	7	2.56	14	82	14
20	2e	----	----	2.83	14	100	14
16 repeat	0d6	2.83	7	----	----	0	14
Tests with constant total spectral energy Hs = 2.83m and Tp2 = 11s							
21	7b	2.56	7	1.2	11	18	14
22	7c	2	7	2	11	50	14
23	7d	1.2	7	2.56	11	82	14
24	7e	----	----	2.83	11	100	14
Tests with constant total spectral energy Hs = 2.83m and Tp2 = 19s							
25	8b	2.56	7	1.2	19	18	14
26	8c	2	7	2	19	50	14
7	8d	1.2	7	2.56	19	82	14
28	8e	----	----	2.83	19	100	14
Tests with constant total spectral energy Hs = 2.12m and Tp2 = 11s							
29	9b	1.91	7	0.94	11	18	14
30	9c	1.5	7	1.5	11	50	14
31	9d	0.94	7	1.91	11	82	14
32	9e	----	----	2.12	11	100	14

Table 4.1 Overtopping summary

Uni-modal waves

Condition	Sea bed slope 1:?	Depth of water (m)	Structure slope 1:?	Crest Freeboard (m)	Protoype Avg.Dschrg Q (l/s/m)		Condition	Sea bed slope 1:?	Depth of water (m)	Structure slope 1:?	Crest Freeboard (m)	Protoype Avg.Dschrg Q (l/s/m)
0a2	50	14	2	4	3		0a2	50	14	4	4	
0b2	50	14	2	4	24		0b2	50	14	4	4	19
0c2	50	14	2	4	81		0c2	50	14	4	4	
0d2/4e	50	14	2	4	165		0d2/4e	50	14	4	4	177
0e2	50	14	2	4	-		0e2	50	14	4	4	
0f2	50	14	2	4	316		0f2	50	14	4	4	363
0g2	50	14	2	4	-		0g2	50	14	4	4	
0a4	50	14	2	4	-		0a4	50	14	4	4	
0b4/3a	50	14	2	4	34		0b4/3a	50	14	4	4	6
0c4	50	14	2	4	72		0c4	50	14	4	4	20
0d4	50	14	2	4	177		0d4	50	14	4	4	54
0e4	50	14	2	4	277		0e4	50	14	4	4	115
0f4	50	14	2	4	341		0f4	50	14	4	4	181
0g4	50	14	2	4	369		0g4	50	14	4	4	273
0a6	50	14	2	4	-		0a6	50	14	4	4	
0b6	50	14	2	4	8		0b6	50	14	4	4	
0c6	50	14	2	4	-		0c6	50	14	4	4	
0d6/2a	50	14	2	4	74		0d6/2a	50	14	4	4	53
0e6/1a	50	14	2	4	-		0e6/1a	50	14	4	4	
0f6	50	14	2	4	162		0f6	50	14	4	4	77
0g6/4a	50	14	2	4	-		0g6/4a	50	14	4	4	
0a2	50	12	2	6	-		0a2	50	12	4	6	
0b2	50	12	2	6	-		0b2	50	12	4	6	
0c2	50	12	2	6	-		0c2	50	12	4	6	
0d2/4e	50	12	2	6	33		0d2/4e	50	12	4	6	13
0e2	50	12	2	6	-		0e2	50	12	4	6	
0f2	50	12	2	6	62		0f2	50	12	4	6	21
0g2	50	12	2	6	-		0g2	50	12	4	6	
0a4	50	12	2	6	-		0a4	50	12	4	6	
0b4/3a	50	12	2	6	-		0b4/3a	50	12	4	6	
0c4	50	12	2	6	4		0c4	50	12	4	6	1
0d4	50	12	2	6	16		0d4	50	12	4	6	2
0e4	50	12	2	6	-		0e4	50	12	4	6	
0f4	50	12	2	6	34		0f4	50	12	4	6	5
0g4	50	12	2	6	-		0g4	50	12	4	6	
							0b2	20	14	4	4	19
0d2/4e	20	14	2	4	167		0d2/4e	20	14	4	4	188
0f2	20	14	2	4	361		0f2	20	14	4	4	433
0a4	20	14	2	4	3		0a4	20	14	4	4	1
0d4	20	14	2	4	133		0d4	20	14	4	4	47
0f4	20	14	2	4	379		0f4	20	14	4	4	181
0d6/2a	20	14	2	4	87		0d6/2a	20	14	4	4	17
0f6	20	14	2	4	267		0f6	20	14	4	4	68
0f2	20	14	2	4	157		0f2	20	12	4	6	69
0c4	20	12	2	6	10		0c4	20	12	4	6	2
0f4	20	12	2	6	98		0f4	20	12	4	6	15

Table 4.1 continued

0b2	10	14	2	4	39		0b2	10	14	4	4	19
0d2/4e	10	14	2	4	147		0d2/4e	10	14	4	4	166
0f2	10	14	2	4	376		0f2	10	14	4	4	406
0a4	10	14	2	4	3		0a4	10	14	4	4	1
0d4	10	14	2	4	193		0d4	10	14	4	4	43
0f4	10	14	2	4	432		0f4	10	14	4	4	182
0d6/2a	10	14	2	4	116		0d6/2a	10	14	4	4	17
0f6	10	14	2	4	368		0f6	10	14	4	4	83
0f2	10	12	2	6	227		0f2	10	12	4	6	133
0c4	10	12	2	6	19		0c4	10	12	4	6	2
0f4	10	12	2	6	98		0f4	10	12	4	6	23
0b2	7	14	2	4	35							
0d2/4e	7	14	2	4	122							
0f2	7	14	2	4	428							
0a4	7	14	2	4	4							
0d4	7	14	2	4	193							
0f4	7	14	2	4	356							
0d6/2a	7	14	2	4	122							
0f6	7	14	2	4	376							
0f2	7	12	2	6	201							
0c4	7	12	2	6	31							
0f4	7	12	2	6	123							

Table 4.1 continued

Bi-modal waves

Condition	Sea bed slope 1:?	Depth of water (m)	Structure slope 1:?	Crest Freeboard (m)	Protoype Avg.Dschrg Q (l/s/m)		Condition	Sea bed slope 1:?	Depth of water (m)	Structure slope 1:?	Crest Freeboard (m)	Protoype Avg.Dschrg Q (l/s/m)
1a	50	14	2	4	137		1a	50	14	4	4	30
1b	50	14	2	4	162		1b	50	14	4	4	84
1c	50	14	2	4	206		1c	50	14	4	4	145
1d	50	14	2	4	252		1d	50	14	4	4	168
1e	50	14	2	4	272		1e	50	14	4	4	232
2a	50	14	2	4	74		2a	50	14	4	4	13
2a1	50	14	2	4	78		2a1	50	14	4	4	20
2a2	50	14	2	4	77		2a2	50	14	4	4	37
2b	50	14	2	4	92		2b	50	14	4	4	64
2b3	50	14	2	4	111		2b3	50	14	4	4	93
2c	50	14	2	4	135		2c	50	14	4	4	140
2d	50	14	2	4	140		2d	50	14	4	4	157
2e	50	14	2	4	199		2e	50	14	4	4	241
3a	50	14	2	4			3a	50	14	4	4	4
3b	50	14	2	4	28		3b	50	14	4	4	31
3c	50	14	2	4	59		3c	50	14	4	4	70
3d	50	14	2	4	69		3d	50	14	4	4	80
3e	50	14	2	4	161		3e	50	14	4	4	78
4a	50	14	2	4	304		4a	50	14	4	4	123
4b	50	14	2	4	276		4b	50	14	4	4	130
4c	50	14	2	4	192		4c	50	14	4	4	128
4d	50	14	2	4	200		4d	50	14	4	4	140
4e	50	14	2	4			4e	50	14	4	4	187
5b	50	14	2	4	231		5b	50	14	4	4	112
5c	50	14	2	4	159		5c	50	14	4	4	85
5d	50	14	2	4	86		5d	50	14	4	4	64
5e	50	14	2	4	35		5e	50	14	4	4	23
6b	50	14	2	4	233		6b	50	14	4	4	79
6c	50	14	2	4	127		6c	50	14	4	4	38
6d	50	14	2	4	46		6d	50	14	4	4	18
6e	50	14	2	4			6e	50	14	4	4	
1a	50	16	2	2	543							
1b	50	16	2	2	515		1b	50	16	4	2	348
1c	50	16	2	2	584		1c	50	16	4	2	516
1d	50	16	2	2	592		1d	50	16	4	2	869
1e	50	16	2	2	738		1e	50	16	4	2	
2a	50	16	2	2	311		2a	50	16	4	2	164
2a1	50	16	2	2	337		2a1	50	16	4	2	197
2a2	50	16	2	2	297		2a2	50	16	4	2	222
2b	50	16	2	2	299		2b	50	16	4	2	249
2b3	50	16	2	2	281		2b3	50	16	4	2	295
2c	50	16	2	2	305		2c	50	16	4	2	345
2d	50	16	2	2	315		2d	50	16	4	2	398
2e	50	16	2	2	443		2e	50	16	4	2	574
3a	50	16	2	2	172		3a	50	16	4	2	79
3b	50	16	2	2	119		3b	50	16	4	2	109
3c	50	16	2	2	129		3c	50	16	4	2	173

Table 4.1 continued

3d	50	16	2	2	108		3d	50	16	4	2	190
3e	50	16	2	2	291		3e	50	16	4	2	333
4a	50	16	2	2	922		4a	50	16	4	2	
4b	50	16	2	2			4b	50	16	4	2	
4c	50	16	2	2	603		4c	50	16	4	2	423
4d	50	16	2	2	676		4d	50	16	4	2	499
4e	50	16	2	2			4e	50	16	4	2	394
5b	50	16	2	2			5b	50	16	4	2	
5c	50	16	2	2	525		5c	50	16	4	2	356
5d	50	16	2	2	242		5d	50	16	4	2	259
5e	50	16	2	2	88		5e	50	16	4	2	149
6b	50	16	2	2			6b	50	16	4	2	441
6c	50	16	2	2	464		6c	50	16	4	2	261
6d	50	16	2	2	206		6d	50	16	4	2	146
6e	50	16	2	2	2		6e	50	16	4	2	107
1a	20	14	2	4	199		1a	20	14	4	4	18
1b	20	14	2	4	201		1b	20	14	4	4	89
1c	20	14	2	4	270		1c	20	14	4	4	168
1d	20	14	2	4	270		1d	20	14	4	4	215
1e	20	14	2	4	344		1e	20	14	4	4	254
2a	20	14	2	4	74		2a	20	14	4	4	16
2b	20	14	2	4	99		2b	20	14	4	4	69
5d	20	14	2	4	99		5d	20	14	4	4	74
6d	20	14	2	4	55		6d	20	14	4	4	19
1a	10	14	2	4	251		1a	10	14	4	4	39
1b	10	14	2	4	241		1b	10	14	4	4	91
1c	10	14	2	4	258		1c	10	14	4	4	162
1d	10	14	2	4	261		1d	10	14	4	4	210
1e	10	14	2	4	347		1e	10	14	4	4	261
2a	10	14	2	4	74		2a	10	14	4	4	17
2b	10	14	2	4	104		2b	10	14	4	4	69
5d	10	14	2	4	111		5d	10	14	4	4	63
6d	10	14	2	4	71		6d	10	14	4	4	21
1a	7	14	2	4	255							
1b	7	14	2	4	249							
1c	7	14	2	4	256							
1d	7	14	2	4	249							
1e	7	14	2	4	330							
2a	7	14	2	4	74							
2b	7	14	2	4	106							
5d	7	14	2	4	116							
6d	7	14	2	4	69							

Table 4.2 Wave reflection summary

Uni-modal waves

Condition	Sea bed Slope 1:?	Depth of Water (m)	Structure Slope 1:?	ξ_m	Cr	Continuous Slope
0b4	50	14	2	2.57	0.72	
0b6	50	14	2	1.93	0.54	
0c4	50	12	2	2.52	0.54	
0c4	50	14	2	2.46	0.66	
0d2	50	12	2	3.68	0.64	
0d4	50	12	2	2.53	0.51	
0d4	50	14	2	2.54	0.62	
0d6	50	14	2	2.34	0.6	
0e4	50	14	2	2.61	0.59	
0f2	50	12	2	3.9	0.47	
0f2	50	14	2	3.44	0.56	
0f4	50	12	2	3.09	0.77	
0f4	50	14	2	2.61	0.56	
0f6	50	14	2	2.31	0.53	
0g4	50	14	2	2.73	0.53	
0b2	50	14	4	1.75	0.39	
0b4	50	14	4	1.29	0.2	
0d2	50	12	4	1.84	0.39	
0d2	50	14	4	1.8	0.43	
0d4	50	12	4	1.26	0.24	
0d4	50	14	4	1.27	0.21	
0e4	50	14	4	1.31	0.24	
0f2	50	12	4	1.95	0.37	
0f2	50	14	4	1.72	0.39	
0f4	50	12	4	1.55	0.28	
0f4	50	14	4	1.3	0.27	
0g4	50	14	4	1.37	0.31	
0a2	50	14	4	1.8	0.35	*
0a4	50	12	4	1.23	0.22	*
0a4	50	14	4	1.27	0.2	*
0a6	50	14	4	1.12	0.2	*
0b2	50	14	4	1.75	0.54	*
0b4	50	12	4	1.28	0.22	*
0b4	50	14	4	1.23	0.21	*
0b6	50	14	4	0.96	0.18	*
0c2	50	14	4	1.67	0.49	*
0c6	50	14	4	1.11	0.17	*
0d2	50	12	4	1.84	0.37	*
0d2	50	14	4	1.8	0.4	*
0d4	50	12	4	1.26	0.23	*
0d4	50	14	4	1.27	0.21	*
0d6	50	14	4	1.17	0.18	*
0e2	50	14	4	1.71	0.38	*
0e4	50	14	4	1.31	0.23	*
0e6	50	14	4	1.11	0.19	*
0a2	50	14	2	3.59	0.79	*
0a4	50	12	2	2.46	0.55	*
0a4	50	14	2	2.55	0.64	*
0a6	50	14	2	2.24	0.54	*
0b2	50	14	2	3.51	0.73	*
0b4	50	12	2	2.57	0.53	*
0b4	50	14	2	2.46	0.64	*
0b6	50	14	2	1.93	0.53	*
0c2	50	14	2	3.34	0.68	*
0c4	50	12	2	2.52	0.51	*
0c6	50	14	2	2.21	0.52	*
0d2	50	12	2	3.68	0.51	*

Table 4.2 continued

0d2	50	14	2	3.6	0.62	*
0d4	50	12	2	2.53	0.45	*
0d4	50	14	2	2.54	0.59	*
0d6	50	14	2	2.34	0.55	*
0e2	50	14	2	3.41	0.59	*
0e4	50	14	2	2.61	0.55	*
0e6	50	14	2	2.23	0.49	*
0d2	20	14	2	3.45	0.67	
0f2	20	14	2	3.25	0.58	
0a4	20	14	2	2.56	0.65	
0d4	20	14	2	2.44	0.6	
0f4	20	14	2	2.63	0.57	
0d6	20	14	2	2.28	0.57	
0f6	20	14	2	2.18	0.49	
0f2	20	12	2	3.62	0.6	
0c4	20	12	2	2.47	0.57	
0f4	20	12	2	2.87	0.49	
0b2	20	14	4	1.69	0.38	
0d2	20	14	4	1.72	0.42	
0f2	20	14	4	1.62	0.43	
0a4	20	14	4	1.28	0.2	
0d4	20	14	4	1.22	0.17	
0f4	20	14	4	1.31	0.24	
0f6	20	14	4	1.14	0.17	
0f2	20	12	4	1.09	0.41	
0c4	20	12	4	1.81	0.22	
0f4	20	12	4	1.24	0.28	
0b2	10	14	2	3.36	0.79	
0d2	10	14	2	3.49	0.72	
0f2	10	14	2	3.33	0.65	
0a4	10	14	2	2.5	0.64	
0d4	10	14	2	2.34	0.61	
0f4	10	14	2	2.44	0.59	
0d6	10	14	2	2.24	0.58	
0f6	10	14	2	2	0.5	
0f2	10	12	2	3.25	0.6	
0c4	10	12	2	2.41	0.58	
0f4	10	12	2	2.56	0.54	
0b2	10	14	4	1.68	0.39	
0d2	10	14	4	1.74	0.44	
0f2	10	14	4	1.67	0.44	
0a4	10	14	4	1.25	0.2	
0d4	10	14	4	1.17	0.19	
0f4	10	14	4	1.22	0.24	
0d6	10	14	4	1.12	0.17	
0f6	10	14	4	1	0.17	
0f2	10	12	4	1.63	0.48	
0c4	10	12	4	1.21	0.24	
0f4	10	12	4	1.28	0.31	
0b2	7	14	2	3.51	0.79	
0d2	7	14	2	4.48	0.71	
0f2	7	14	2	3.29	0.68	
0a4	7	14	2	2.46	0.64	
0d4	7	14	2	2.46	0.61	
0f4	7	14	2	2.48	0.6	
0d6	7	14	2	2.27	0.56	
0f6	7	14	2	2.08	0.48	
0f2	7	12	2	3.23	0.69	
0c4	7	12	2	2.35	0.59	
0f4	7	12	2	2.44	0.61	

Table 4.2 continued

Bi-modal waves

Condition	Sea bed Slope 1:?	Depth of Water (m)	Structure Slope 1:?	ξ_m	Cr
1a	50	14	2	2.23	0.68
1a	50	16	2	2.18	0.47
1b	50	14	2	2.41	0.56
1b	50	16	2	2.36	0.54
1c	50	14	2	2.53	0.58
1c	50	16	2	2.6	0.57
1c	50	16	4	1.3	0.29
1d	50	14	2	2.75	0.57
1d	50	16	2	2.89	0.59
1d	50	16	4	1.44	0.32
1e	50	16	2	3.06	0.57
2a1	50	14	2	2.39	0.6
2a1	50	16	2	2.44	0.55
2a1	50	16	4	1.26	0.2
2a2	50	14	2	2.5	0.61
2a2	50	16	2	2.49	0.58
2a	50	16	2	2.5	0.54
2a2	50	16	4	1.24	0.24
2a	50	16	4	1.25	0.19
2b	50	14	2	2.59	0.64
2b	50	16	2	2.66	0.61
2b3	50	14	2	2.8	0.66
2b3	50	16	2	2.86	0.65
2b3	50	16	4	1.43	0.34
2b	50	16	4	1.33	0.29
2c	50	14	2	3.08	0.68
2c	50	16	2	3.19	0.68
2c	50	16	4	1.59	0.4
2d	50	16	4	1.88	0.43
2d	50	14	2	3.53	0.7
2d	50	16	2	3.76	0.7
2e	50	14	2	3.83	0.62
2e	50	16	2	4	0.61
2e	50	16	4	2	0.49
3a	50	16	2	2.8	0.62
3a	50	16	4	1.4	0.23
3b	50	14	2	3.16	0.75
3b	50	16	2	3.42	0.72
3b	50	16	4	1.71	0.34
3c	50	14	2	3.79	0.82
3c	50	16	2	4.1	0.78
3c	50	16	4	2.05	0.43
3d	50	14	2	4.85	0.87
3d	50	16	2	5.26	0.81
3d	50	16	4	2.63	0.53
3e	50	14	2	5.74	0.71
3e	50	16	2	6.37	0.72
4a	50	14	2	2.39	0.5
4a	50	16	2	2.28	0.46
4b	50	14	2	2.39	0.52
4c	50	14	2	2.39	0.56
4c	50	16	2	2.38	0.53
4c	50	16	4	1.19	0.25
4d	50	14	2	2.42	0.57
4d	50	16	2	2.52	0.54
4d	50	16	4	1.26	0.27
5b	50	14	2	2.35	0.54
5c	50	14	2	2.34	0.56
5c	50	16	2	2.31	0.52

Table 4.2 continued

5c	50	16	4	1.15	0.23
5d	50	14	2	2.42	0.62
5d	50	16	2	2.5	0.58
5d	50	16	4	1.25	0.24
5e	50	14	2	5.96	0.79
5e	50	16	2	6.12	0.78
6b	50	16	4	1.14	0.2
6c	50	14	2	0.72	0.59
6c	50	16	2	2.41	0.51
6d	50	16	2	2.39	0.56
6d	50	16	4	1.2	0.19
6e	50	16	4	6.67	0.9
1a	20	14	4	1.09	0.16
1b	20	14	4	1.17	0.23
1c	20	14	4	1.27	0.27
1d	20	14	4	1.37	0.3
1e	20	14	4	1.46	0.38
2a	20	14	4	1.14	0.18
2b	20	14	4	1.27	0.27
5d	20	14	4	1.19	0.22
6d	20	14	4	1.14	0.19
1a	20	14	2	2.19	0.5
1b	20	14	2	2.34	0.54
1c	20	14	2	2.54	0.59
1d	20	14	2	2.75	0.59
1e	20	14	2	2.91	0.6
2a	20	14	2	2.28	0.57
2b	20	14	2	2.54	0.61
5d	20	14	2	2.39	0.55
6d	20	14	2	2.28	0.56
1a	10	14	4	1.07	0.16
1b	10	14	4	1.13	0.24
1c	10	14	4	1.21	0.29
1d	10	14	4	1.21	0.32
1e	10	14	4	1.34	0.38
2b	10	14	4	1.09	0.28
5d	10	14	4	1.16	0.21
6d	10	14	4	1.09	0.19
1a	10	14	2	2.14	0.5
1b	10	14	2	2.26	0.56
1c	10	14	2	2.41	0.59
1d	10	14	2	2.41	0.63
1e	10	14	2	2.69	0.66
2a	10	14	2	2.18	0.58
2b	10	14	2	2.32	0.63
5d	10	14	2	2.19	0.55
6d	10	14	2	2.13	0.55
1a	7	14	2	2.11	0.5
1b	7	14	2	2.26	0.58
1c	7	14	2	2.43	0.63
1d	7	14	2	2.68	0.67
1e	7	14	2	2.9	0.7
2a	7	14	2	2.28	0.57
2b	7	14	2	2.56	0.64
5d	7	14	2	2.35	0.55
6d	7	14	2	2.28	0.55

Table 4.3 Run-up summary

1:50 approach slope uni-modal waves

Condition	Depth of Water (m)	Structure Slope 1:?	ξ_m	$R_{u2\%}$ / H_{si} Ch 20	$R_{u13.6\%}$ / H_{si} Ch 20	$R_{u0.1\%}$ / H_{si} Ch 20	$R_{u2\%}$ / H_{si} Ch 21	$R_{u13.6\%}$ / H_{si} Ch 21	$R_{u0.1\%}$ / H_{si} Ch 21
0d2	12	2	3.68	3.38	2.55	4.11	3.38	2.76	3.9
0f2	12	2	3.9	3.73	2.69	4.92	4.04	3.02	4.83
0d4	12	2	2.53	2.62	1.81	2.99	2.7	2.06	3.14
0f4	12	2	3.09	3.07	2.34	3.47	3.42	2.72	4.2
0b2	14	2	3.51	2.69	1.66	3.47	3.99	2.98	5.15
0c2	14	2	3.34	3.5	2.02	4.55	4.07	2.86	4.73
0d2	14	2	3.6	3.72	2.46	4.02	4.3	3.41	4.82
0e2	14	2	3.41	3.06	2.55	3.28	3.96	3.31	4.33
0f2	14	2	3.44	2.93	2.11	3.86	2.79	2.08	3.34
0a4	14	2	2.54	3.13	2.01	4.81	4.38	3.37	4.9
0b4	14	2	2.57	2.54	1.57	3.28	3.56	2.72	4.43
0c4	14	2	2.46	3.28	1.62	4.52	4.11	2.66	4.67
0d4	14	2	2.54	3.02	1.78	3.52	3.74	2.64	4.31
0e4	14	2	2.61	2.86	1.92	3.1	3.47	2.84	3.93
0f4	14	2	2.61	2.65	1.94	2.81	3.57	2.94	4.04
0a6	14	2	2.24	3.12	1.98	6.65	4.11	3.4	6.67
0b6	14	2	1.93	2.55	1.73	3.81	3.89	2.99	5.49
0c6	14	2	2.21	2.69	1.67	3.78	3.65	2.68	4.92
0d6	14	2	2.34	2.86	1.72	3.37	3.81	2.72	4.59
0e6	14	2	2.22	2.7	1.74	3.28	3.55	2.65	4.24
0f6	14	2	2.31	2.45	1.74	2.85	3.51	2.69	4.15
0g6	14	2	2.39	2.69	2.15	2.8	3.84	3.32	4.35
0d2	12	4	1.84	1.81	1.34	2.2	1.73	1.28	2.38
0f2	12	4	1.95	2.03	1.45	2.59	2.03	1.41	2.77
0d4	12	4	1.26	1.34	0.91	1.58	1.3	0.85	1.57
0f4	12	4	1.55	1.66	1.18	2.09	1.59	1.15	2.07
0b2	14	4	1.75	2.16	1.39	3.24	2.06	1.33	3.13
0c2	14	4	1.67	2.12	1.41	2.76	2.03	1.42	2.89
0d2	14	4	1.8	2.28	1.45	2.72	2.22	1.44	2.96
0e2	14	4	1.71	1.91	1.52	2.25	1.95	1.51	2.2
0f2	14	4	1.72	1.7	1.42	2.07	1.76	1.42	2.13
0a4	14	4	1.27	1.66	1.06	2.05	1.41	0.84	2.26
0b4	14	4	1.29	1.55	0.98	2.22	1.58	1.04	1.85
0c4	14	4	1.23	1.61	1	1.92	1.4	1.03	1.85
0d4	14	4	1.27	1.51	1.07	2.04	1.51	1.02	1.7
0e4	14	4	1.31	1.43	1.09	1.9	1.4	1.05	1.73
0f4	14	4	1.3	1.44	1.05	1.66	1.34	1.05	1.63
0g4	14	4	1.37	1.64	1.23	1.9	1.61	1.2	2.04
0a6	14	4	1.12	1.45	0.94	1.83	1.33	0.82	1.79
0b6	14	4	0.96	1.31	0.94	1.91	1.32	0.94	1.65
0c6	14	4	1.11	1.43	0.82	1.76	1.42	0.85	1.62
0d6	14	4	1.17	1.46	0.92	1.79	1.37	0.94	1.82
0e6	14	4	1.11	1.34	0.91	1.63	1.36	0.91	1.46
0f6	14	4	1.16	1.43	0.99	1.96	1.43	0.97	1.91
0g6	14	4	1.2	1.38	0.98	1.8	1.29	0.95	1.8

Table 4.3 continued

Bi-modal waves

Condition	Depth of Water (m)	Structure Slope 1:?	ξ_m	$R_{u2\%} / H_{si}$ Ch 20	$R_{u13.6\%} / H_{si}$ Ch 20	$R_{u0.1\%} / H_{si}$ Ch 20	$R_{u2\%} / H_{si}$ Ch 21	$R_{u13.6\%} / H_{si}$ Ch 21	$R_{u0.1\%} / H_{si}$ Ch 21
1a	14	2	2.22	2.76	1.79	3.37	3.64	2.74	4.07
1b	14	2	2.41	2.99	2.06	3.79	4.02	3.06	4.82
1c	14	2	2.53	3.08	2.2	3.57	4.06	3.1	4.39
1d	14	2	2.75	3.13	2.33	3.53	3.9	3.21	4.54
3a	14	2	2.57	2.58	1.7	3.82	3.65	2.83	4.9
3b	14	2	3.16	4.05	2	4.98	4.93	3.09	5.65
3c	14	2	3.79	4.7	2.23	5.88	5.54	3.14	6.56
3d	14	2	4.85	5.12	2.43	5.89	5.85	3.19	6.44
3e	14	2	5.74	5.12	3.49	5.51	5.61	4.13	5.89
5b	14	2	2.35	2.69	1.95	3.03	3.61	2.86	4.44
5c	14	2	2.34	3.14	2	3.41	3.84	2.94	4.14
5d	14	2	2.42	3.36	2.11	4.58	4.65	3.18	5.35
5e	14	2	5.96	4.22	2.66	8.04	5.06	3.59	8.43
1a	16	2	2.18	3.04	1.87	3.18	3.85	2.91	4.41
1b	16	2	2.36	3.11	2.11	3.29	4.21	3.16	4.55
1c	16	2	2.6	2.91	2.11	3.04	3.9	3.05	4.34
3a	16	2	2.8	3.41	2.23	5.11	4.97	3.62	6.53
3b	16	2	3.42	3.47	2.15	4.08	4.6	3.3	5.48
3c	16	2	4.1	3.61	2.09	5.93	4.57	3.26	6.55
3d	16	2	5.26	3.52	2.15	5.6	4.68	2.88	6.26
5b	16	2	2.29	2.56	2.05	2.79	3.82	2.87	4.1
5c	16	2	2.31	2.99	2.12	3.25	3.88	2.84	4.52
5d	16	2	2.5	3.58	2.03	4.11	4.72	3.19	5.41
5e	16	2	6.11	3.75	2.29	5.14	4.79	3.31	6.16
1a	14	4	1.11	1.44	0.98	2	1.36	0.89	1.65
1b	14	4	1.2	1.75	1.3	2.23	1.73	1.28	1.99
1c	14	4	1.27	1.82	1.35	2.24	1.79	1.34	2.36
1d	14	4	1.38	1.92	1.41	2.34	1.88	1.38	2.31
1e	14	4	1.51	1.74	1.32	1.93	1.73	1.27	2
3a	14	4	1.29	1.62	1.02	2.17	1.57	0.97	1.91
3b	14	4	1.58	3.05	1.91	3.65	3.1	1.83	3.5
3c	14	4	1.89	3.65	2.42	4.25	3.61	2.39	4.32
3d	14	4	2.42	3.81	2.58	4.43	3.71	2.56	4.29
3e	14	4	2.87	3.41	2.73	3.84	3.33	2.56	4.03
5b	14	4	1.18	1.59	1.13	2.11	1.55	1.13	2.1
5c	14	4	1.17	1.83	1.34	2.28	1.83	1.28	2.2
5d	14	4	1.21	2.56	1.75	2.86	2.46	1.67	2.72
5e	14	4	2.98	3.59	2.26	4.71	3.46	2.17	4.4
1a	16	4	1.09	1.76	1.25	2.07	1.71	1.21	1.94
1b	16	4	1.18	1.78	1.2	2.02	1.78	1.23	2.03
1c	16	4	1.3	1.76	1.35	2.01	1.79	1.36	2.19
3a	16	4	1.4	1.79	1.21	2.87	1.84	1.17	2.77
3b	16	4	1.71	3.05	2.04	3.96	2.97	1.99	4.02
3c	16	4	2.05	3.39	2.46	4.8	3.41	2.38	4.59
3d	16	4	2.63	3.63	2.62	5.37	3.57	2.48	4.73
5b	16	4	1.14	1.69	1.27	2.12	1.68	1.19	2.25
5c	16	4	1.15	1.9	1.42	2.39	1.89	1.34	2.53
5d	16	4	1.25	2.55	1.73	3.08	2.49	1.71	3.31
5e	16	4	3.06	3.22	2.12	4.41	3.28	2.22	8.77

Table 4.4 Run-down summary

1:50 approach slope uni-modal waves

Condition	Depth of Water (m)	Structure Slope 1:?	ξ_m	$Rd_{2\%} / H_{si}$ Ch 20	$Rd_{13.6\%} / H_{si}$ Ch 20	$Rd_{0.1\%} / H_{si}$ Ch 20	$Rd_{2\%} / H_{si}$ Ch 21	$Rd_{13.6\%} / H_{si}$ Ch 21	$Rd_{0.1\%} / H_{si}$ Ch 21
0d2	12	2	3.68	1.59	1.46	1.74	1.41	1.29	1.58
0f2	12	2	3.90	1.77	1.65	1.83	1.56	1.43	1.75
0d4	12	2	2.53	1.59	1.33	1.68	1.22	1.12	1.37
0f4	12	2	3.09	1.99	1.83	2.08	1.55	1.42	1.74
0b2	14	2	3.51	1.22	0.98	1.31	1.40	1.28	1.57
0c2	14	2	3.34	1.12	0.91	1.28	1.42	1.30	1.60
0d2	14	2	3.60	1.18	1.02	1.29	1.45	1.33	1.63
0e2	14	2	3.41	1.25	1.04	1.38	1.48	1.36	1.66
0f2	14	2	3.44	1.39	1.30	1.43	1.46	1.34	1.65
0a4	14	2	2.54	1.44	1.14	1.55	1.10	1.01	1.23
0b4	14	2	2.57	1.13	0.93	1.27	1.16	1.07	1.31
0c4	14	2	2.46	1.18	0.94	1.32	1.08	0.99	1.22
0d4	14	2	2.54	1.24	1.04	1.52	1.16	1.06	1.30
0e4	14	2	2.61				1.33	1.22	1.49
0f4	14	2	2.61	1.39	1.15	1.55	1.31	1.20	1.47
0g4	14	2	2.73				1.49	1.36	1.67
0a6	14	2	2.24	1.47	1.20	1.62	1.02	0.94	1.15
0b6	14	2	1.93	1.26	1.02	1.42	0.97	0.89	1.09
0c6	14	2	2.21	1.36	1.06	1.45	0.94	0.87	1.06
0d6	14	2	2.34	1.22	1.00	1.37	1.06	0.97	1.19
0e6	14	2	2.22	1.31	1.07	1.48	1.07	0.98	1.20
0f6	14	2	2.31	1.38	1.10	1.52	1.22	1.12	1.37
0g6	14	2	2.39	1.58	1.35	1.67	1.30	1.20	1.47
0d2	12	4	1.84	1.55	1.39	1.64	1.41	1.29	1.58
0f2	12	4	1.95	1.68	1.52	1.75	1.56	1.43	1.75
0d4	12	4	1.26	1.30	1.07	1.53	1.22	1.12	1.37
0f4	12	4	1.55	1.73	1.46	1.88	1.55	1.42	1.74
0b2	14	4	1.75	1.48	1.24	1.78	1.40	1.28	1.57
0c2	14	4	1.67	1.46	1.21	1.65	1.42	1.30	1.60
0d2	14	4	1.80	1.54	1.28	1.80	1.45	1.33	1.63
0e2	14	4	1.71	1.54	1.27	1.74	1.48	1.36	1.66
0f2	14	4	1.72	1.64	1.37	1.75	1.46	1.34	1.65
0a4	14	4	1.27	1.19	0.98	1.34	1.10	1.01	1.23
0b4	14	4	1.29	1.16	1.02	1.44	1.16	1.07	1.31
0c4	14	4	1.23	1.13	0.99	1.24	1.08	0.99	1.22
0d4	14	4	1.27	1.19	1.05	1.45	1.16	1.06	1.30
0e4	14	4	1.31	1.30	1.12	1.60	1.33	1.22	1.49
0f4	14	4	1.30	1.43	1.15	1.62	1.31	1.20	1.47
0g4	14	4	1.37	1.58	1.28	1.80	1.49	1.36	1.67
0a6	14	4	1.12	1.07	0.87	1.20	1.02	0.94	1.15
0b6	14	4	0.96	1.05	0.87	1.18	0.97	0.89	1.09
0c6	14	4	1.11	1.08	0.88	1.14	0.94	0.87	1.06
0d6	14	4	1.17	1.13	0.95	1.50	1.06	0.97	1.19
0e6	14	4	1.11	1.12	0.93	1.31	1.07	0.98	1.20
0f6	14	4	1.16	1.25	1.00	1.54	1.22	1.12	1.37
0g6	14	4	1.20	1.28	1.06	1.66	1.30	1.20	1.47

Table 4.4 continued

Bi-modal waves

Condition	Depth of Water (m)	Structure Slope 1:?	ξ_m	$Rd_{2\%} / H_{si}$ Ch 20	$Rd_{13.6\%} / H_{si}$ Ch 20	$Rd_{0.1\%} / H_{si}$ Ch 20	$Rd_{2\%} / H_{si}$ Ch 21	$Rd_{13.6\%} / H_{si}$ Ch 21	$Rd_{0.1\%} / H_{si}$ Ch 21
1a	14	2	2.22	1.67	1.41	1.86	1.59	1.46	1.79
1b	14	2	2.41	1.66	1.41	1.92	1.59	1.46	1.78
1c	14	2	2.53	1.61	1.38	1.86	1.44	1.32	1.62
1d	14	2	2.75	1.59	1.36	1.77	1.41	1.30	1.59
3a	14	2	2.57	1.51	1.30	1.72	1.55	1.42	1.74
3b	14	2	3.16	1.68	1.41	1.97	1.60	1.47	1.80
3c	14	2	3.79	1.57	1.37	1.73	1.45	1.33	1.63
3d	14	2	4.85	1.51	1.31	1.61	1.31	1.20	1.47
3e	14	2	5.74	1.46	1.30	1.68	1.38	1.26	1.55
5b	14	2	2.35	1.66	1.46	1.80	1.50	1.38	1.69
5c	14	2	2.34	1.65	1.41	1.95	1.53	1.40	1.72
5d	14	2	2.42	1.44	1.18	1.51	1.57	1.44	1.77
5e	14	2	5.96	1.30	1.13	1.53	1.40	1.28	1.57
1a	16	2	2.18	1.87	1.62	2.17	1.79	1.64	2.01
1b	16	2	2.36	1.90	1.65	2.03	1.78	1.63	2.00
1c	16	2	2.60	1.71	1.52	1.83	1.60	1.47	1.80
3a	16	2	2.80	2.18	1.92	2.44	2.22	2.04	2.49
3b	16	2	3.42	2.06	1.78	2.38	2.29	2.10	2.57
3c	16	2	4.10	1.82	1.55	1.95	1.87	1.71	2.10
3d	16	2	5.26	1.54	1.31	1.77	1.57	1.44	1.77
5b	16	2	2.29	1.85	1.56	2.08	1.71	1.57	1.92
5c	16	2	2.31	1.84	1.59	2.11	1.72	1.58	1.93
5d	16	2	2.50	1.96	1.66	2.19	1.93	1.77	2.17
5e	16	2	6.11	1.77	1.48	1.99	1.77	1.63	1.99
1a	14	4	1.11	1.18	0.98	1.51	1.22	1.12	1.37
1b	14	4	1.20	1.51	1.26	1.74	1.36	1.25	1.53
1c	14	4	1.27	1.63	1.28	1.93	1.61	1.47	1.81
1d	14	4	1.38	1.62	1.31	1.81	1.41	1.29	1.58
1e	14	4	1.51	1.54	1.25	1.73	1.47	1.35	1.65
3a	14	4	1.29	1.20	1.05	1.38	1.12	1.03	1.26
3b	14	4	1.58	1.84	1.46	2.07	1.76	1.62	1.98
3c	14	4	1.89	1.80	1.56	2.13	1.76	1.62	1.98
3d	14	4	2.42	1.69	1.47	1.85	1.54	1.41	1.73
3e	14	4	2.87	1.63	1.48	1.73	1.40	1.29	1.58
5b	14	4	1.18	1.48	1.20	1.66	1.34	1.23	1.50
5c	14	4	1.17	1.51	1.23	1.81	1.40	1.28	1.57
5d	14	4	1.21	1.73	1.33	2.07	1.64	1.50	1.84
5e	14	4	2.98	1.89	1.66	2.09	1.73	1.58	1.94
1a	16	4	1.09	1.32	1.12	1.53	1.27	1.16	1.42
1b	16	4	1.18	1.31	1.11	1.52	1.29	1.18	1.45
1c	16	4	1.30	1.47	1.18	1.70	1.41	1.29	1.59
3a	16	4	1.40	1.44	1.22	1.63	1.33	1.22	1.50
3b	16	4	1.71	2.20	1.82	2.43	2.04	1.87	2.29
3c	16	4	2.05	2.13	1.81	2.28	1.88	1.72	2.11
3d	16	4	2.63	1.98	1.70	2.10	1.76	1.62	1.98
5b	16	4	1.14	1.39	1.16	1.64	1.29	1.18	1.45
5c	16	4	1.15	1.46	1.24	1.78	1.40	1.28	1.57
5d	16	4	1.25	1.74	1.51	2.08	1.74	1.60	1.96
5e	16	4	3.06	2.13	1.81	2.34	1.97	1.81	2.22

Table 4.5 Wave overtopping velocities

Event	Time after Start (s)	Time taken between probes		Velocity between probes	
		1-2 (s)	2-3 (s)	1-2 (m/s)	2-3 (m/s)
1	34	0.358	0.501	2.8	2
2	94.5	0.264	0.385	3.79	2.6
3					
4	268.1	0.21	0.304	4.76	3.29
5	373.5	0.461	0.662	2.17	1.51
6	385.9	0.206	0.371	4.86	2.69
7	457.1	0.34	0.47	2.94	2.13
8					
9	617.6	0.25	0.304	3.99	3.29
10					
11					
12					
13	962.8	0.241	0.358	4.14	2.8
14					
15	1074.4	0.192	0.233	5.2	4.3
16					
17	1302.3	0.47	0.59	2.13	1.69
18	1342	0.268	0.3	3.73	3.34
19	1426.1	0.479	0.577	2.09	1.73
20	1519.5	0.474	0.756	2.11	1.32
21	1567.8	0.716	0.908	1.4	1.1
22	1675.4	0.291	0.483	3.44	2.07
23	1704.2	0.371	0.827	2.69	1.21
24	1714.2	0.3	0.492	3.34	2.03
25	1753.2	0.246	0.286	4.07	3.49
26	1779.7	0.219	0.496	4.56	2.01
27	1789.3	0.215	0.268	4.66	3.73
28	1914.5	0.438	0.559	2.28	1.79
29	1948.4	0.197	0.255	5.08	3.92
30	2073	0.206	0.304	4.86	3.29
31	2180.2	0.487	0.608	2.05	1.64
32					
33	2267	0.286	0.434	3.49	2.31
34	2331.1	0.286	0.483	3.49	2.07
35	2375.7	0.42	0.514	2.38	1.94
36					
37	2541	0.282	0.438	3.55	2.28
38					
39	2682.6	0.094	0.456	10.65	2.19
40	2809.6	0.277	0.492	3.61	2.03
41	2852.5	0.233	0.277	4.3	3.61
42					
43	2918.1	0.255	0.367	3.92	2.73
44					
45					
46	3087.4	0.197	0.282	5.08	3.55
47	3202.8	0.528	0.747	1.89	1.34
48	3252.9	0.402	0.635	2.48	1.57

Table 4.5 continued

49	3300	0.335	0.648	2.98	1.54
50	3382.3	0.461	0.595	2.17	1.68
51	3495.9	0.344	0.456	2.9	2.19
52	3516.5	0.246	0.268	4.07	3.73
53	3553.6	0.098	0.51	10.16	1.96
54	3589.6	0.282	0.398	3.55	2.51
55	3721.8	0.286	0.563	3.49	1.77
56	3796.1	0.192	0.241	5.2	4.14
57	3854.4	0.349	0.326	2.87	3.06
58	3974.1	0.3	0.394	3.34	2.54
59	4066.5	0.219	0.349	4.56	2.87
60	4106.6	0.241	0.371	4.14	2.69
61					
62	4288.8	0.228	0.295	4.38	3.39
63					
64	4459.7	0.532	0.447	1.88	2.24
65	4595.5	0.492	0.729	2.03	1.37

Table 4.6 Armour movements

Seabed Slope	1:50
Structure slope	1 : 2
Total number of rocks	700

			Armour Movements		Damage	Corresponding
		Test name	>=1.0D_{n50}	0.5-1.0 D_{n50}	(%)	Damage Level (S)
Spectra	Uni-modal	0b2a275	5	5	0.71	0.6
Water depth (m)	14	0c2a275	18	9	2.57	2.1
Sea-steepness	0.02	0d2a275	50	7	7.14	5.7
Number of waves	1000	0e2a275	140	3	20.0	16.0
Damage collection	Cumulative	0f2a275	Complete failure			
Spectra	Uni-modal	0b4a275	9	4	1.29	1.0
Water depth (m)	14	0c4a275	15	9	2.14	1.7
Sea-steepness	0.04	0d4a275	35	10	5.00	4.0
Number of waves	1000	0e4a275	86	3	12.29	9.8
Damage collection	Cumulative	0f4a275	Complete failure			
Spectra	Uni-modal	0c4a285	4	1	0.57	0.5
Water depth (m)	16	0d4a285	9	4	1.29	1.0
Sea-steepness	0.04	0e4a285	53	10	7.57	6.1
Number of waves	1000	0f4a285	Complete failure			
Damage collection	Cumulative					
Spectra	Bi-modal	1aa275	17	8	2.43	1.9
Water depth (m)	14	1ba275	16	9	2.29	1.8
Wind sea	Varying	1ca275	39	9	5.57	4.5
Swell-sea	Varying	1da275	24	13	3.43	2.7
Energy	Constant	1ea275	29	12	4.14	3.3
Number of waves	500					
Damage collection	Individual					
Spectra	Bi-modal	4aa275	13	2	1.86	1.5
Water depth (m)	14	4ba275	15	3	2.14	1.7
Wind sea	Varying	4ca275	9	6	1.29	1.0
Swell-sea	Varying	4da275	11	3	1.57	1.3
Return Period	Constant	4ea275	19	3	2.71	2.2
Number of waves	500					
Damage collection	Individual					
Spectra	Bi-modal	4ea275	19	3	2.71	2.2
Water depth (m)	14	2da275	19	3	2.71	2.2
Wind sea	Varying	1ca275	38	5	5.43	4.3
Swell-sea	Constant	4ca275	40	2	5.71	4.6
Number of waves	500					
Damage collection	Cumulative					

Table 4.6 continued

Seabed slope	1:20
Structure slope	1 : 2
Total number of rocks	700

			Armour Movements		Damage	Corresponding
		Test name	>=1.0D_{n50}	0.5-1.0 D_{n50}	(%)	Damage Level (S)
Spectra	Uni-modal	0b2a272	6	8	0.86	0.7
Water depth (m)	14	0c2a272	30	11	4.29	3.4
Sea-steepness	0.02	0d2a272	116	9	16.57	13.3
Number of waves	1000	0e2a272	Complete failure			
Damage collection	Cumulative	0f2a272	Complete failure			
Spectra	Uni-modal	0b4a272	23	7	3.29	2.6
Water depth (m)	14	0c4a272	38	25	5.43	4.3
Sea-steepness	0.04	0d4a272	Complete failure			
Number of waves	1000	0e4a272	Complete failure			
Damage collection	Cumulative	0f4a272				
Spectra	Uni-modal	0c4a282	34	35	4.86	3.9
Water depth (m)	16	0d4a282	148	23	21.14	16.9
Sea-steepness	0.04	0e4a282	Complete failure			
Number of waves	1000	0f4a282				
Damage collection	Cumulative					
Spectra	Bi-modal	1aa272	68	19	9.71	7.8
Water depth (m)	14	1ba272	78	27	11.14	8.9
Wind sea	Varying	1ca272	105	30	15.0	12.0
Swell-sea	Varying	1da272	128	32	18.29	14.6
Energy	Constant	1ea272	Complete failure			
Number of waves	500					
Damage collection	Individual					
Spectra	Bi-modal	4aa272	83	15	11.86	9.5
Water depth (m)	14	4ba272	72	20	10.29	8.2
Wind sea	Varying	4ca272	69	23	9.86	7.9
Swell-sea	Varying	4da272	79	31	11.29	9.0
Return Period	Constant	4ea272	51	27	7.29	5.8
Number of waves	500					
Damage collection	Individual					
Spectra	Bi-modal	4ea272	42	18	2.71	2.2
Water depth (m)	14	2da272	46	38	2.71	2.2
Wind sea	Varying	1ca272	70	47	5.43	4.3
Swell-sea	Constant	4ca272	97	52	5.71	4.6
Number of waves	500					

Table 4.7 Wave transmissions - seawall

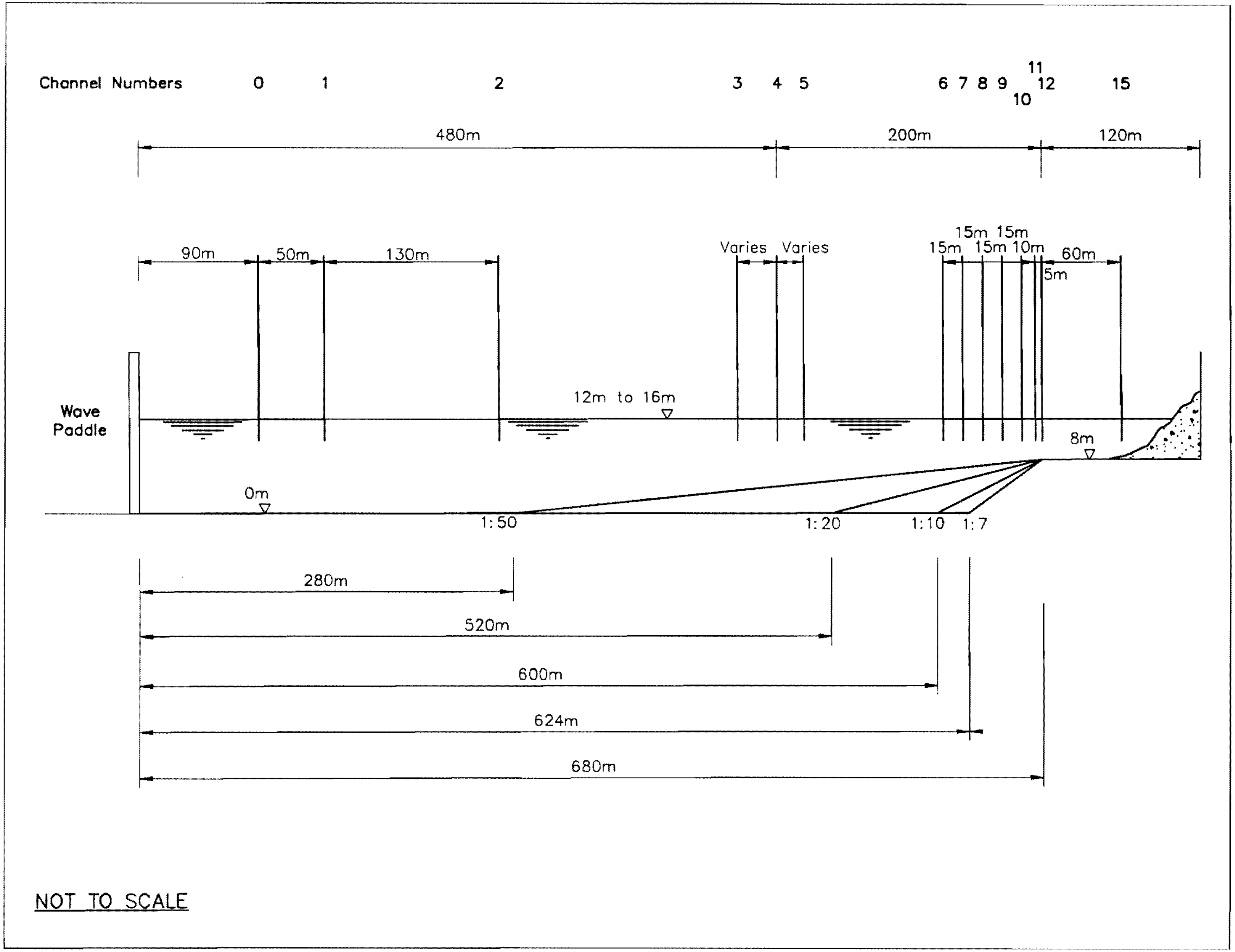
Test	Seastate	Structure slope 1:?	Structural Variable	Bed slope 1:?	SWL (m)	Freebaord R (m)	With structure		With structure		Without Structure		
							H_{st} (15) (m)	T_{mt} (15) (s)	H_{st} (16) (m)	T_{mt} (16) (s)	H_{si} (15) (m)	T_{mo} (s)	$C_t=H_{st}/H_{si}$ (%)
0a2c475	Uni-modal	4	Crest	50	14	4	0.03	7.07	0.03	7.38	1.36	7.04	2.12
0b2c475	Uni-modal	4	Crest	50	14	4	0.15	5.66	0.15	5.43	1.90	8.10	8.01
0c2c475	Uni-modal	4	Crest	50	14	4	0.52	7.15	0.51	6.14	2.47	8.88	20.73
0d2c475	Uni-modal	4	Crest	50	14	4	0.92	10.02	0.83	7.73	3.04	10.17	27.44
0e2c475	Uni-modal	4	Crest	50	14	4	1.13	10.37	1.01	7.66	3.47	10.57	29.20
0f2c475	Uni-modal	4	Crest	50	14	4	1.23	9.67	1.07	7.08	3.57	11.10	29.92
0g2c475	Uni-modal	4	Crest	50	14	4	1.22	9.13	1.07	6.59	3.46	11.35	30.84
0a2b85	Uni-modal	2	berm	50	16	2	0.17	3.71	0.14	3.33	1.36	7.04	10.60
0b2b85	Uni-modal	2	berm	50	16	2	0.34	4.32	0.29	3.99	1.90	8.10	15.20
0c2b85	Uni-modal	2	berm	50	16	2	0.62	6.60	0.53	5.46	2.47	8.88	21.34
0d2b85	Uni-modal	2	berm	50	16	2	0.91	8.66	0.80	6.99	3.04	10.17	26.32
0e2b85	Uni-modal	2	berm	50	16	2	1.21	10.66	1.03	8.50	3.47	10.57	29.66
0f2b85	Uni-modal	2	berm	50	16	2	1.59	11.98	1.51	10.73	3.57	11.10	42.30
0g2b85	Uni-modal	2	berm	50	16	2	1.65	10.62	1.44	9.47	3.46	11.35	41.65
1ab85	Bi-modal	2	berm	50	16	2	0.63	4.43	0.60	4.20	3.14	6.23	19.07
1bb85	Bi-modal	2	berm	50	16	2	0.70	4.80	0.63	4.40	3.05	6.79	20.82
1cb85	Bi-modal	2	berm	50	16	2	0.88	5.93	0.77	5.14	3.29	7.74	23.52
1db85	Bi-modal	2	berm	50	16	2	1.00	6.86	0.88	6.01	3.40	8.68	26.00
1eb85	Bi-modal	2	berm	50	16	2	1.34	10.59	1.38	9.66	3.92	9.55	35.17
4ab85	Bi-modal	2	berm	50	16	2	1.05	6.73	1.03	6.11	3.85	7.30	26.74
4bb85	Bi-modal	2	berm	50	16	2	0.94	5.74	0.90	5.13	3.55	7.15	25.38
4cb85	Bi-modal	2	berm	50	16	2	0.81	5.48	0.79	4.86	3.14	7.00	25.02
4db85	Bi-modal	2	berm	50	16	2	1.02	6.97	0.96	6.12	3.36	7.60	28.43
4eb85	Bi-modal	2	berm	50	16	2	0.87	8.12	0.81	6.25	2.90	10.40	28.03
0a2b75	Uni-modal	2	berm	50	14	4	0.07	6.71	0.04	6.63	1.36	7.04	2.64
0b2b75	Uni-modal	2	berm	50	14	4	0.12	5.58	0.11	6.36	1.90	8.10	5.84
0c2b75	Uni-modal	2	berm	50	14	4	0.29	5.30	0.34	5.13	2.47	8.88	13.89
0d2b75	Uni-modal	2	berm	50	14	4	0.47	6.00	0.56	5.01	3.04	10.17	18.26
0e2b75	Uni-modal	2	berm	50	14	4	0.78	6.71	0.83	5.62	3.47	10.57	23.99
0f2b75	Uni-modal	2	berm	50	14	4	0.91	7.05	0.90	5.46	3.57	11.10	25.32
0g2b75	Uni-modal	2	berm	50	14	4	1.02	6.58	1.01	5.45	3.46	11.35	29.22
1ab75	Bi-modal	2	berm	50	14	4	0.20	3.60	0.20	3.24	2.65	6.22	7.40
1bb75	Bi-modal	2	berm	50	14	4	0.28	4.25	0.32	3.84	2.82	6.80	11.34
1cb75	Bi-modal	2	berm	50	14	4	0.38	4.17	0.44	3.83	2.98	7.45	14.81
1db75	Bi-modal	2	berm	50	14	4	0.46	4.80	0.50	4.03	3.11	8.27	16.16
1eb75	Bi-modal	2	berm	50	14	4	0.66	6.43	0.70	5.23	3.21	9.49	21.76
4ab75	Bi-modal	2	berm	50	14	4	0.36	4.27	0.40	3.93	2.95	7.28	13.64
4bb75	Bi-modal	2	berm	50	14	4	0.35	3.88	0.36	3.47	3.04	7.15	11.81
4cb75	Bi-modal	2	berm	50	14	4	0.39	3.97	0.38	3.40	2.94	6.95	12.74
4db75	Bi-modal	2	berm	50	14	4	0.46	5.15	0.51	4.37	3.08	7.20	16.63
4eb75	Bi-modal	2	berm	50	14	4	0.46	5.89	0.56	5.26	3.04	10.17	18.36
0a2c275	Uni-modal	2	crest	50	14	4	0.28	4.16	0.40	3.61	1.36	7.04	29.38
0b2c275	Uni-modal	2	crest	50	14	4	0.56	4.71	0.74	4.03	1.90	8.10	38.82
0c2c275	Uni-modal	2	crest	50	14	4	0.69	4.80	0.87	3.88	2.47	8.88	35.22
0d2c275	Uni-modal	2	crest	50	14	4	1.02	6.00	1.01	4.86	3.04	10.17	33.23
0e2c275	Uni-modal	2	crest	50	14	4	1.13	5.65	1.18	4.54	3.47	10.57	33.98
0f2c275	Uni-modal	2	crest	50	14	4	1.23	5.89	1.31	5.02	3.57	11.10	36.69
0g2c275	Uni-modal	2	crest	50	14	4	1.35	6.14	1.38	5.10	3.46	11.35	39.92
1ac275	Bi-modal	2	crest	50	14	4	0.73	4.43	0.93	3.76	2.65	6.22	34.93
1bc275	Bi-modal	2	crest	50	14	4	0.76	4.12	0.90	3.60	2.82	6.80	31.93
1cc275	Bi-modal	2	crest	50	14	4	0.87	4.61	0.98	3.84	2.98	7.45	33.04
1dc275	Bi-modal	2	crest	50	14	4	0.96	5.06	1.03	4.25	3.11	8.27	33.10
1ec275	Bi-modal	2	crest	50	14	4	1.12	5.81	1.18	4.74	3.21	9.49	36.74
4ac275	Bi-modal	2	crest	50	14	4	0.94	4.38	1.09	3.87	2.95	7.28	36.97
4bc275	Bi-modal	2	crest	50	14	4	0.90	4.46	0.99	3.95	3.04	7.15	32.71
4dc275	Bi-modal	2	crest	50	14	4	0.83	5.18	0.90	4.40	3.08	7.20	29.25
4ec275	Bi-modal	2	crest	50	14	4	0.92	6.56	1.04	5.18	3.04	10.17	34.22

Table 4.8 Transmission results – vertical wall

Test Name	Seastate	Bed slope	SWL (m)	Freeboard R (m)	Without Structure H_{si} (m)	With Structure H_{st} (m)	nominal T_{mo} (s)	R/H_{si}	R*	$C_t=H_{st}/H_{si}$ (%)
0f2v65	Uni-modal	1:50	12	11	2.29	0.1542	11.3	4.8	0.205	6.73
0c4v65	Uni-modal	1:50	12	11	2	0.1506	6.3	5.5	0.394	7.53
0f4v65	Uni-modal	1:50	12	11	2.27	0.1059	8	4.85	0.291	4.67
0d4v75	Uni-modal	1:50	14	9	2.65	0.02435	6.9	3.4	0.256	0.92
0f4v75	Uni-modal	1:50	14	9	3.2	0.01655	8	2.81	0.201	0.52
0d6v75	Uni-modal	1:50	14	9	2.34	0.05084	6.1	3.85	0.308	2.17
0f6v75	Uni-modal	1:50	14	9	2.76	0.03027	6.5	3.26	0.266	1.10
1av75	Bi-modal	1:50	14	9	2.65	0	6.1	3.4	0.289	0.00
1bv75	Bi-modal	1:50	14	9	2.82	0	6.8	3.19	0.252	0.00
1cv75	Bi-modal	1:50	14	9	2.98	0.01204	7.45	3.02	0.223	0.40
1dv75	Bi-modal	1:50	14	9	3.11	0.02914	8.27	2.89	0.197	0.94
1ev75	Bi-modal	1:50	14	9	3.21	0.01613	9.49	2.8	0.169	0.50
2av75	Bi-modal	1:50	14	9	2.42	0	6.22	3.72	0.297	0.00
2bv75	Bi-modal	1:50	14	9	2.51	0	6.81	3.59	0.266	0.00
5dv75	Bi-modal	1:50	14	9	2.49	0	6.25	3.61	0.291	0.00
6dv75	Bi-modal	1:50	14	9	2.14	0	5.72	4.21	0.343	0.00
0f2v62	Uni-modal	1:20	12	11	2.32	0.2584	11.3	4.74	0.204	11.14
0c4v62	Uni-modal	1:20	12	11	1.89	0.1229	6.3	5.82	0.405	6.50
0f4v62	Uni-modal	1:20	12	11	2.07	0.1619	8	5.31	0.305	7.82
a0b2v72	Uni-modal	1:20	14	9	2.07	0.06181	8.9	4.35	0.224	2.99
a0d2v72	Uni-modal	1:20	14	9	2.91	0.1486	10	3.09	0.168	5.11
0f2v72	Uni-modal	1:20	14	9	3.53	0.2142	11.3	2.55	0.135	6.07
0a4v72	Uni-modal	1:20	14	9	1.48	0	4.9	6.08	0.482	0.00
0d4v72	Uni-modal	1:20	14	9	2.85	0.01426	6.9	3.16	0.247	0.50
0f4v72	Uni-modal	1:20	14	9	3.22	0	8	2.8	0.2	0.00
0d6v72	Uni-modal	1:20	14	9	2.59	0.01331	6.1	3.47	0.293	0.51
0f6v72	Uni-modal	1:20	14	9	2.91	0.01284	6.5	3.09	0.259	0.44
0f2v67	Uni-modal	1:7	12	11	2.57	0.1268	11.3	4.28	0.194	4.93
0c4v67	Uni-modal	1:7	12	11	2	0.03531	6.3	5.5	0.394	1.77
0f4v67	Uni-modal	1:7	12	11	2.32	0.01423	8	4.74	0.288	0.61
a0b2v77	Uni-modal	1:7	14	9	2.08	0.04573	8.9	4.33	0.224	2.20
a0d2v77	Uni-modal	1:7	14	9	1.92	0.07342	10	4.69	0.207	3.82
0f2v77	Uni-modal	1:7	14	9	3.74	0.09425	11.3	2.41	0.131	2.52
0a4v77	Uni-modal	1:7	14	9	1.44	0.01575	4.9	6.25	0.489	1.09
0d4v77	Uni-modal	1:7	14	9	2.89	0.00533	6.9	3.11	0.245	0.18
0f4v77	Uni-modal	1:7	14	9	3.39	0.01448	8	2.65	0.195	0.43
0d6v77	Uni-modal	1:7	14	9	2.66	0	6.1	3.38	0.289	0.00
0f6v77	Uni-modal	1:7	14	9	3.05	0	6.5	2.95	0.253	0.00

Figures

Figure 2.1 Absorbing wave flume: wave probe locations



NOT TO SCALE

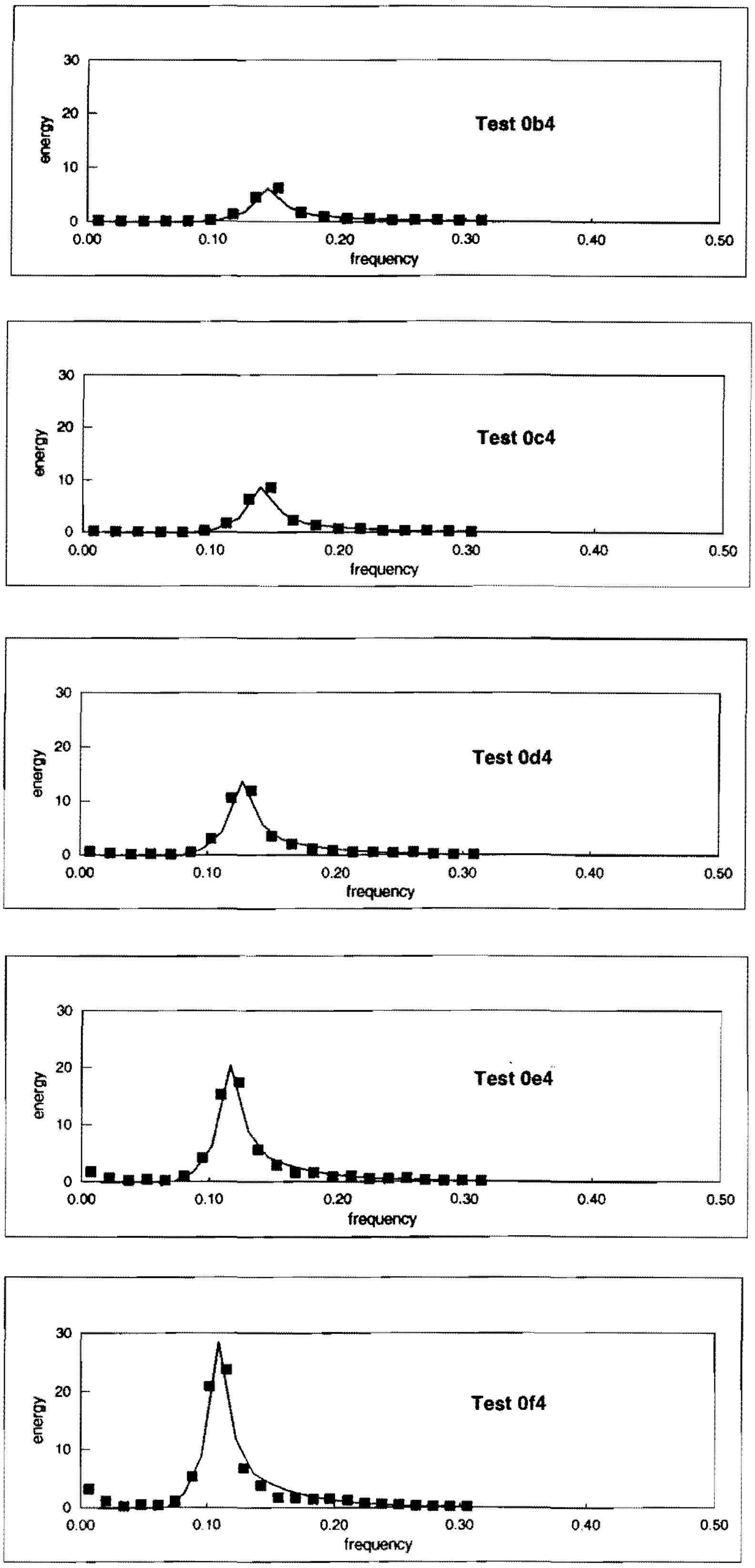


Figure 2.2 Example calibrated uni-modal spectra

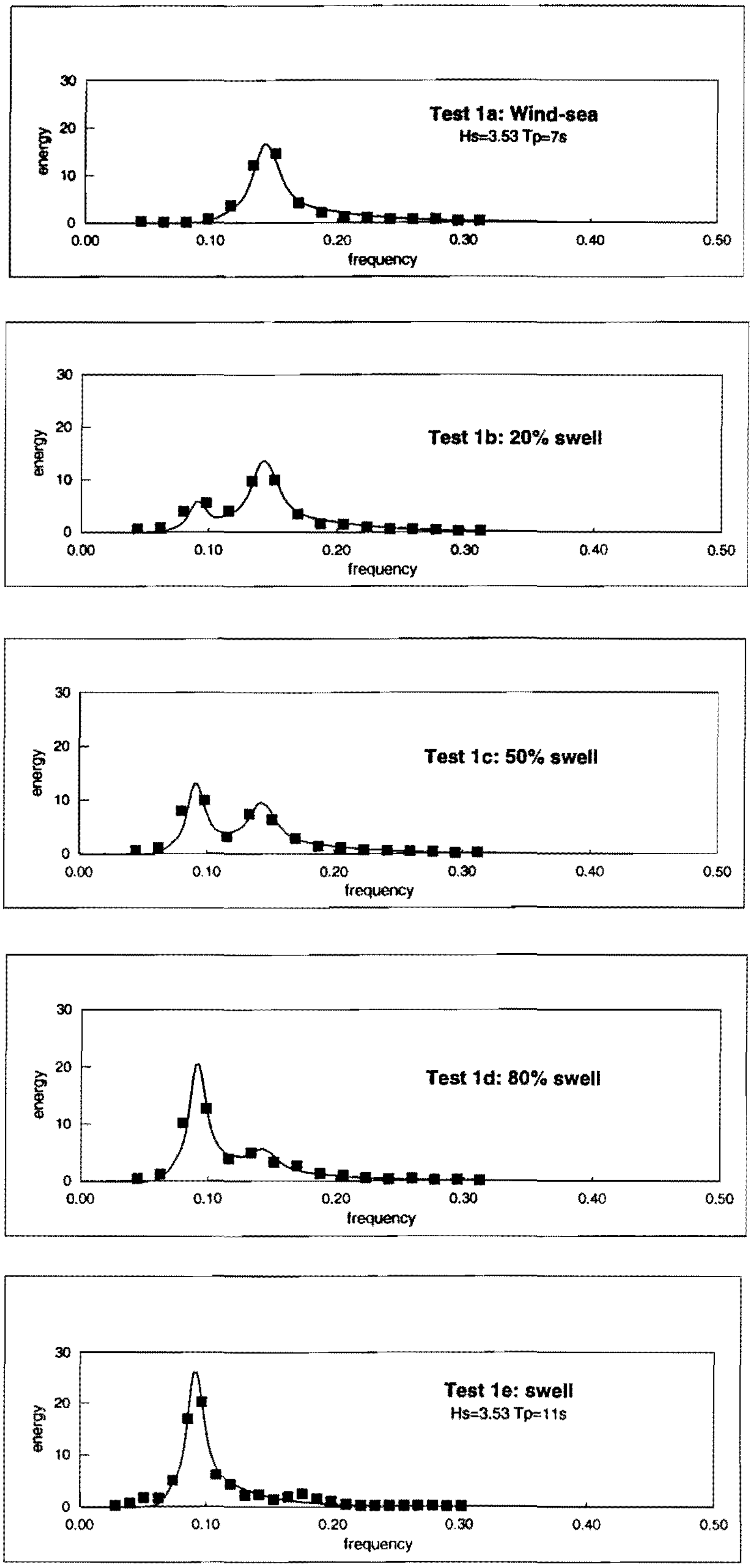


Figure 2.3 **Example calibrated bi-modal spectra**

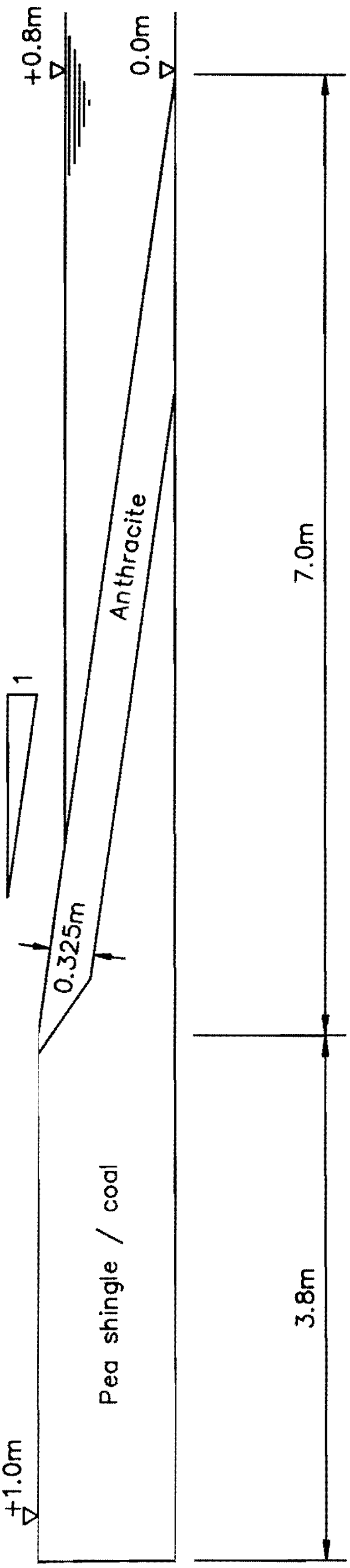


Figure 2.4 Model beach cross-section

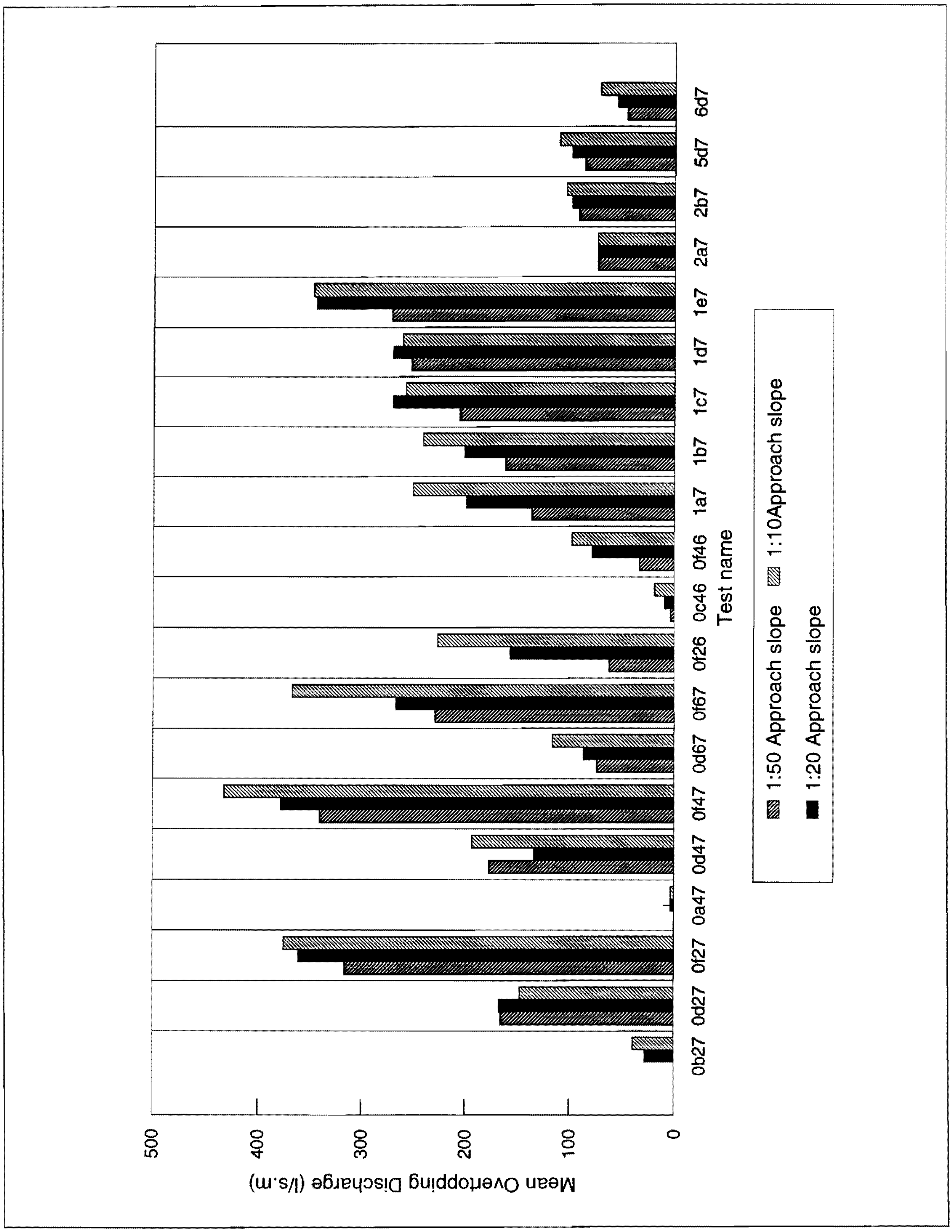


Figure 4.1 1:2 structure overtopping performance with different approach slopes

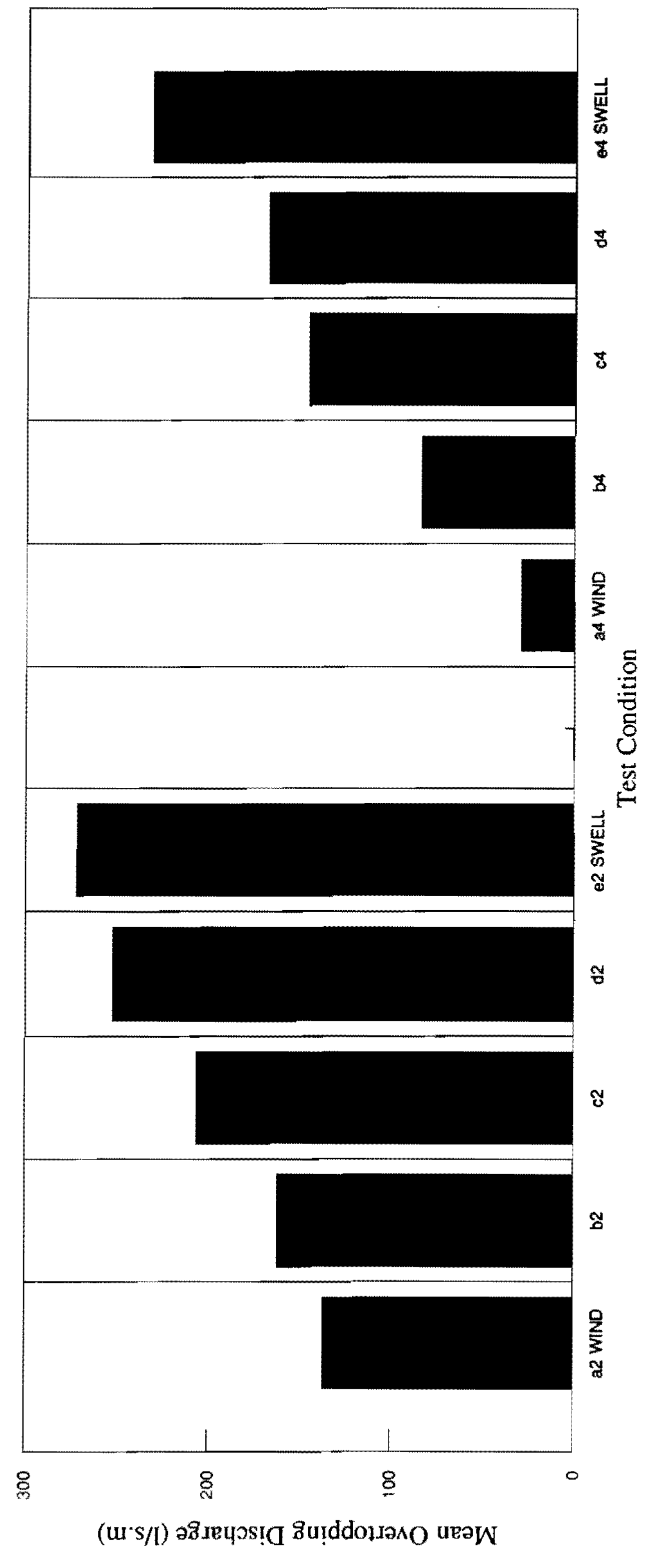


Figure 4.2 Influence of bi-modal spectra on overtopping performance

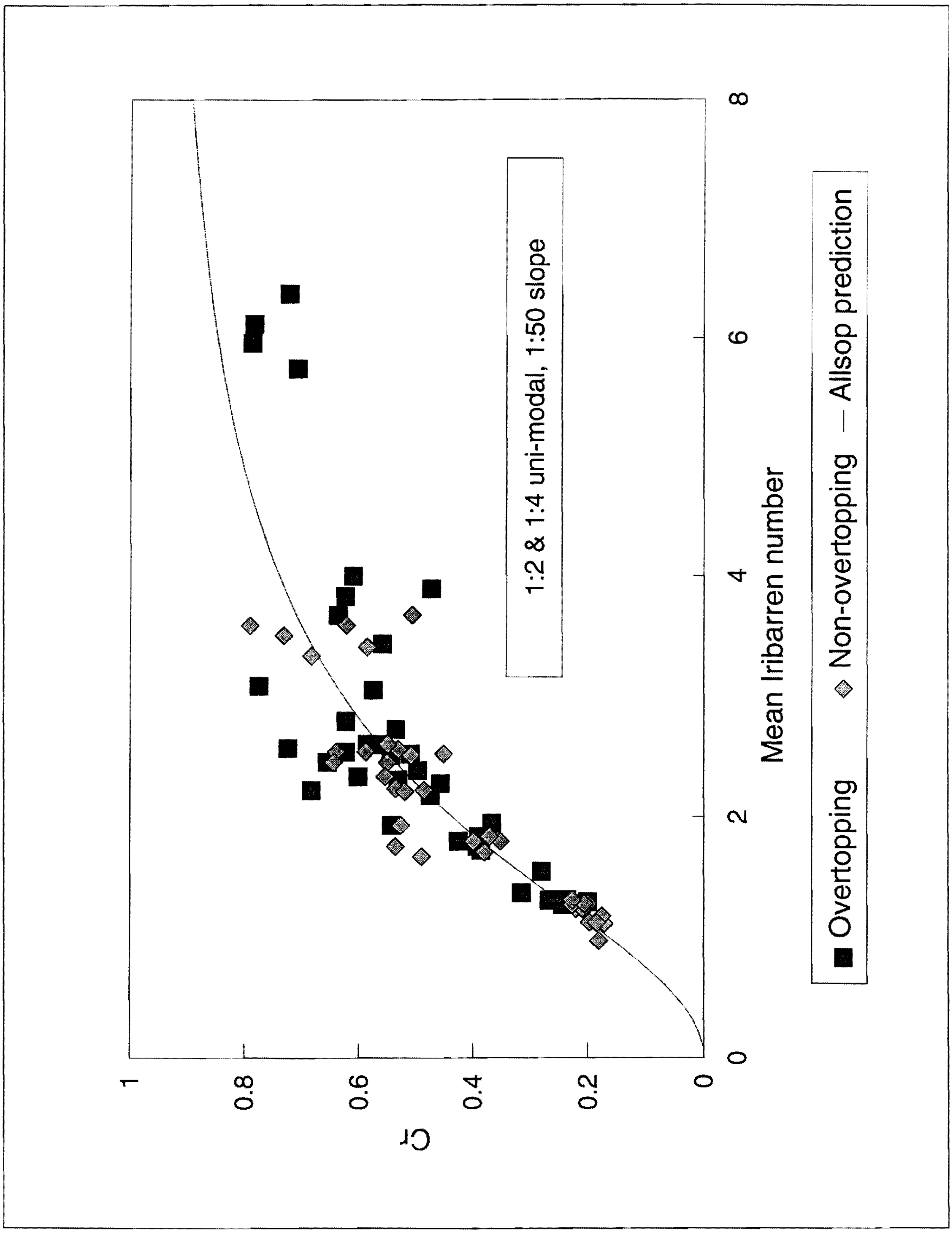


Figure 4.3 Reflection performance of overtopping and non-overtopping structures

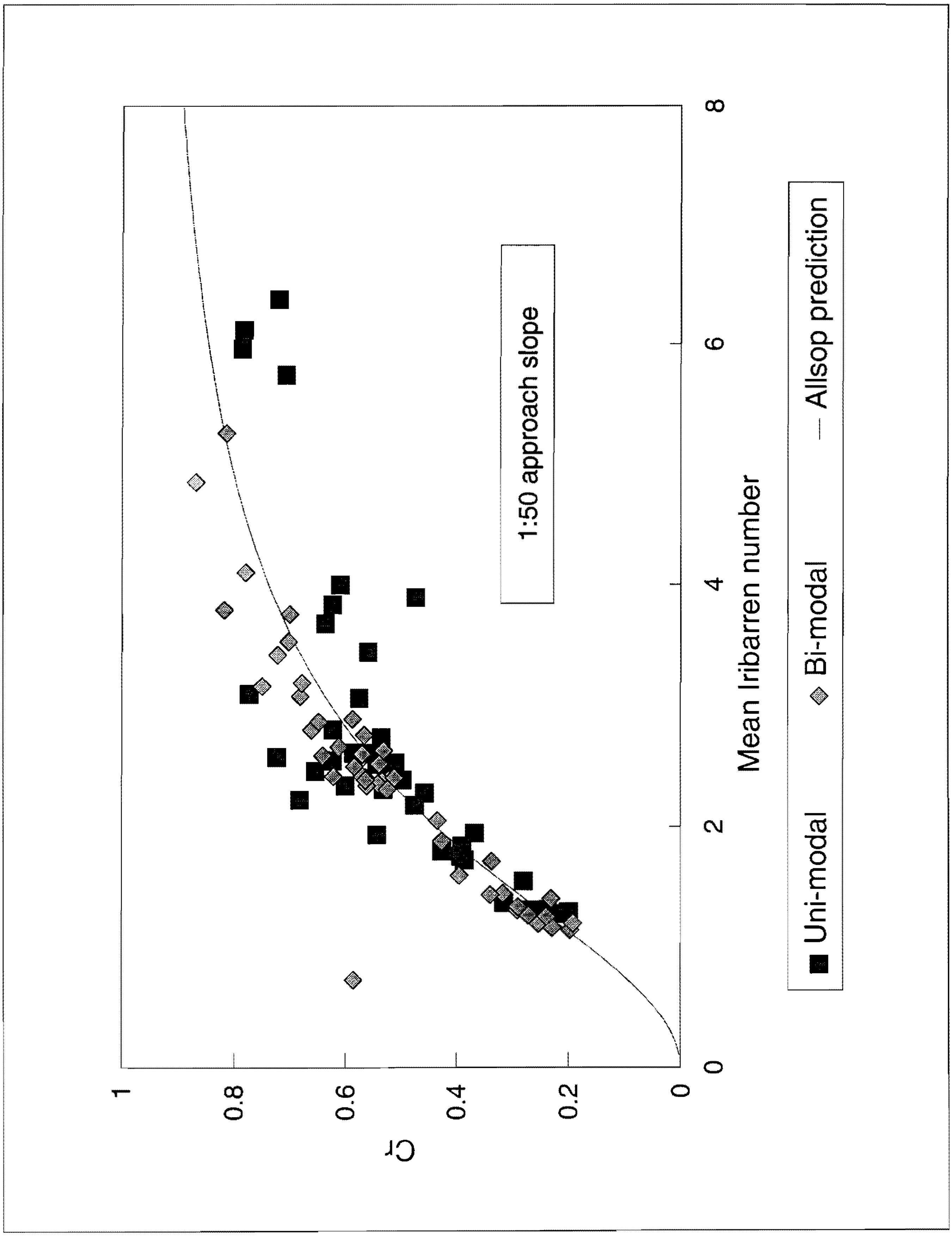


Figure 4.4 Reflection performance of uni-modal and bi-modal spectra

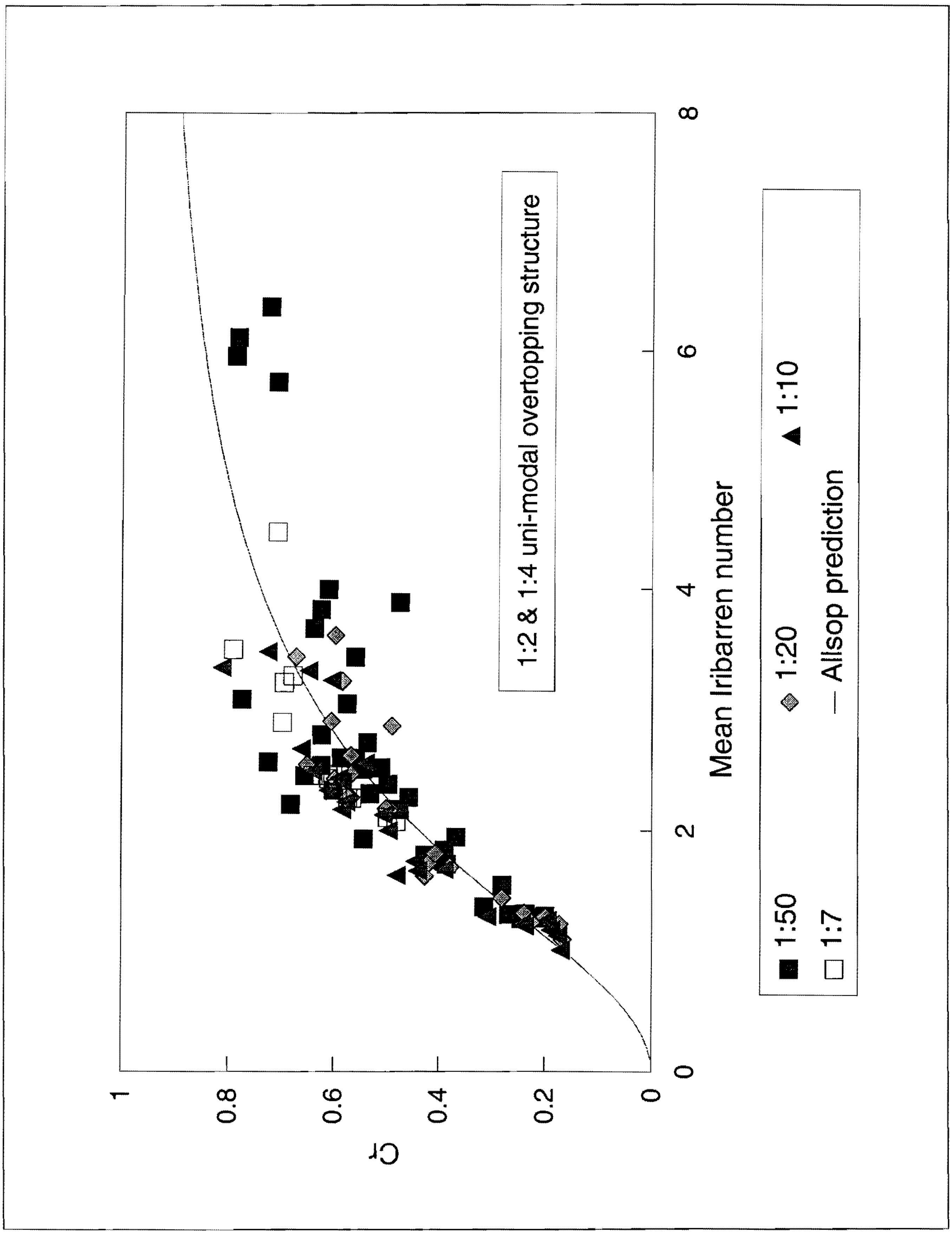


Figure 4.5 Reflection performance with different approach slopes

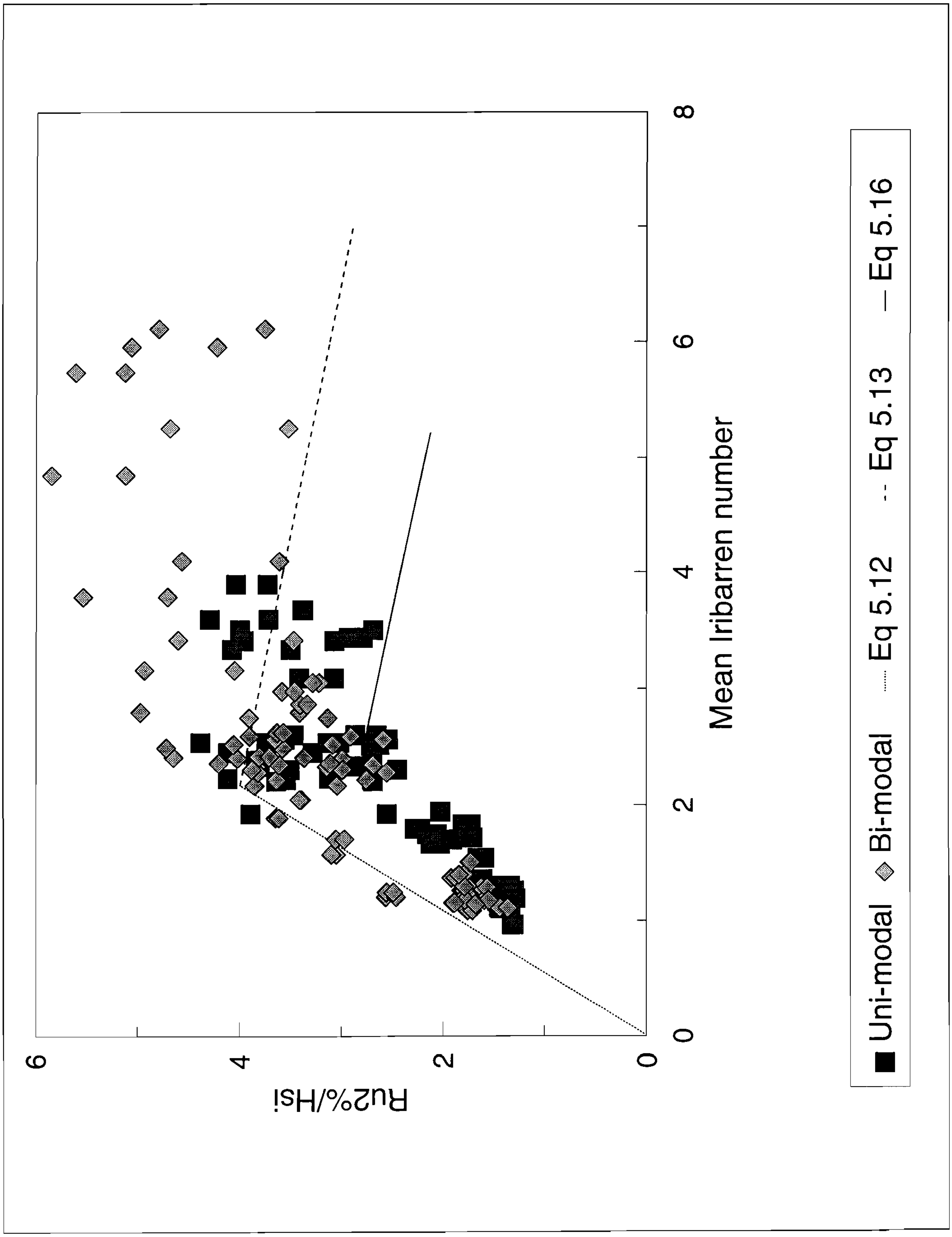


Figure 4.6 Run-up performance

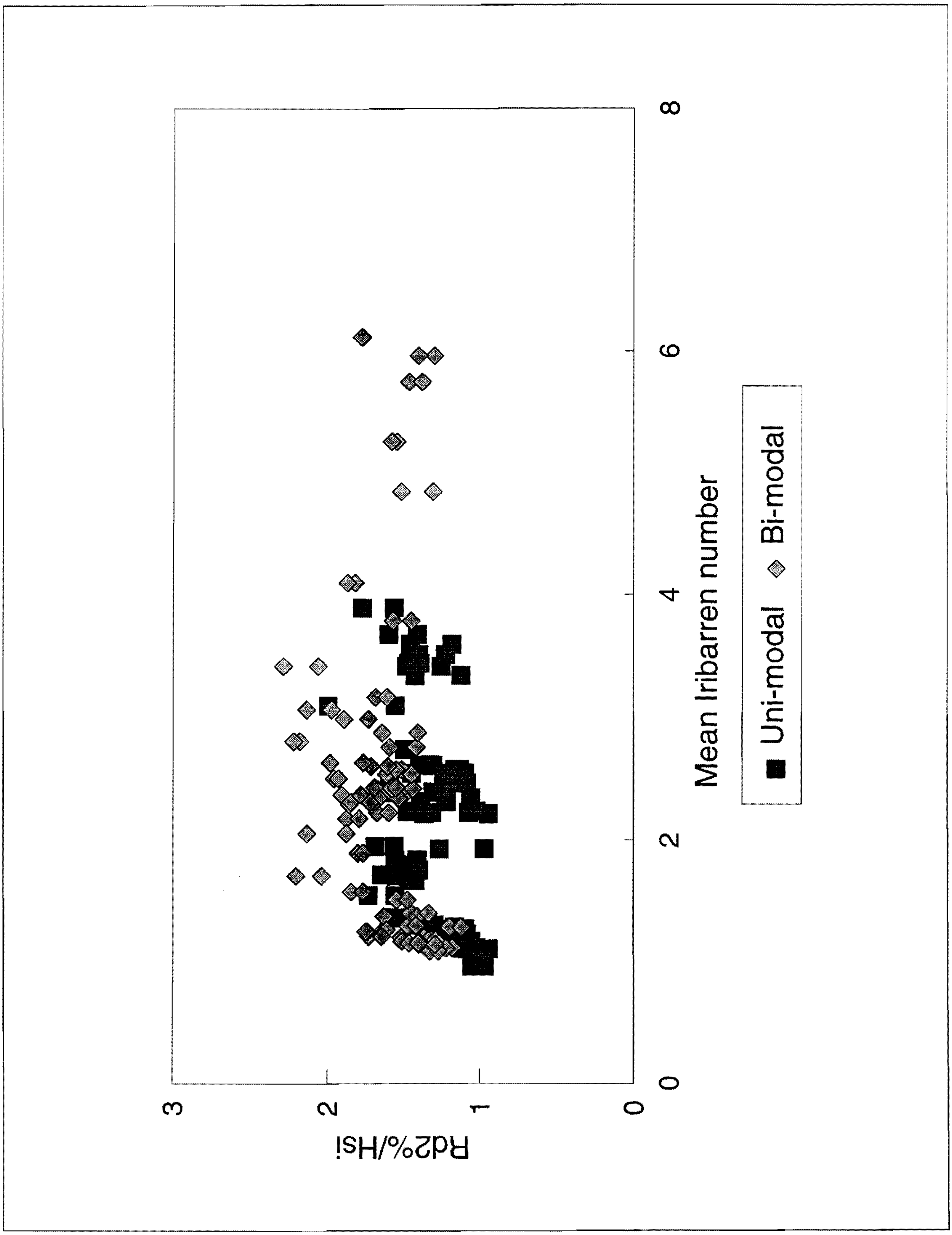


Figure 4.7 Run-down performance

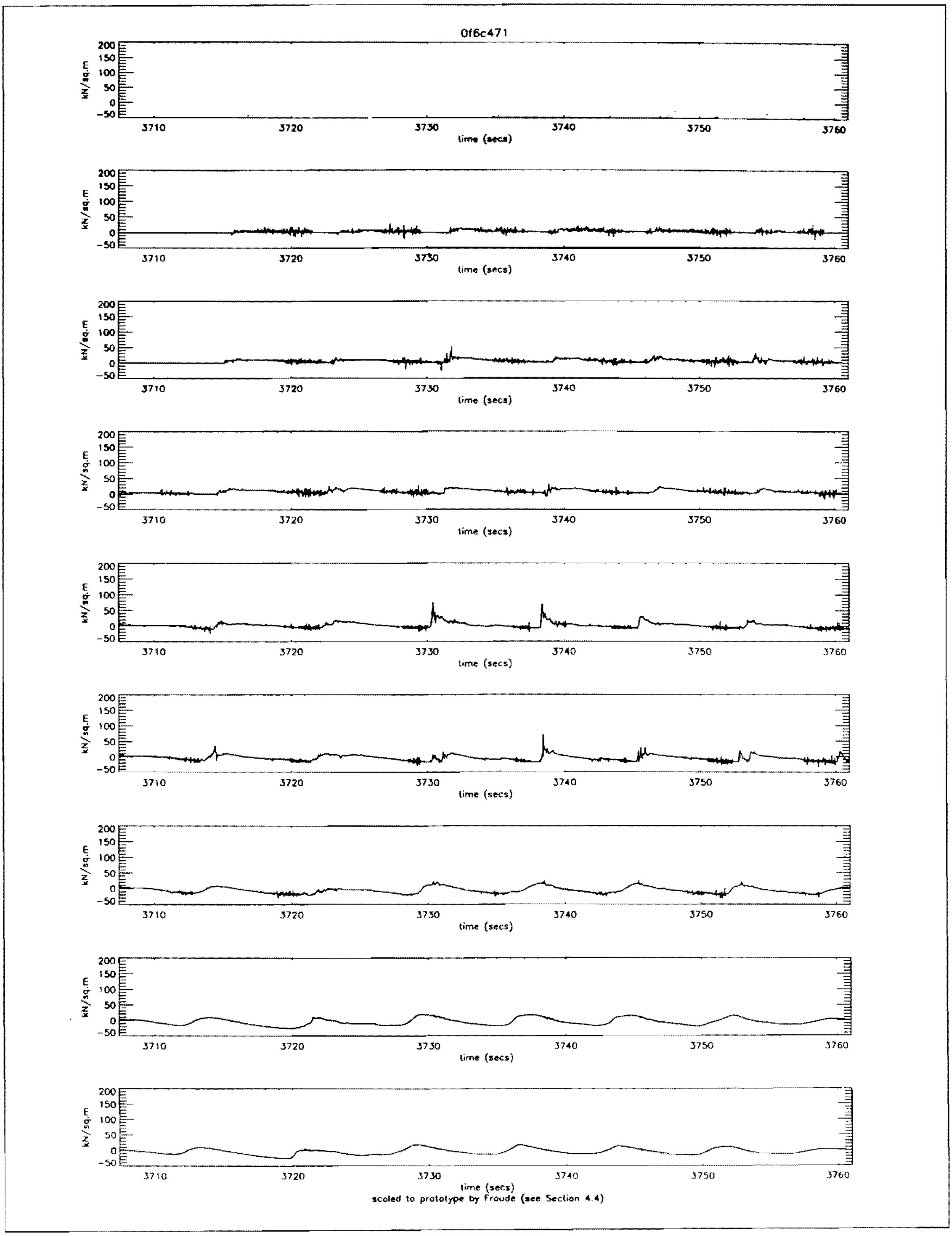


Figure 4.8 Wave pressure measurements: 1:4 structure

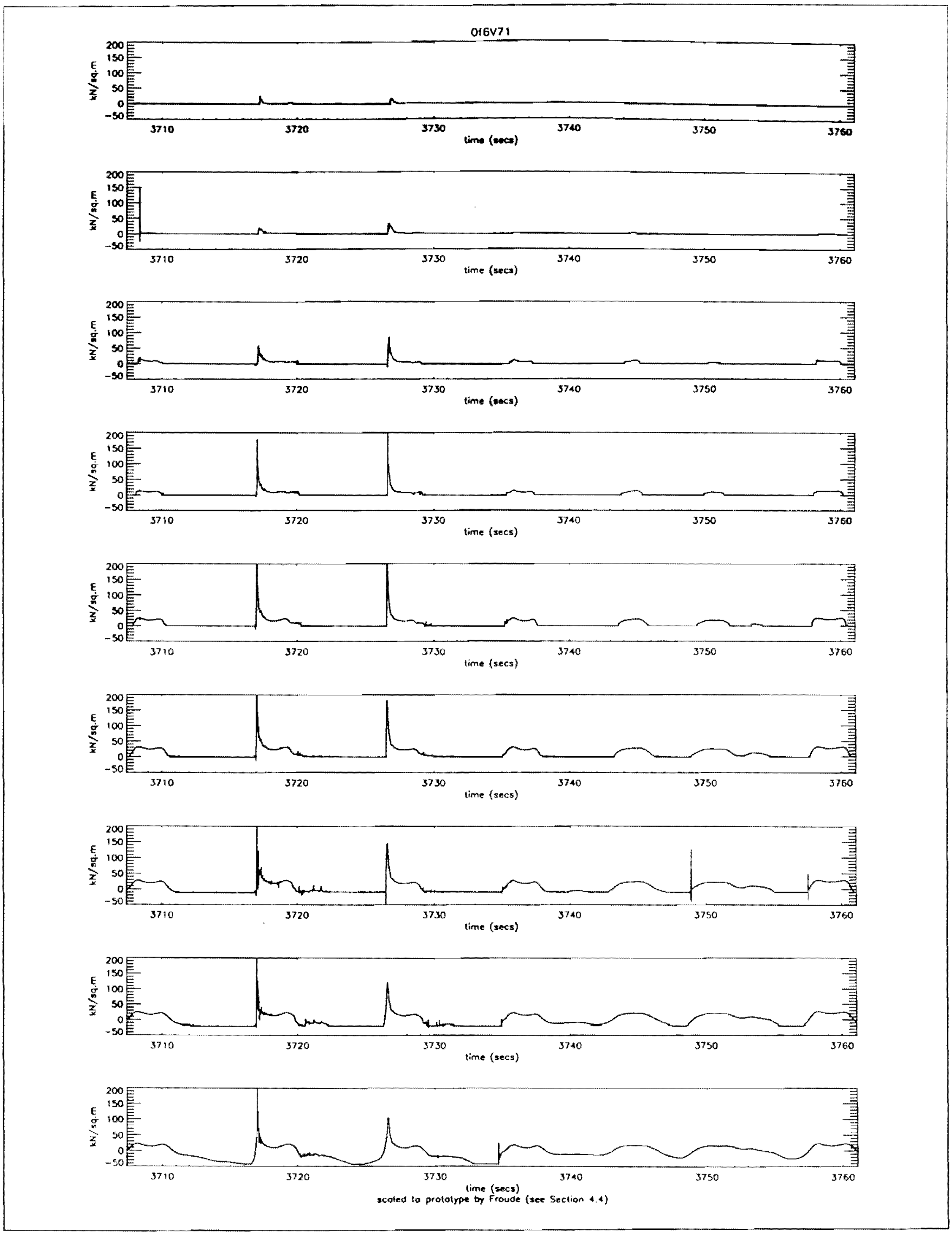


Figure 4.9 Wave pressure measurements: vertical structure

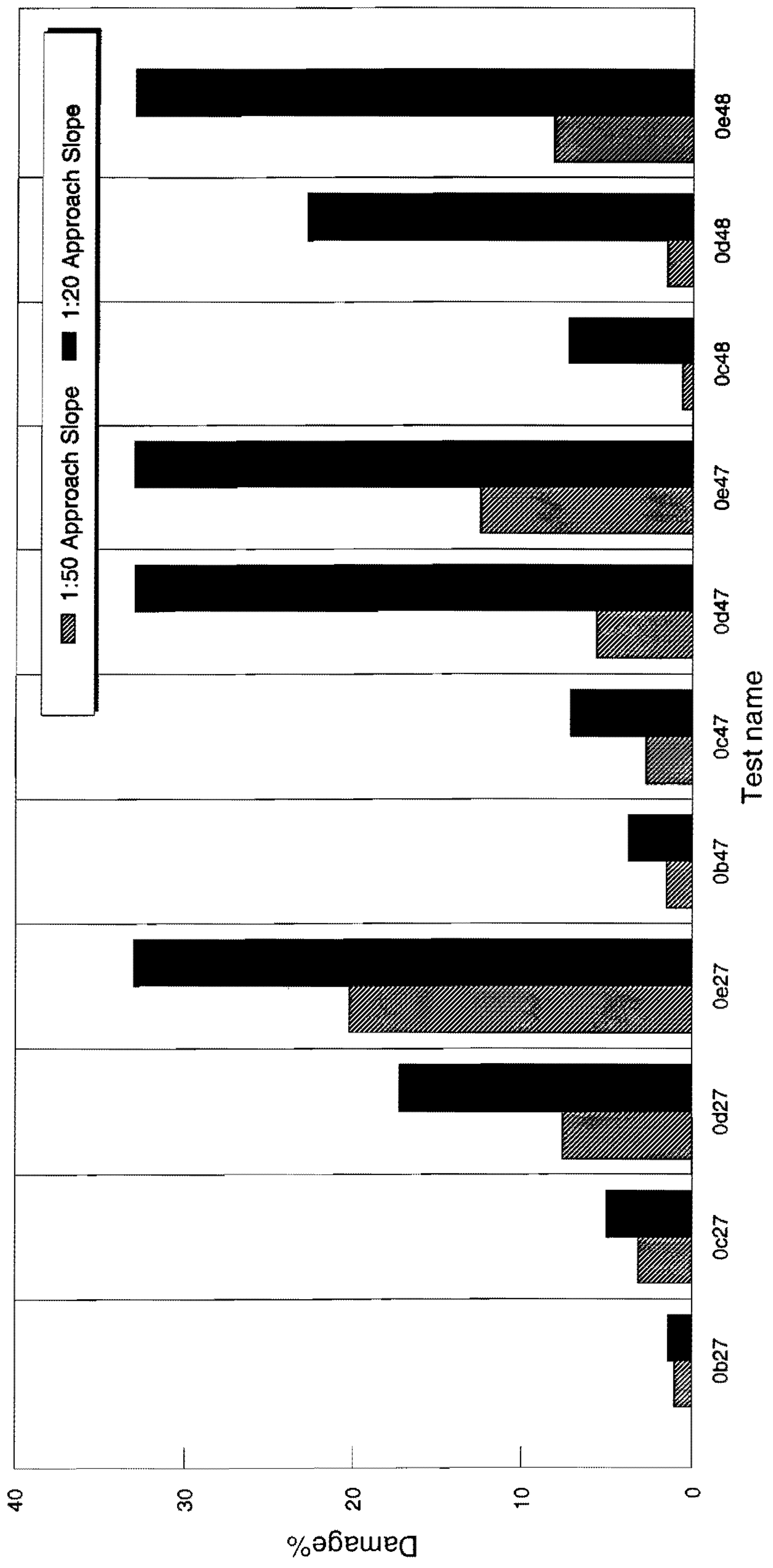


Figure 4.10 Armour displacements: uni-modal spectra

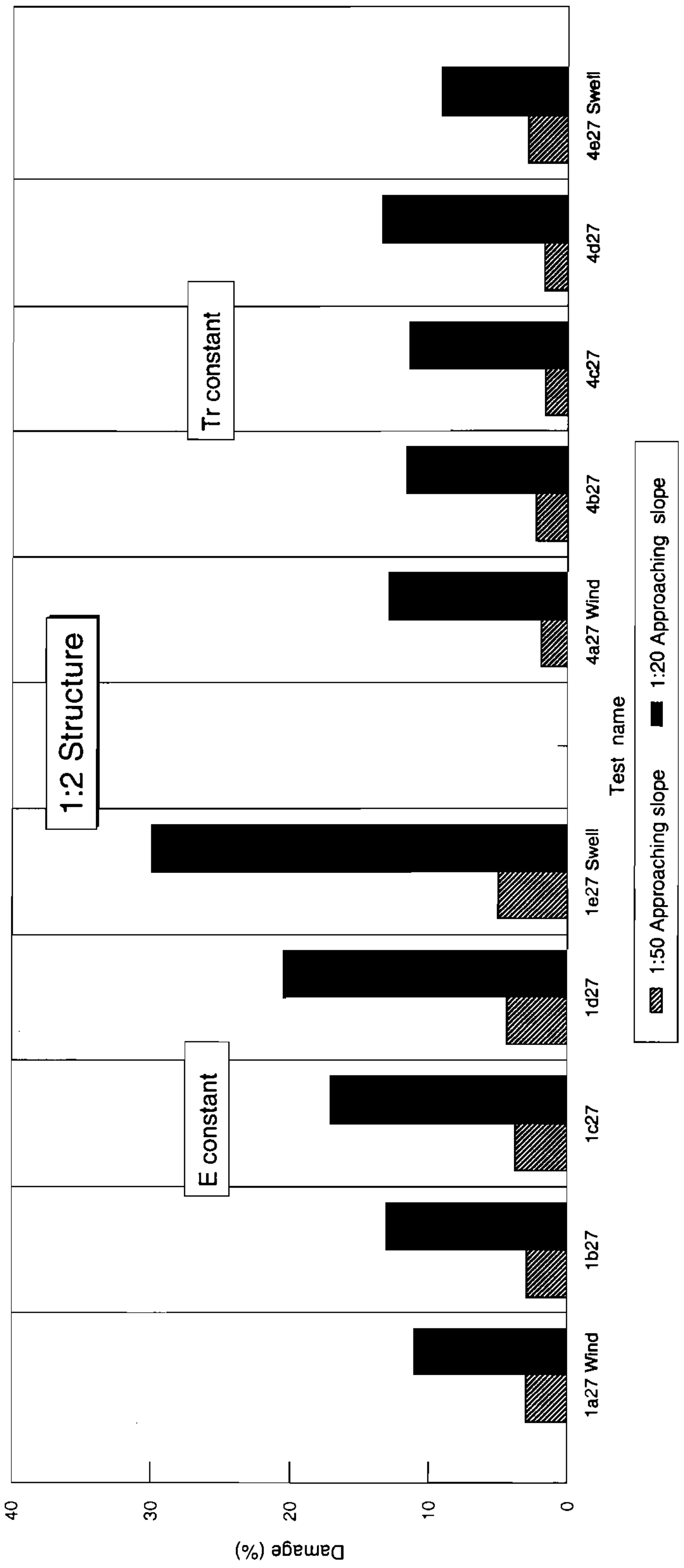


Figure 4.11 Armour displacements: bi-modal spectra

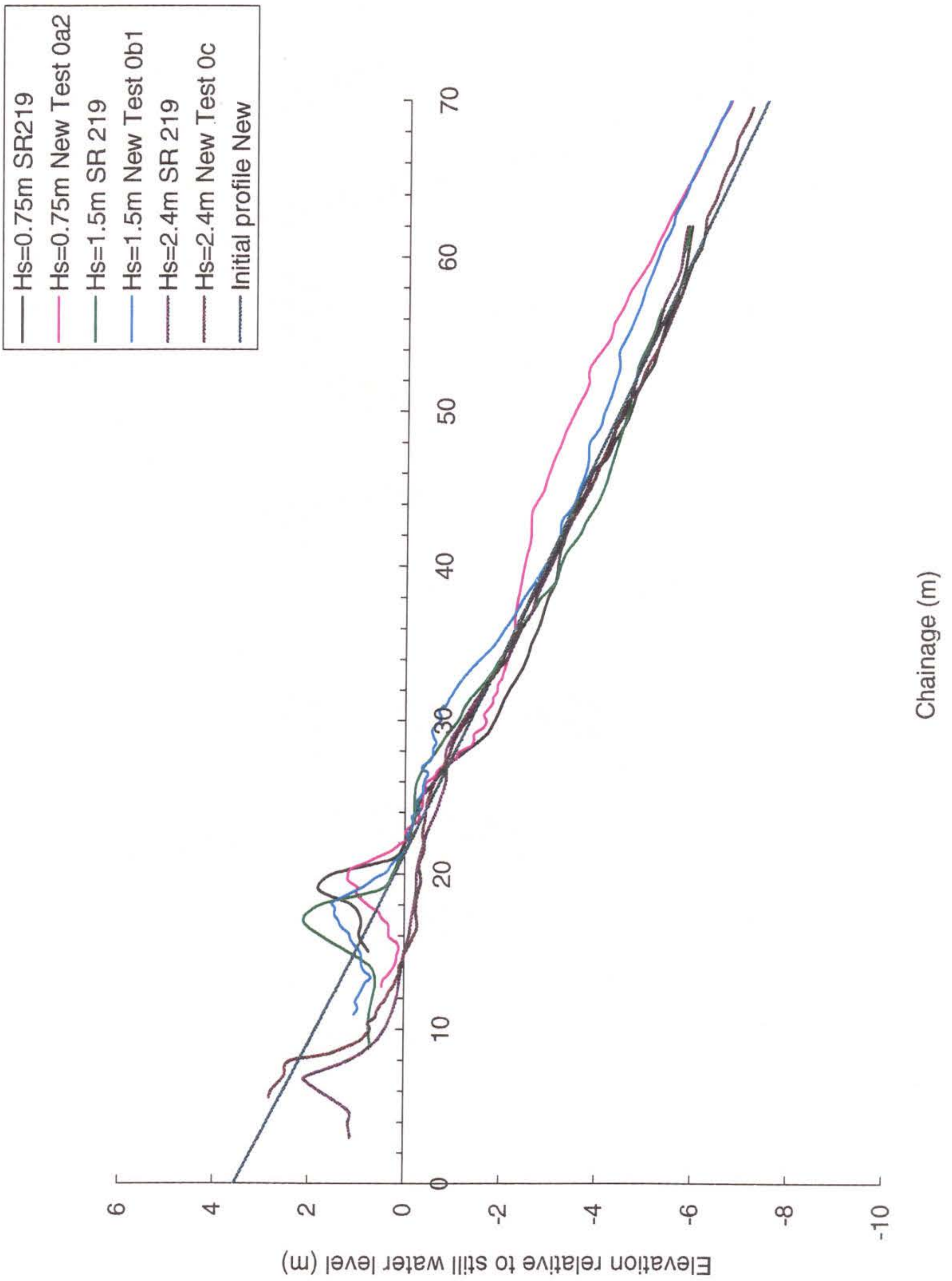


Figure 6.1 Comparison of profiles with Powell, 1990 (Reference 8)

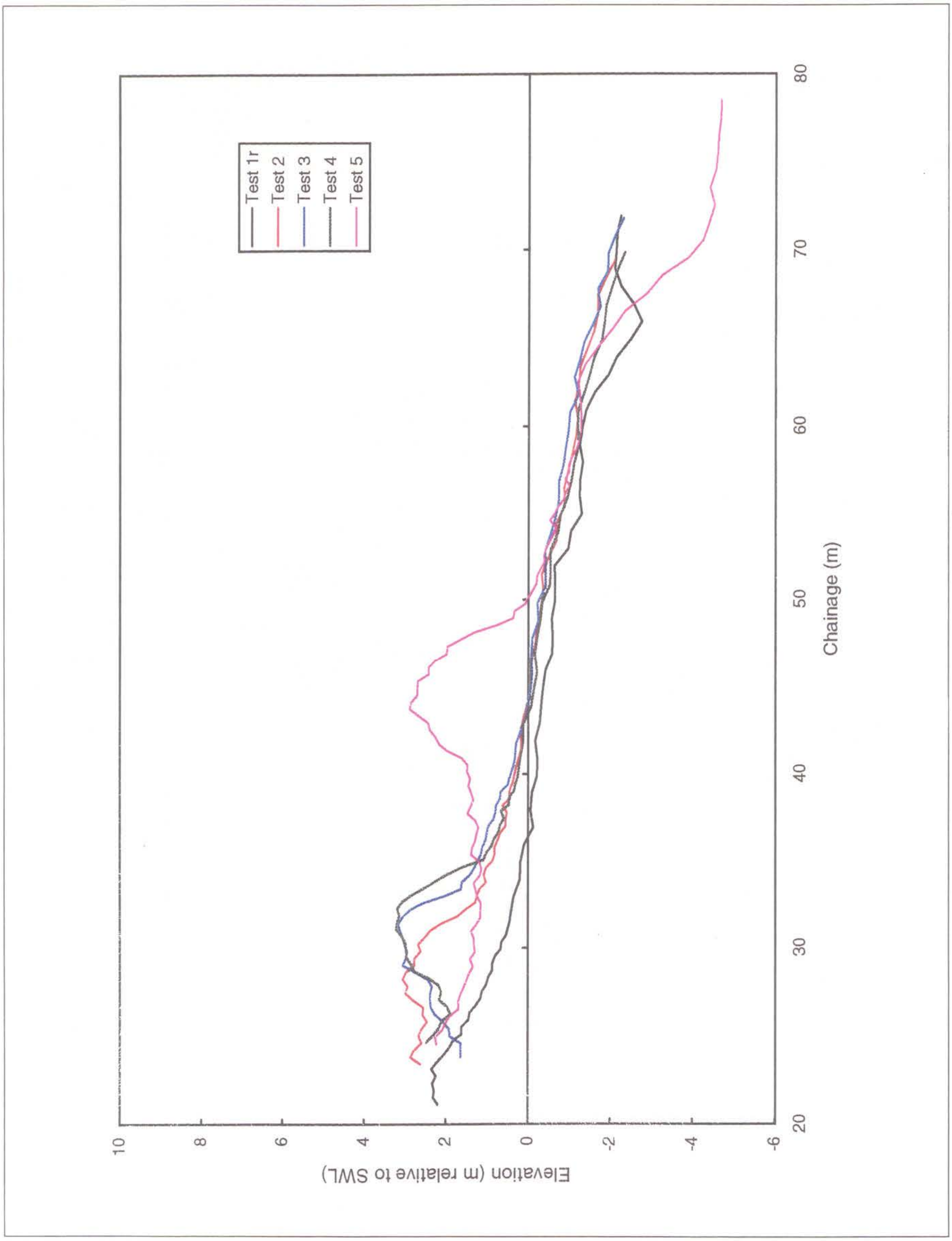


Figure 6.2 Beach profiles – Constant return period (Tests 1-5)

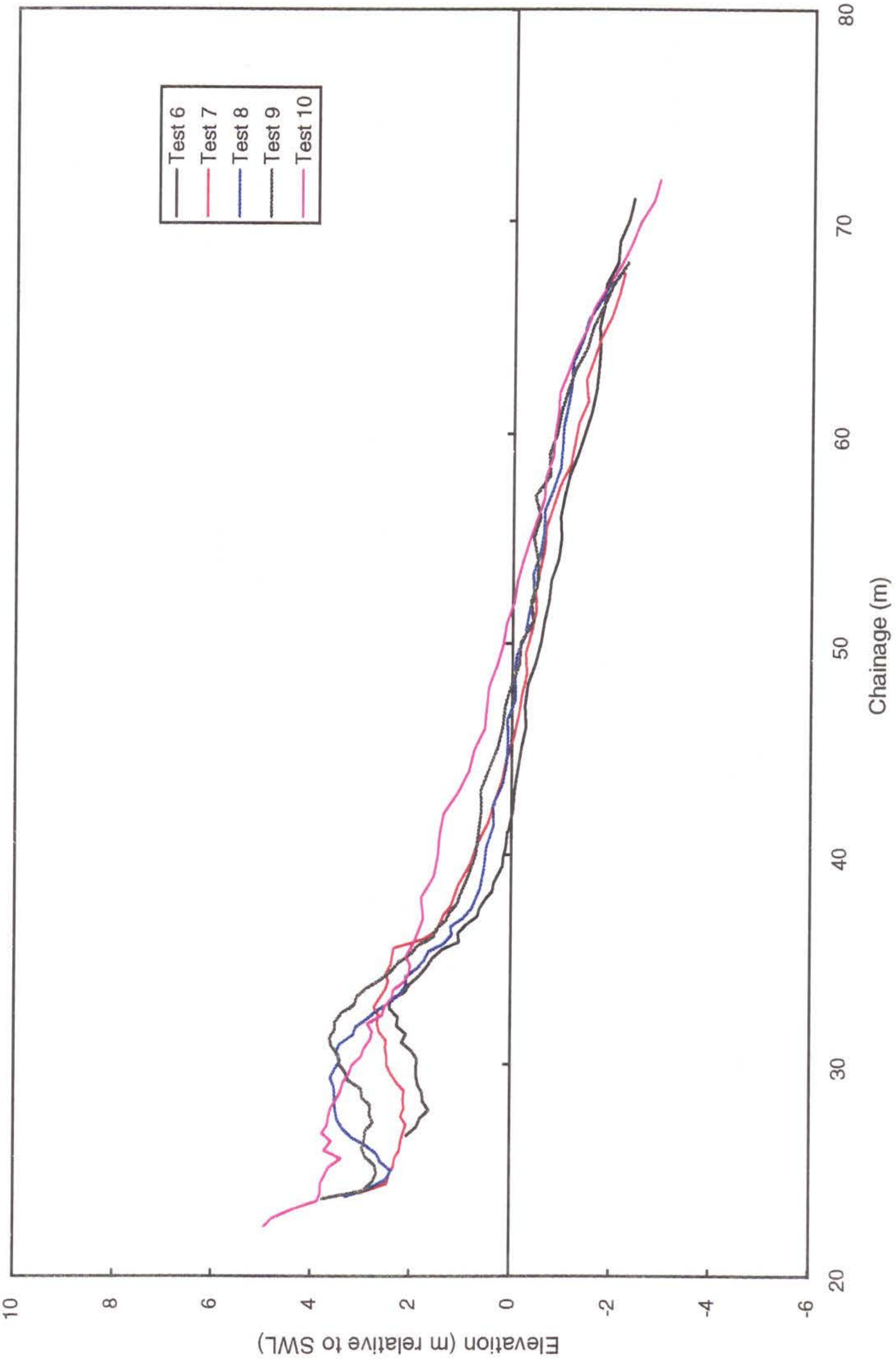


Figure 6.3 Beach profiles – Constant total energy: H_s = 3.53m, $T_{p(swell)}$ = 11s (Tests 6-10)

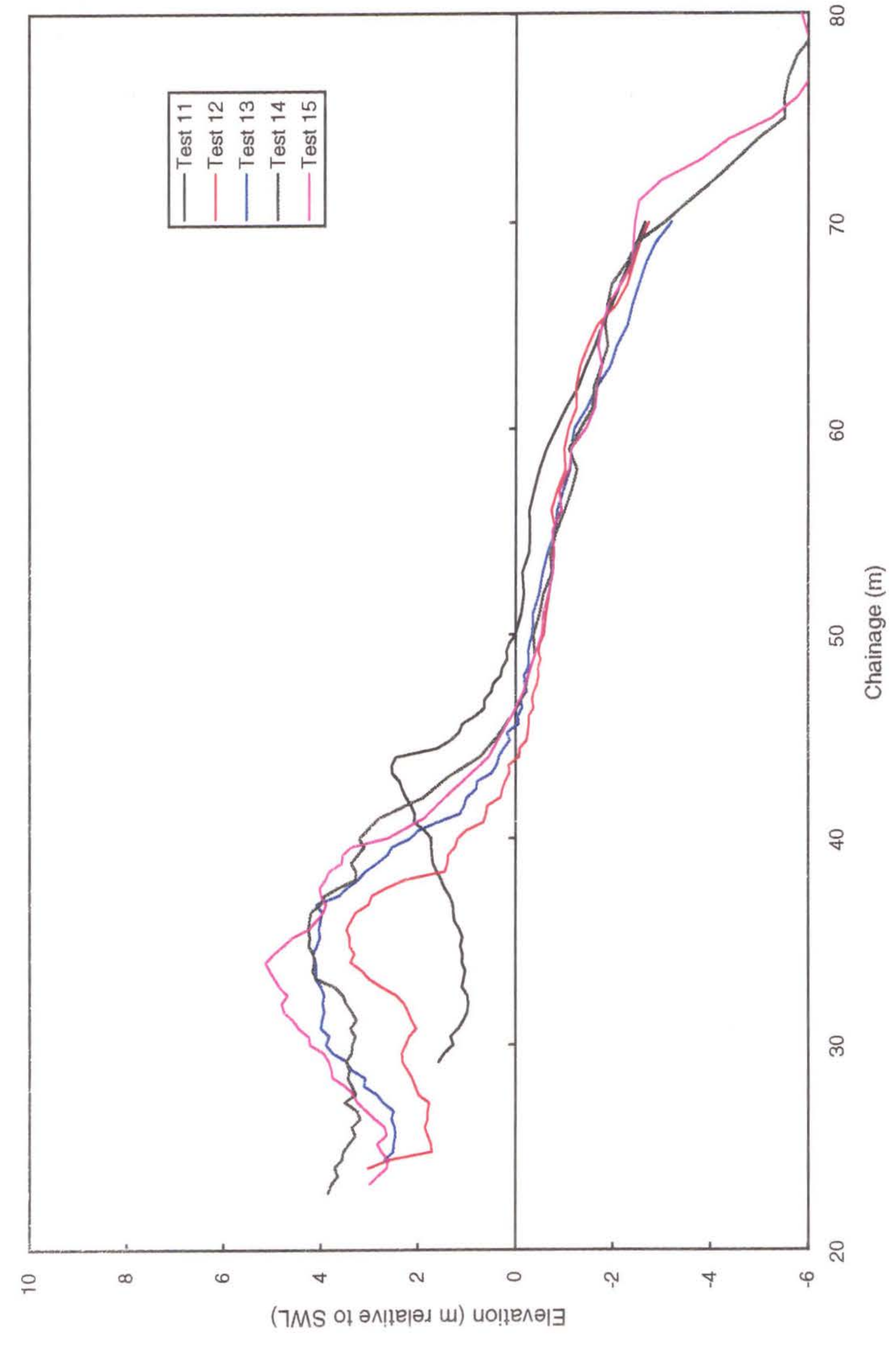


Figure 6.4 Beach profiles – Constant total energy: H_s = 2.12m, $T_{p(swell)}$ = 19s (Tests 11-15)

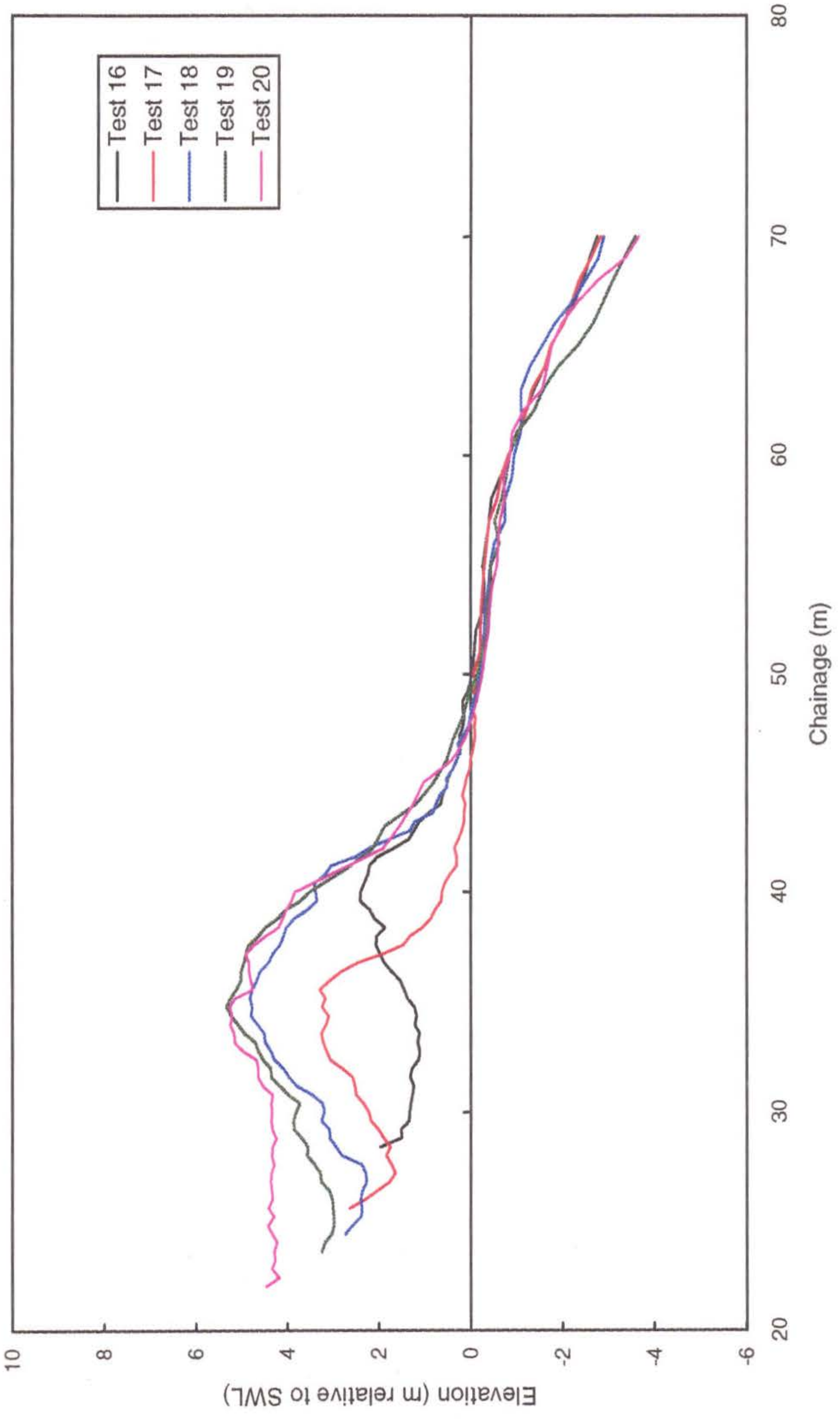


Figure 6.5 Beach profiles – Constant total energy: H_s = 2.83m, $T_{p(swell)}$ = 14s (Tests 16-20)

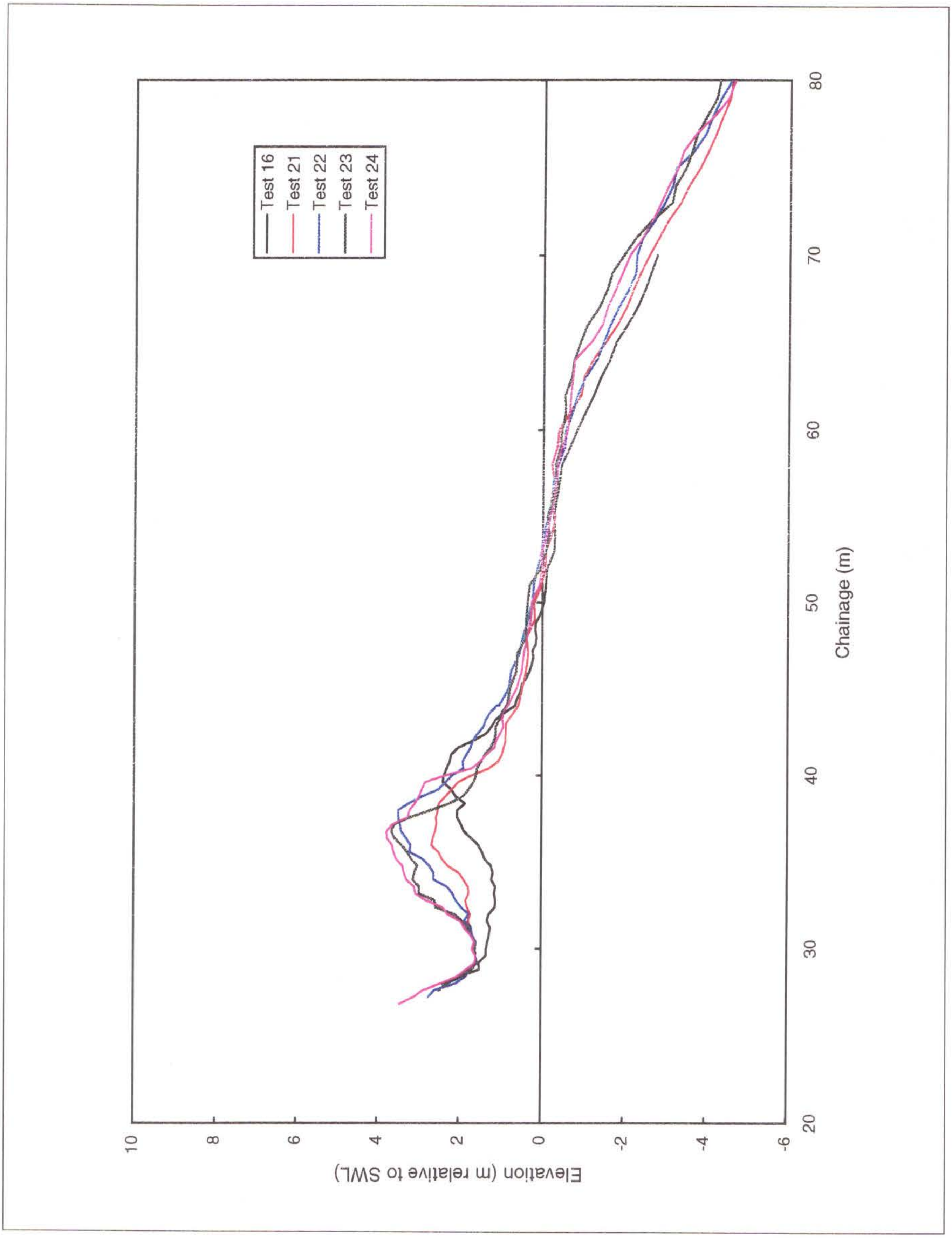


Figure 6.6 Beach profiles – Constant total energy: H_s = 2.83m, $T_{p(swell)}$ = 11s (Tests 16 and 21-24)

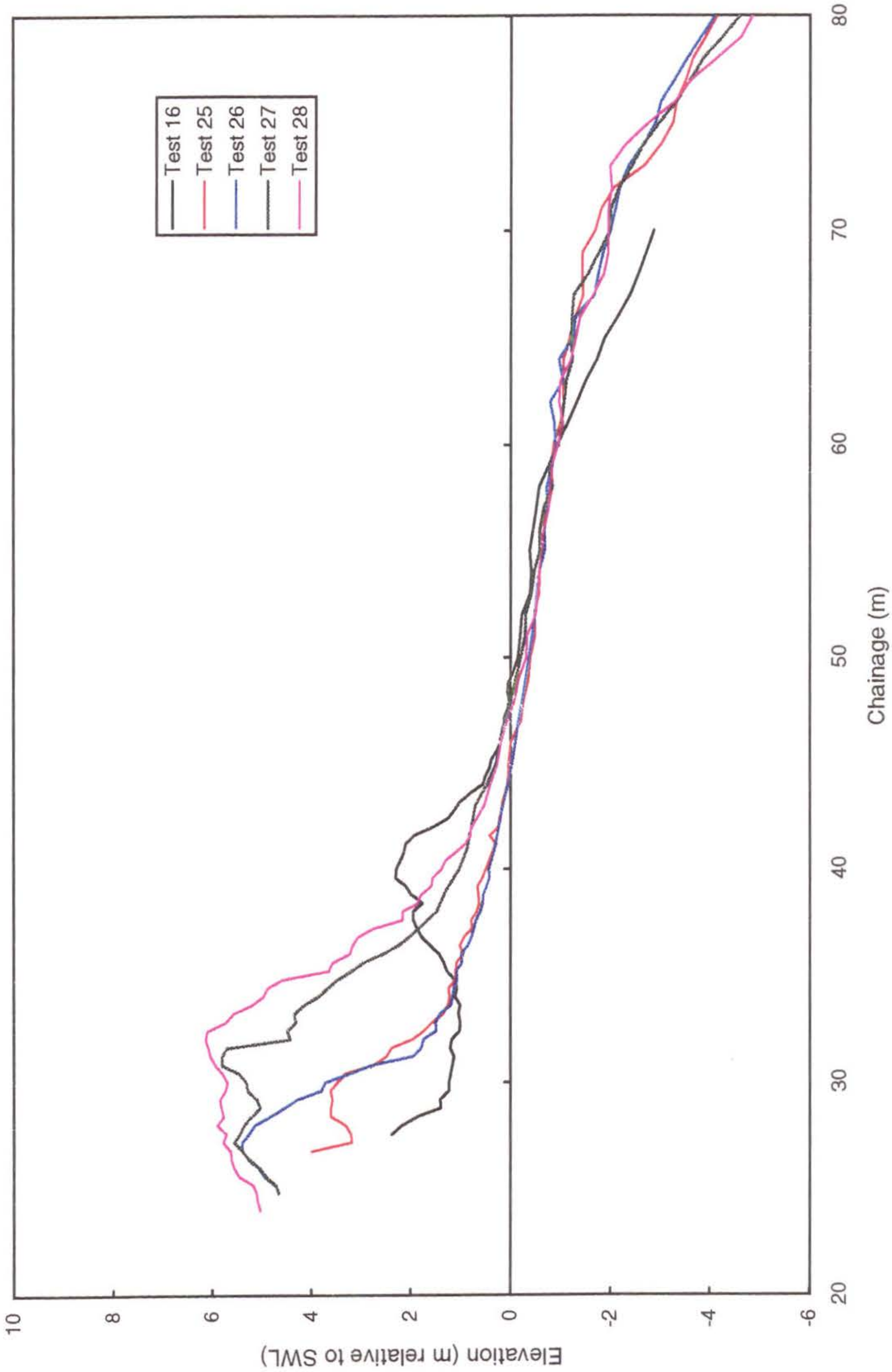


Figure 6.7 Beach profiles – Constant total energy: $H_s = 2.83m$, $T_{p(swell)} = 19s$ (Tests 16 and 25-28)

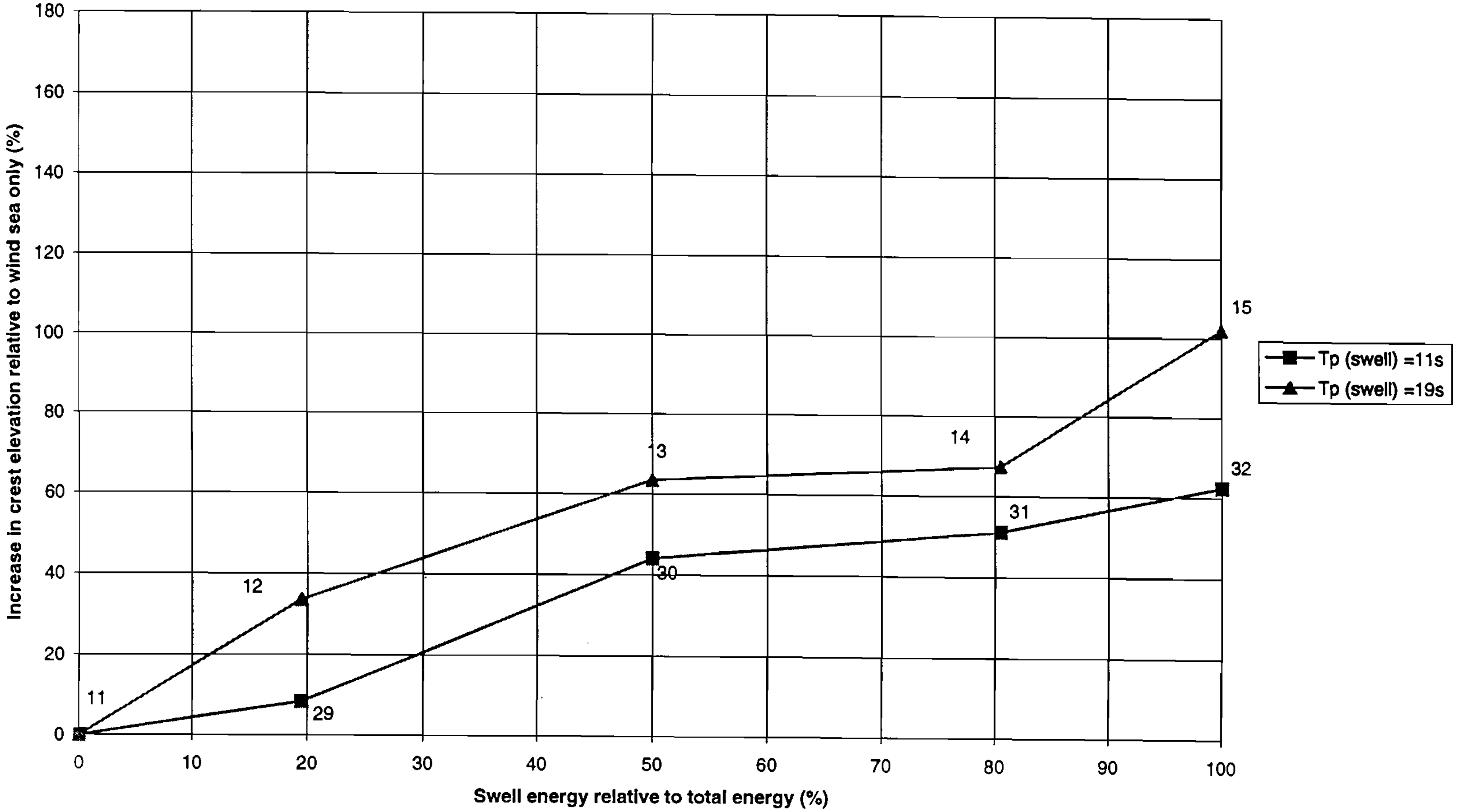


Figure 6.8 Swell influence on crest elevation: H_s = 2.12m

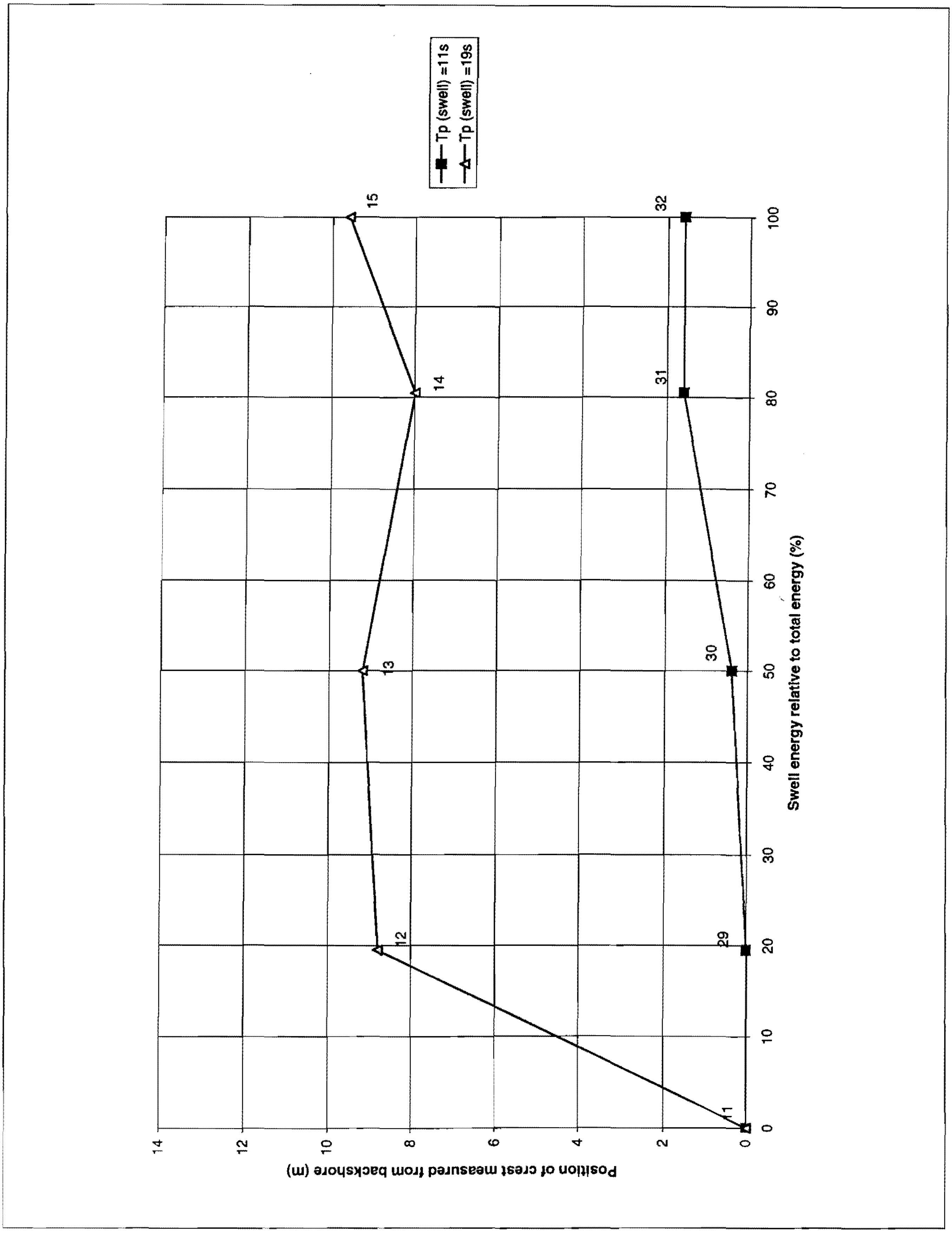


Figure 6.9 Swell influence on crest cut-back: H_s = 2.12m

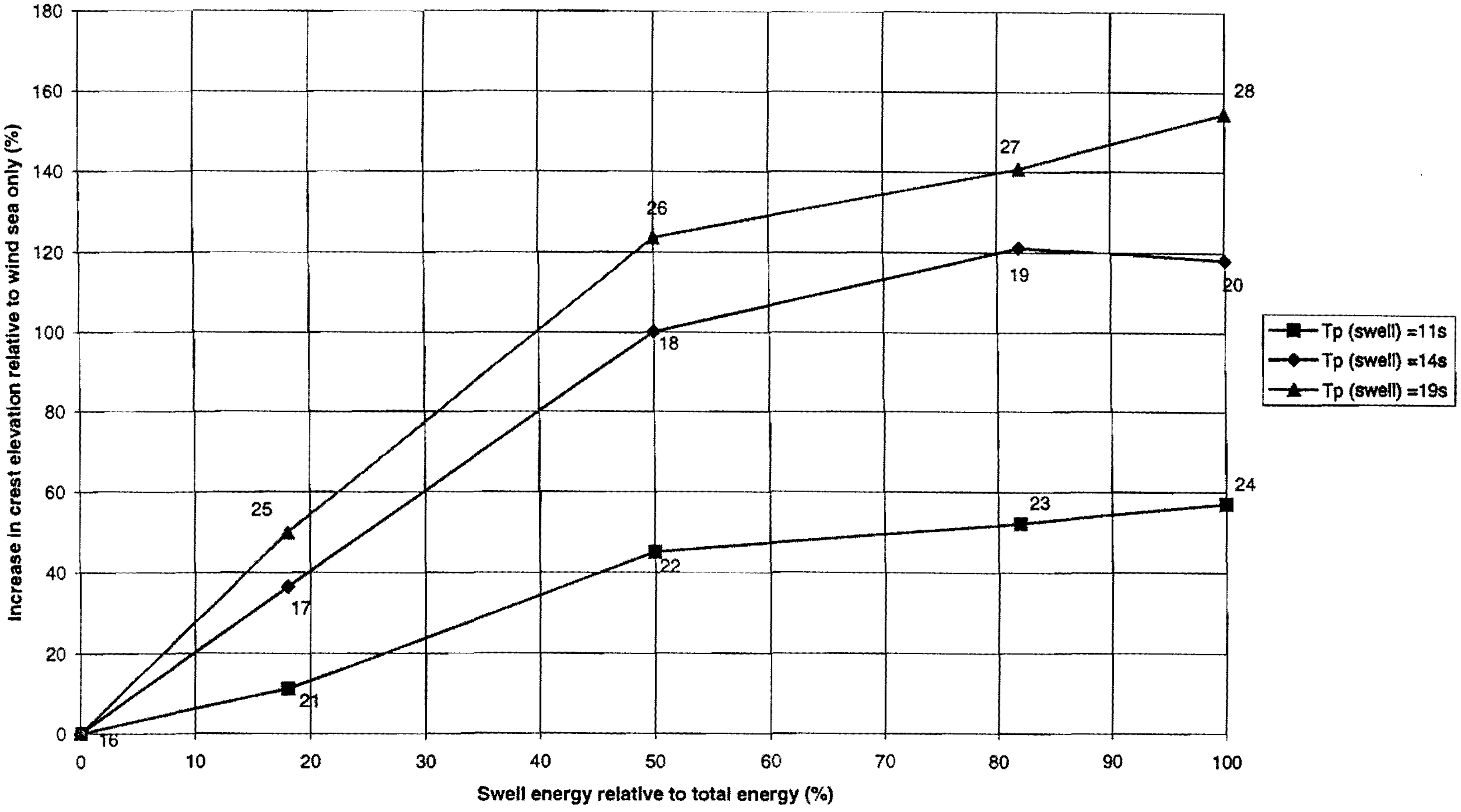


Figure 6.10 Swell influence on crest elevation: H_s = 2.83m

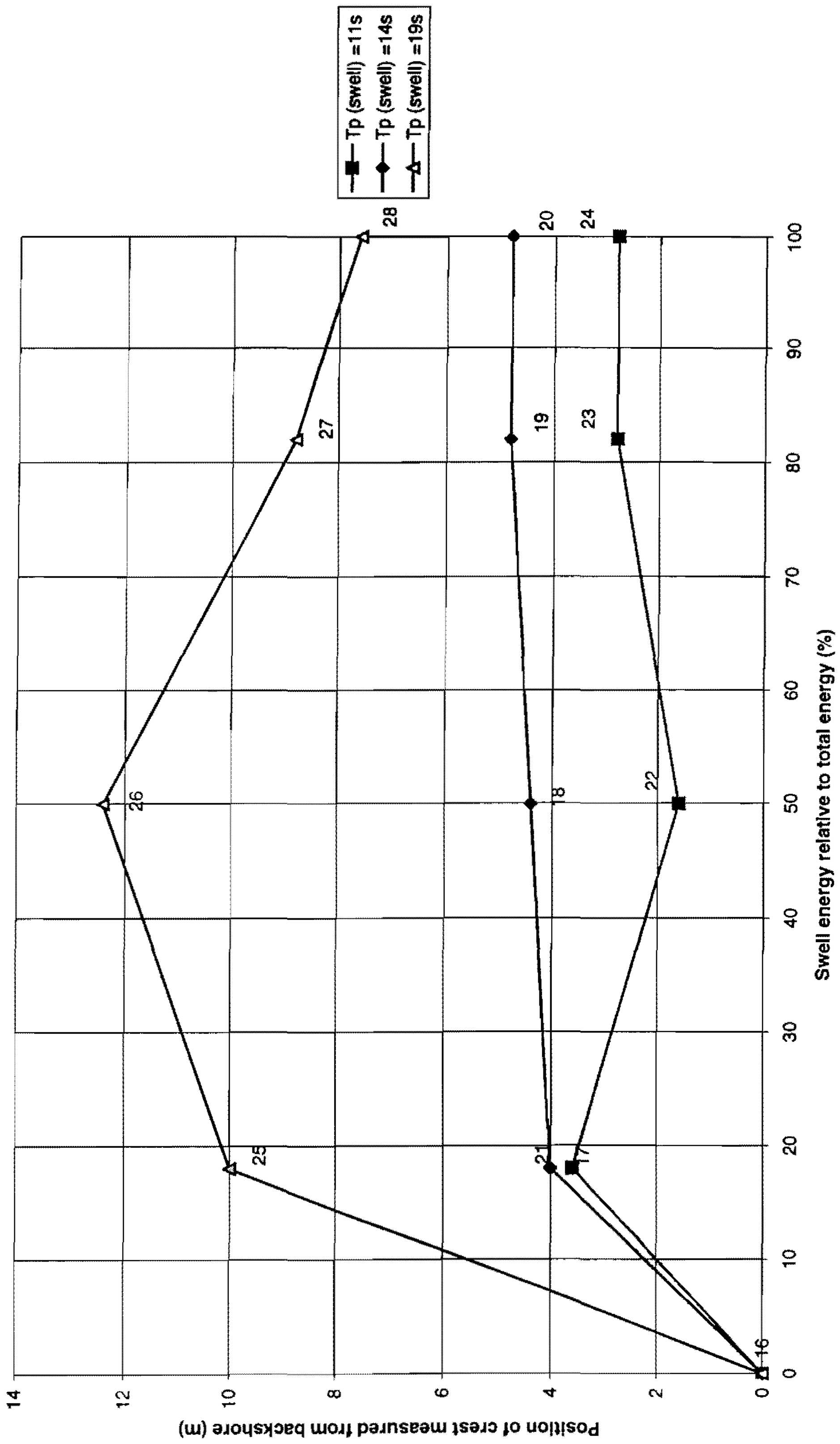


Figure 6.11 Swell influence on crest cut-back: H_s = 2.83m

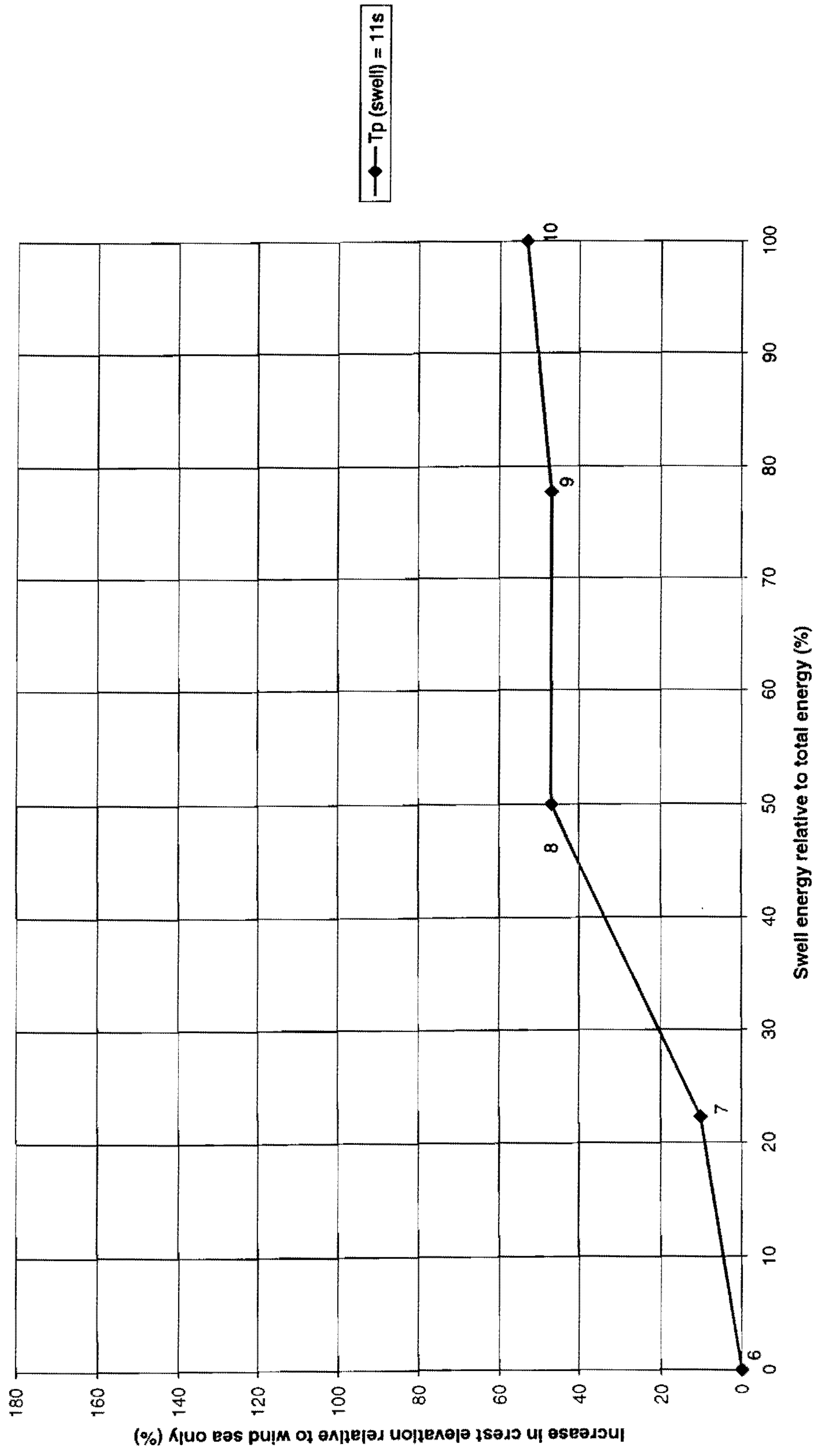


Figure 6.12 Swell influence on crest elevation: H_s = 3.53m

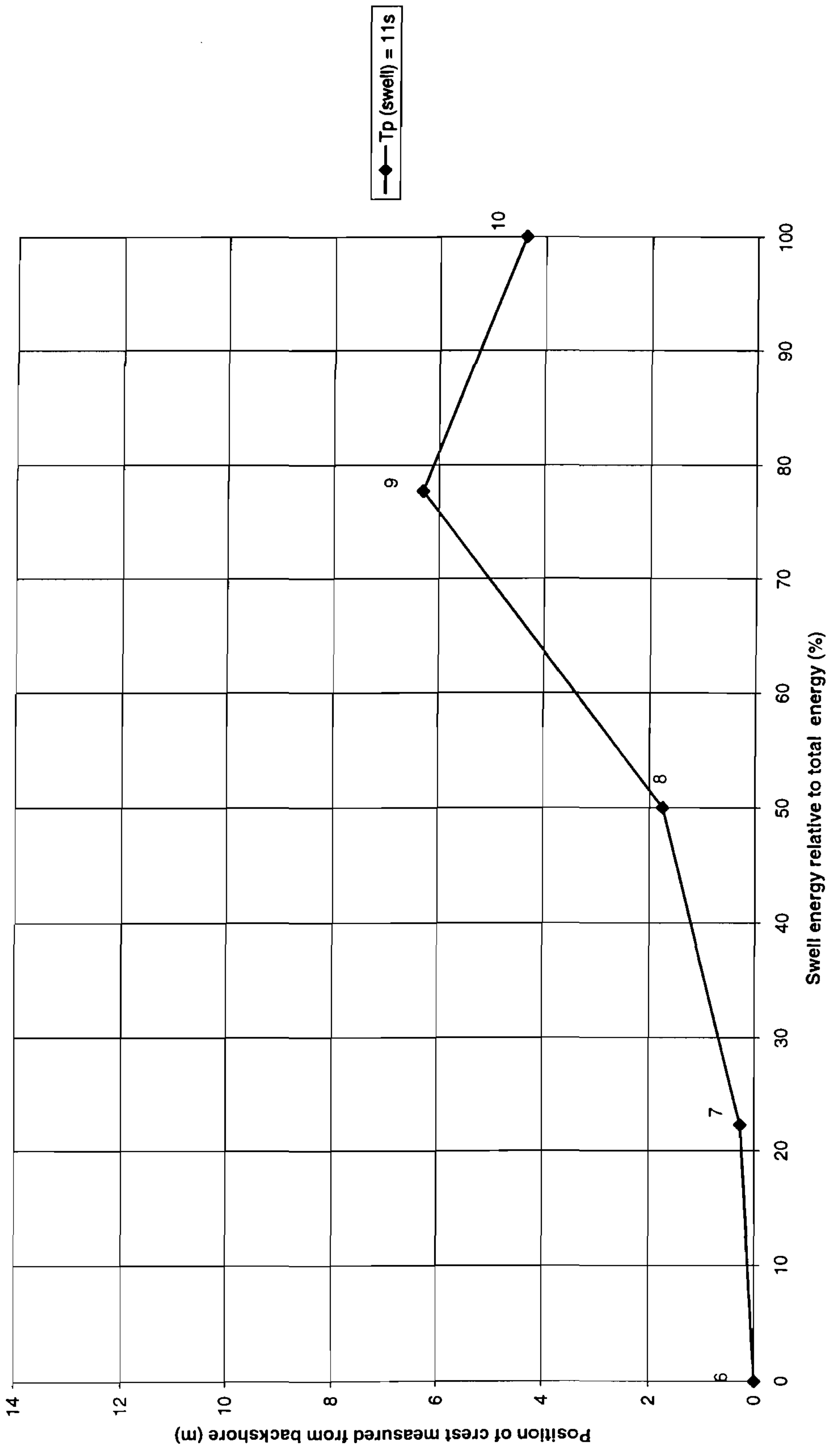


Figure 6.13 Swell influence on crest cut-back: H_s = 3.53m

Plates

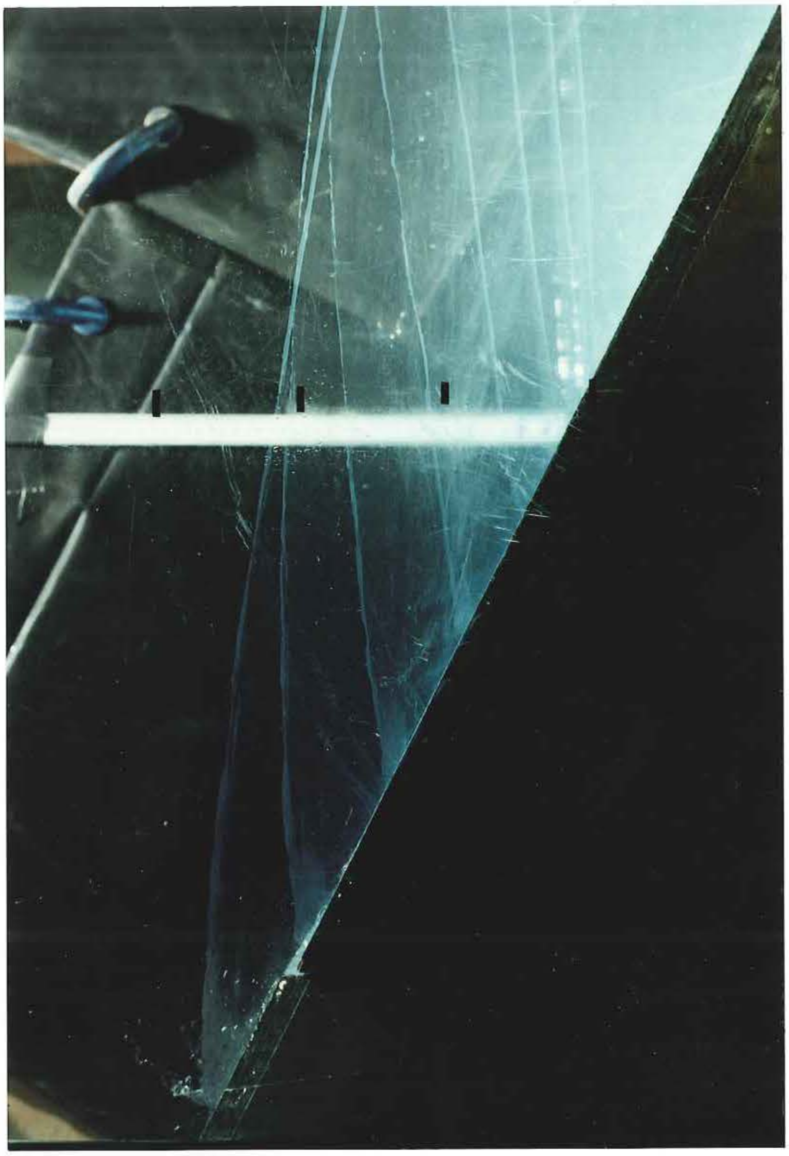


Plate 1 Non-overtopping 1:2 seawall, H=2m

Plate 2 Overtopping 1:2 seawall, H=2.4m

Appendices

Appendix 1

Summary of tests on structures

Appendix 1 Summary of tests on structure

1:50 seabed slope

Condition	SWL (m)	s_{mo}	H_{so} (m)	T_{mo} (s)	Overtopping discharge			Overtopping velocity			Reflections				Pressures on walls			Run-up/down		Armour Movements	Transmissions				Calibration Source
					1:2	1:4	1:2 berm	1:2	1:4	1:2 berm	1:2	1:4	1:2 berm	Vertical	1:2	1:4	Vertical	1:2	1:4	1:2	1:2	1:4	1:2 berm	Vertical	
UNI-MODAL WAVES																									
0a2	12	0.02	1.58	7.17																					3a
0b2	12	0.02	2.06	8.08																					3a
0c2	12	0.02	2.5	8.73																					3a
0d2/4e	12	0.02	2.91	10.16	x	x					x	x			x	x		x	x						3a
0e2	12	0.02	3.52	10.33																					3a
0f2	12	0.02	4.18	10.62	x	x					x	x		x	x	x	x	x	x					x	3a
0g2	12	0.02	5.17	11.07																					3a
0a4	12	0.04	1.58	4.88							x	x						x	x						3a
0b4/3a	12	0.04	2.26	6.18							x	x						x	x						3a
0c4	12	0.04	2.66	6.28	x	x					x	x		x	x	x	x	x	x					x	3a
0d4	12	0.04	3.14	7.05	x	x					x	x			x	x		x	x						3a
0e4	12	0.04	3.66	7.61																					3a
0f4	12	0.04	4.03	8.15	x	x					x	x		x	x	x	x	x	x					x	3a
0g4	12	0.04	4.6	8.45																					3a
0a6	12	0.06	1.54	4.12																					3a
0b6	12	0.06	2.12	4.73																					3a
0c6	12	0.06	2.66	5.4																					3a
0d6/2a	12	0.06	2.98	6.17																					3a
0e6/1a	12	0.06	3.71	6.25																					3a
0f6	12	0.06	4.23	6.72																					3a
0g6/4a	12	0.06	4.63	7.2																					3a
0a2	14	0.02	1.49	7.04	x			x	x	x	x	x	x		x			x	x		x	x	x		3a
0b2	14	0.02	1.88	8.1	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		3a
0c2	14	0.02	2.36	8.88	x			x	x	x	x	x	x		x			x	x	x	x	x	x		3a
0d2/4e	14	0.02	2.73	10.17	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		3a
0e2	14	0.02	3.38	10.57				x	x	x	x	x	x					x	x	x	x	x	x		3a
0f2	14	0.02	3.99	11.1	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		3a
0g2	14	0.02	4.8	11.35				x	x	x			x								x	x	x		3a

0a4	14	0.04	1.53	4.82					x	x		x			x	x	x					3a
0b4/3a	14	0.04	2.21	6.11	x	x			x	x			x	x		x	x	x				3a
0c4	14	0.04	2.47	6.24	x	x			x	x			x	x		x	x	x				3a
0d4	14	0.04	3.03	7.1	x	x			x	x		x	x	x	x	x	x	x			x	3a
0e4	14	0.04	3.53	7.75	x	x			x	x			x	x		x	x	x				3a
0f4	14	0.04	3.82	8.09	x	x			x	x		x	x	x	x	x	x	x			x	3a
0g4	14	0.04	4.38	8.58	x	x			x	x			x	x		x	x					3a
0a6	14	0.06	1.48	4.05					x	x						x	x					3a
0b6	14	0.06	2.04	4.13	x				x	x			x			x	x					3a
0c6	14	0.06	2.51	5.35					x	x						x	x				x	3a
0d6/2a	14	0.06	2.77	6.09	x	x			x	x		x	x	x	x	x	x					3a
0e6/1a	14	0.06	3.53	6.22					x	x						x	x					3a
0f6	14	0.06	4.01	6.71	x	x			x	x		x	x	x	x	x	x				x	3a
0g6/4a	14	0.06	4.46	7.28												x	x					3a
0a2	16	0.02	1.5	6.9				x			x									x		2
0b2	16	0.02	2	8				x			x									x		2
0c2	16	0.02	2.5	8.9				x			x									x		2
0d2	16	0.02	2.76	10.0				x			x									x		2
0e2	16	0.02	3.5	10.6				x			x									x		2
0f2	16	0.02	4	11.3				x			x									x		2
0g2	16	0.02	4.5	12							x									x		1a
0c4	16	0.04	2.5	6.3							x							x				2
0d4	16	0.04	3	6.9							x							x				2
0e4	16	0.04	3.5	7.5							x							x				2
0f4	16	0.04	4	8							x							x				2
BI-MODAL WAVES																						
1a	14		3.53	6.22	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	3a
1b	14		3.41	6.8	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	3a
1c	14		3.45	7.45	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	3a
1d	14		3.43	8.27	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	3a
1e	14		3.52	9.49	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	3a
2a	14		2.77	6.09	x	x			x	x		x	x	x	x						x	3a
2a1	14		2.87	6.22	x	x			x	x			x	x								3a
2a2	14		2.79	6.51	x	x			x	x			x	x								3a
2b	14		2.65	6.81	x	x			x	x		x	x	x	x						x	3a

Appendix 1 *Continued*

2b3	14	2.57	7.44	x	x			x	x			x	x								3a
2c	14	2.64	8.57	x	x			x	x			x	x								3a
2d	14	2.68	10.1	x	x			x	x			x	x				x				3a
2e	14	2.86	11.61	x	x			x	x			x	x								3a
3a	14	2.21	6.11	x	x			x	x			x	x		x	x					3a
3b	14	1.85	7.24	x	x			x	x			x	x		x	x					3a
3c	14	1.87	9.2	x	x			x	x			x	x		x	x					3a
3d	14	1.84	11.9	x	x			x	x			x	x		x	x					3a
3e	14	2.08	15.13	x	x			x	x			x	x		x	x					3a
4a	14	4.46	7.28	x	x	x	x	x	x	x		x	x				x	x	x		
4b	14	4.21	7.15	x	x	x	x	x	x	x		x	x				x	x	x		3a
4c	14	3.71	6.95	x	x	x	x	x	x	x		x	x				x		x		3a
4d	14	3.62	7.2	x	x	x	x	x	x	x		x	x				x	x	x		3a
4e	14	2.73	10.17	x	x	x	x	x	x	x		x	x				x	x	x		3a
5b	14	4	7.05	x	x			x	x			x	x		x	x					3a
5c	14	3.55	6.7	x	x			x	x			x	x		x	x					3a
5d	14	2.8	6.25	x	x			x	x		x	x	x	x	x	x				x	3a
5e	14	1.37	12.55	x	x			x	x			x	x		x	x					3a
6b	14	3.88	6.84	x	x			x	x			x	x								3a
6c	14	3.35	6.3	x	x			x	x			x	x								3a
6d	14	2.61	5.72	x	x			x	x		x	x	x	x						x	3a
6e	14	0.7	17.2																		3a
1a	16	3.76	6.23	x			x	x		x		x			x	x			x		3a
1b	16	3.3	6.79	x	x		x	x	x	x		x	x		x	x			x		3a
1c	16	3.35	7.74	x	x		x	x	x	x		x	x		x	x			x		3a
1d	16	3.34	8.68	x	x		x	x	x	x		x	x		x	x			x		3a
1e	16	3.78	9.55	x			x	x		x		x							x		3a
2a	16	3	6.15	x	x			x	x			x	x								3a
2a1	16	2.76	6.34	x	x			x	x			x	x								3a
2a2	16	2.64	6.44	x	x			x	x			x	x								3a
2b	16	2.54	6.84	x	x			x	x			x	x								3a
2b3	16	2.47	7.42	x	x			x	x			x	x								3a
2c	16	2.55	8.64	x	x			x	x			x	x								3a
2d	16	2.6	10.45	x	x			x	x			x	x								3a
2e	16	3.09	11.86	x	x			x	x			x	x								3a

Appendix 1 *Continued*

3a	16	2.36	6.1	x	x				x	x		x	x		x	x			3a
3b	16	1.73	7.38	x	x				x	x		x	x		x	x			3a
3c	16	1.81	9.38	x	x				x	x		x	x		x	x			3a
3d	16	1.8	12.37	x	x				x	x		x	x		x	x			3a
3e	16	2.32	16	x	x				x	x		x	x						3a
4a	16	4.84	7.3	x				x	x		x	x						x	3a
4b	16	4.04	7.15					x			x							x	3a
4c	16	3.53	7	x	x			x	x	x	x	x	x					x	3a
4d	16	3.61	7.6	x	x			x	x	x	x	x	x					x	3a
4e	16	2.9	10.4		x			x		x	x		x					x	3a
5b	16	3.78	6.98						x	x					x	x			3a
5c	16	3.35	6.64	x	x				x	x		x	x		x	x			3a
5d	16	2.65	6.41	x	x				x	x		x	x		x	x			3a
5e	16	1.45	12.95	x	x				x	x		x	x		x	x			3a
6b	16	3.66	6.81		x					x			x						3a
6c	16	3.14	6.62	x	x				x	x		x	x						3a
6d	16	2.41	5.7	x	x				x	x		x	x						3a
6e	16	0.59	17.61	x	x				x	x		x	x						3a
	SOLITARY WAVES																		
Sa	16	1.4						x											1a
Sb	16	2						x											1a
Sc	16	2.4						x											1a
Sa	14	1.4				x	x	x						x					1a
Sb	14	2				x	x	x						x					1a
Sc	14	2.4				x	x	x						x					1a
Sd	14	3				x													1a
Sa	12	1.4				x	x							x					1a
Sb	12	2				x	x							x					1a
Sc	12	2.4				x	x							x					1a
Sd	12	3				x	x							x					1a
Sa	10	1.4				x	x												1a
Sb	10	2				x	x												1a
Sc	10	2.4				x	x												1a
Sd	10	3				x	x												1a

Appendix 1 *Continued*

1:10 seabed slope

Condition	SWL (m)	s_{mo}	H_{so} (m)	T_{mo} (s)	Overtopping discharge 1:2	Overtopping discharge 1:4	Overtopping discharge 1:2 berm	Overtopping velocity 1:2	Overtopping velocity 1:4	Overtopping velocity 1:2 berm	Reflections 1:2	Reflections 1:4	Reflections 1:2 berm	Reflections Vertical	Pressures on walls 1:2	Pressures on walls 1:4	Pressures on walls Vertical	Run-up/down 1:2	Run-up/down 1:4	Armour Movements 1:2	Transmissions 1:2	Transmissions 1:4	Transmissions 1:2 berm	Transmissions Vertical	Calibration Source
UNI-MODAL WAVES																									
0f2	12	0.02	3.56	10.91	x	x		x	x		x	x		x	x	x	x							x	3b
0c4	12	0.04	2.44	6.29	x	x		x	x		x	x		x	x	x	x							x	3b
0f4	12	0.04	3.85	8.12	x	x		x	x		x	x		x	x	x	x							x	3b
0b2	14	0.02	1.94	8.10		x		x	x		x	x		x	x	x	x			x				x	3b
0c2	14	0.02	2.5	8.9																x					2
0d2/4e	14	0.02	2.69	10.02	x	x		x	x		x	x		x	x	x	x			x				x	3b
0e2	14	0.02	3.5	10.60																x					2
0f2	14	0.02	3.76	11.19	x	x		x	x		x	x		x	x	x	x			x				x	3b
0a4	14	0.04	1.53	4.84	x	x		x	x		x	x		x	x	x	x							x	3b
0b4	14	0.04	2.12	6.10																x					2
0c4	14	0.04	2.5	6.3																x					2
0d4	14	0.04	3.00	6.96	x	x		x	x		x	x		x	x	x	x			x				x	3b
0e4	14	0.04	3.5	7.5																x					2
0f4	14	0.04	3.74	8.34	x	x		x	x		x	x		x	x	x	x			x				x	3b
0d6/2a	14	0.06	2.73	6.15	x	x		x	x		x	x		x	x	x	x							x	3b
0f6	14	0.06	3.95	6.65	x	x		x	x		x	x		x	x	x	x							x	3b
0c4	16	0.04	2.5	6.3																x					2
0d4	16	0.04	3	6.9																x					2
0e4	16	0.04	3.5	7.5																x					2
0f4	16	0.04	4	8																x					2
BI-MODAL WAVES																									
1a	14		3.47	6.26	x	x		x	x		x	x			x	x				x					3b
1b	14		3.33	6.81	x	x		x	x		x	x			x	x				x					3b
1c	14		3.06	7.68	x	x		x	x		x	x			x	x				x					3b
1d	14		3.34	8.53	x	x		x	x		x	x			x	x				x					3b
1e	14		3.47	9.47	x	x		x	x		x	x			x	x				x					3b

2a	14	2.73	6.15	x	x	x	x	x	x	x	x					3b
2b	14	2.65	6.92	x	x	x	x	x	x	x	x					3b
2d	14	2.68	10.10											x		2
4a	14	4.40	7.00											x		2
4b	14	4.21	7.15											x		2
4c	14	3.71	6.95											x		2
4d	14	3.62	7.20											x		2
4e	14	2.76	10											x		3b
5d	14	2.79	6.53	x	x	x	x	x	x	x	x					3b
6d	14	2.53	5.82	x	x	x	x	x	x	x	x					3b
	SOLITARY WAVES															
Sa	14	1.4				x				x						1a
Sb	14	2				x				x		x				1a
Sc	14	2.4				x				x		x				1a
Sd	14	3														1a
Sa	12	1.4				x				x						1a
Sb	12	2				x				x						1a
Sc	12	2.4				x				x						1a
Sd	12	3				x				x						1a

Appendix 1 *Continued*

1:20 seabed slope

Condition	SWL (m)	s_{mo}	H_{so} (m)	T_{mo} (s)	Overtopping discharge			Overtopping velocity			Reflections				Pressures on walls			Run-up/down		Armour Movements	Transmissions				Calibration Source
					1:2	1:4	1:2 berm	1:2	1:4	1:2 berm	1:2	1:4	1:2 berm	Vertical	1:2	1:4	Vertical	1:2	1:4	1:2	1:2	1:4	1:2 berm	Vertical	
UNI-MODAL SPECTRA																									
0a2	12	0.02	1.54	7.04																					3b
0b2	12	0.02	1.94	8.01																					3b
0d2/4e	12	0.02	2.80	10.09																					3b
0f2	12	0.02	4.11	10.67	x	x		x	x		x	x		x	x	x	x								3b
0a4	12	0.04	1.55	4.86																					3b
0c4	12	0.04	2.47	6.39	x	x		x	x		x	x		x	x	x	x								3b
0d4	12	0.04	3.10	7.12																					3b
0f4	12	0.04	4.00	7.99	x	x		x	x		x	x		x	x	x	x								3b
0d4	12	0.04	2.84	6.15																					3b
0f4	12	0.04	4.05	6.70																					3b
0a2	14	0.02	1.50	6.96																					3b
0b2	14	0.02	1.80	8.01	x	x		x	x		x	x		x	x	x	x								3b
0d2/4e	14	0.02	2.52	9.97	x	x		x	x		x	x		x	x	x	x								3b
0f2	14	0.02	3.81	11.49	x	x		x	x		x	x		x	x	x	x								3b
0a4	14	0.04	1.49	4.78	x	x		x	x		x	x		x	x	x	x								3b
0d4	14	0.04	2.80	7.07	x	x		x	x		x	x		x	x	x	x								3b
0f4	14	0.04	3.99	8.13	x	x		x	x		x	x		x	x	x	x								3b
0d6/2a	14	0.06	2.56	6.17	x	x		x	x		x	x		x	x	x	x								3b
0f6	14	0.06	3.76	6.64	x	x		x	x		x	x		x	x	x	x								3b
BI-MODAL WAVES																									
1a	14		3.43	6.22	x	x		x	x		x	x		x	x	x	x								3b
1b	14		3.35	6.70	x	x		x	x		x	x		x	x	x	x								3b
1c	14		3.39	7.51	x	x		x	x		x	x		x	x	x	x								3b
1d	14		3.29	8.35	x	x		x	x		x	x		x	x	x	x								3b
1e	14		3.48	9.53	x	x		x	x		x	x		x	x	x	x								3b

Appendix 1 *Continued*

2a	14	2.61	6.14	x	x	x	x	x	x	x	x	x	x				3b
2b	14	2.51	6.82	x	x	x	x	x	x	x	x	x	x				3b
3a	14	2.25	6.15														3b
3b	14	1.93	7.45														3b
3c	14	1.89	9.00														3b
3d	14	1.94	11.77														3b
3e	14	2.27	14.90														3b
5b	14	3.81	7.00														3b
5c	14	3.35	6.69														3b
5d	14	2.78	6.51	x	x	x	x	x	x	x	x	x	x				3b
5e	14	1.48	12.36														3b
6d	14	2.47	5.85	x	x	x	x	x	x	x	x	x	x				3b
SOLITARY WAVES																	
Sa	14	1.4				x							x				1a
Sb	14	2				x							x				1a
Sc	14	2.4				x							x				1a
Sd	14	3															1a

Appendix 1 *Continued*

1:7 seabed slope

Condition	SWL (m)	s_{mo}	H_{so} (m)	T_{mo} (s)	Overtopping discharge			Overtopping velocity			Reflections				Pressures on walls			Run-up/down		Armour Movements	Transmissions				Calibration Source
					1:2	1:4	1:2 berm	1:2	1:4	1:2 berm	1:2	1:4	1:2 berm	Vertical	1:2	1:4	Vertical	1:2	1:4	1:2	1:2	1:4	1:2 berm	Vertical	
	UNI-MODAL WAVES																								
0f2	12.00	0.02	4.18	10.69	X			x			x			x	x		x							x	2
0c4	12.00	0.04	2.66	6.30	X			x			x			x	x		x							x	2
0f4	12.00	0.04	4.00	7.99	X			x			x			x	x		x							x	2
0b2	14.00	0.02	1.94	8.13	X			x			x			x	x		x							x	2
0d2/4e	14.00	0.02	1.72	9.99	X			x			x			x	x		x							x	2
0f2	14.00	0.02	4.14	11.38	X			x			x			x	x		x							x	2
0a4	14.00	0.04	1.55	4.75	X			x			x			x	x		x							x	2
0d4	14.00	0.04	3.07	7.02	X			x			x			x	x		x							x	2
0f4	14.00	0.04	4.01	8.18	X			x			x			x	x		x							x	2
0d6/2a	14.00	0.06	2.88	6.15	X			x			x			x	x		x							x	2
0f6	14.00	0.06	4.20	6.60	X			x			x			x	x		x							x	2
	BIMODAL WAVES																								
1a	14.00		3.56	6.30	X			x			x				x										2
1b	14.00		3.46	6.78	X			x			x				x										2
1c	14.00		3.55	7.52	X			x			x				x										2
1d	14.00		3.59	8.45	X			x			x				x										2
1e	14.00		3.71	9.41	X			x			x				x										2
2a	14.00		2.85	6.13	X			x			x				x										2
2b	14.00		2.73	6.86	X			x			x				x										2
5d	14.00		2.86	6.38	X			x			x				x										2
6d	14.00		2.60	5.83	X			x			x				x										2

1:7 seabed slope

SOLITARY WAVES										
Sa	14	1.4				x				1a
Sb	14	2				x				1a
Sc	14	2.4				x				1a
Sd	14	3								1a
Sa	12	1.4				x				1a
Sb	12	2				x				1a
Sc	12	2.4				x				1a
Sd	12	3				x				1a
Sa	10	1.4				x				1a
Sb	10	2				x				1a
Sc	10	2.4				x				1a
Sd	10	3				x				1a

Notes

Calibration source

1a	No calibration available
1b	Original calibration incorrect
2	Numerical model prediction (COSMOS 2d)
3a	Wave calibration (Original)
3b	Wave calibration (later re-done)

Solitary waves

a	Height =1.4m
b	Height =2.0m
c	Height =2.4m
d	Height =3.0m

File name extensions

Reflections, *.bin & *.ref
Run-up/down, transmission, *.raw, *.war, *.asc
Pressures, *cal.bin, *run.bin
Velocity, *.dat

Example Test names

1d275.*, bi-modal waves 1d, structure slope 1:2, SWL=0.7m(14m), 1:50 approach slope
0b2a275.*, uni-modal waves 0b2, 1:2 armoured slope, SWL=0.7m, 1:50 approach slope
Variations
c= slope with horizontal crest used during some velocity and overtopping tests
b= 1:2 bermed slope, r= 1:2 or 1:4 slope with crest & 1:2 rear, e= slope extended for run-up/down (no overtopping)
6 = SWL of 0.6m(12m), 7 = SWL of 0.7m(14m), 8 = SWL of 0.8m(16m)
5, 2, 1 & 7 approach slopes of 1:50, 1:20, 1:10 & 1:7

Appendix 2

Spectral analysis program

Appendix 2 Spectral analysis program

The micro-computer wave spectrum synthesiser produces a random wave spectrum by digitally filtering a white noise signal via a shift register. Varying lengths of wave sequence can be produced on this shift register which is used in conjunction with a clock pulse generator (Ref A.1). This allows a repeatable pseudo-random sequence of outputs to be generated creating sequences of waves with repeat times varying from a few minutes to several tens of years depending on the scaling parameters.

During wave calibrations a short repeating sequence of about 10 minutes duration was programmed on the computer using spectral analysis to define the waves parameters. This involves recording data over one complete wave generation sequence in order to eliminate any statistical uncertainty in the results. The water level at the twin wire wave probe (Ref A.2) is recorded by another micro-computer at every clock pulse of the synthesiser, typically ever 0.1-0.2 seconds. A maximum of 16384 data points can be collected from up to 24 probes at one time using this program. The analogue output of the wave probe, representing a displacement relative to the still water level, is first converted to a digital form by an A-D converter and then to an elevation in prototype metres via the model scale. Hence, at the end of sampling, a series of water level elevations are known for every clock pulse, i.e. up to 16384 points. This program then uses a Fast Fourier Transform technique (Ref A.3) to convert the time base data into the frequency domain and then splits the data into individual sine waves to extract the energy content of each frequency component. From this data the energy/frequency spectrum can be set up from which values of the significant wave height, H_s, and zero down-crossing period, T_m , can be defined using the moments of the spectrum.

References

A.1 Wave spectrum synthesisers. Technical Memo 1/1972, Hydraulics Research Station, June 1972.

A.2 Twin wire wave probe modules. Technical Memo 3/1974, Hydraulics Research Station, October 1974.

A.3 The fast Fourier transform with applications to spectral and cross spectral analysis. Internal Report 100, Hydraulics Research Station, December 1972.

Appendix 3

Armour scaling

Appendix 3 Armour scaling

The test fluid in the model will be fresh water with a specific weight of 1000 kg/m^3. In the prototype however the sea water will have a specific weight of approximately 1025 kg/m^3. This variation in water density means that armour units in the model will be more stable than in the prototype if simply scaled geometrically, thereby under-predicting armour stability. The density of the model armour units is therefore adjusted for correct stability using a relationship based upon Hudson's formula (Ref B1). A prototype density of 2650 kg/m^3 was assumed for the armour rocks. The correction factor for the density is calculated as M_2/M_1 from:

$$(M_1/\rho_1)^{0.333}\,(\rho_1/\rho_{SW}-1) = (M_2/\rho_2)^{0.333}\,(\rho_2/\rho_{FW}-1)$$

where M_1 = prototype mass (kg)
M_2 = model mass (kg)
ρ_1 = 2650 kg/m^3
ρ_2 = 2710 kg/m^3
ρ_{SW} = 1025 kg/m^3
ρ_{FW} = 1000 kg/m^3

From this it may be seen that a 2t rock in sea water has the same stability as a 1.6t rock in fresh water. All rock armour weights were scaled by this factor for the stability tests giving a scaling factor of:

$$1/20^3 \times 0.8149$$

B1. Coastal Engineering Research Centre (1984). Shore Protection Manual, Vol 2. US Govt. Printing Office, Washington.

Appendix 4

Core and underlayer scaling

Appendix 4 Core and underlayer scaling

For the rocks used to construct the internal structure of the breakwater, different scaling laws need to be considered to reflect permeability of the structure as opposed to stability. This reflected the different physical processes occurring within the structure as opposed to those due to direct wave action. At the scale selected for this model study, there may be conditions where the flow through the model underlayer is not completely turbulent. Scale effects would thus affect the flow of water through the underlayer and core. The sizes of material used to form the core/underlayer were therefore adjusted to ensure that their permeability gave correctly-scaled flow conditions. Work by Jensen and Klinting (Ref C1) suggest a method of compensating for scale effects by applying a correction factor. The calculation of the correction factor uses a special Reynolds number, ξ_p, which is defined as the ratio of turbulent to laminar hydraulic gradients. This Reynolds number is defined as:

$$\xi_p = \frac{\beta_o}{\alpha_o} \frac{1}{n_r(1-n_r)^2} \frac{U_p D}{\nu}$$

where α_0 and β_0 are empirical dimensionless coefficients, n_r is the porosity of the prototype rock mound, D is the diameter of the prototype rock (m), ν is the kinematic viscosity of water(m^2 s^{-1}) and U_p is the maximum water particle velocity in the prototype rock mound (m s^{-1}).

The ratio of the rock size in prototype to model, K, is then given by:

$$K = \frac{\xi_p}{2\lambda^{1/2}} \left[\left(1 + 4\lambda^{3/2} \frac{1+\xi_p}{\xi_p^2} \right)^{1/2} - 1 \right]$$

The porosity of model and prototype rock mounds will need to be the same to avoid changes in the potential storage volume.

Certain assumptions were made to enable the above equations to be used in calculating a correction factor. Experimental work by Engelund suggested values for the empirical coefficients of $\alpha_0 = 1500$ and $\beta_0 = 3.6$. The maximum prototype velocity in the mound was estimated at 0.5-1.0 m s^{-1} from some simple calculation of wave velocities and comparisons with velocities calculated by a simple mathematical model of flow in rubble. The porosity of the rock mound, n_r, was also estimated at 35-40%.

There is some scope for error in the calculation of the ratio of prototype to model rock size, K. A series of calculations were therefore completed to carry out sensitivity tests on the variables. These results of K gave a value of =28.2, slightly less than 29.04, the geometric scale and this was used for the preparation of the core and underlayers.

C1. Jensen, O J and Klinting, P (1983). 'Evaluation of Scale Effects in Hydraulic Models by Analysis of Laminar and Turbulent Flows'. Coastal Engineering, pp 319-329.

Appendix 5

Measurement and analysis of wave reflections

Appendix 5 Measurement and analysis of wave reflections

When an incoming wave impinges on a beach or structure it is partially reflected back out to sea. Were it is possible to generate and maintain a pure single wave, then the reflection coefficient of the structure would be given uniquely by:

$$C_r = H_r/H_i$$

where C_r is the reflection coefficient
H_r is the reflected wave height
H_i is the incident wave height

C_r takes a value between 0 when the wave energy is fully absorbed, and 1 for complete reflection, e.g. from a smooth vertical wall in deep water.

Incident and reflected wave energy spectra are usually determined in random wave models from measurements using two or three wave probes placed in a line normal to the incident wave front. The wave probes do not allow the direct measurement of incident and reflected wave energy, but these are calculated from the probe data using an analysis programme developed by Gilbert and Thompson (Ref 1), itself based on a method outlined by Kajima (Ref 2). Cross-spectral analysis between pairs of probes reveals the extent to which conditions at probe 2 (nearer the structure) are directly dependent upon the immediately preceding conditions at probe 1, and vice versa. The auto-spectral density for each probe (S_{11} and S_{22}) and the cross-spectral density (S_{12}) may be routinely derived from measurements using standard computer algorithms. The accuracy of the relationships between these functions and the incident and reflected wave spectra depend on x, the distance between the pair of probes. In order to prevent ambiguity, x must be between zero and half a wavelength, L. Also, to obtain an arithmetically reliable answer, sin kx should be greater than about 0.6, where the wave number is defined $k=2\pi/L$.

This method of analysis calculates the reflection coefficient for each of the frequency bands considered, valid over the range of frequencies related to the probe spacing and local water depth. Three probe spacings are commonly used and selected so that a complete range of valid incident and reflected wave energies are available for $0.5f_p$ - $2.0f_p$ where f_p is the frequency corresponding to the peak of the wave spectrum. Generally wave energy outside of these limits has little importance. If two or more spacings produce valid energies at the same frequency band then the energies are averaged.

In practice, however, the full range of valid input spectrum frequencies cannot always be covered with a single spacing using 2 wave probes. As a result it is standard practice at Wallingford to use three probes with different parts of the spectrum covered by the appropriate pair of probes.

The calibration program and the spectral analysis program used at Wallingford in the model tests requires the order and spacing of the probes and the water depth. Probes 1, 2 and 3 are progressively further away from the wavemaker and the probe spacing is defined as:

x_1 - the distance between probes 1 and 2
x_2 - the distance between probes 1 and 3
x_3 - the distance between probes 2 and 3

The water depth is taken as the depth at the intermediate probe. The analysis algorithm assumes constant depth at the site of the wave probes i.e. a horizontal seabed. Care should therefore be taken to locate the wave probes in an area where the seabed slope is mild. This requirement becomes less important with increasing water depth, i.e. deep water waves are not affected by the seabed topography. The wave probes should not be too close to the reflecting structure or the wave generator. The analysis algorithm assumes linear theory and care should be taken to ensure that the wave probes are not positioned in areas prone to wave breaking and that tests involving the measurement of wave reflections are not made with high sea states where wave breaking would be inevitable.

The reflection coefficient, C_r, is calculated using the following definition:-

$$C_r = H_r/H_i = (S_r/S_i)^{0.5}$$

where $S_r(f_r)$ is the total reflected wave energy which is dependant on the wave frequency of the reflected wave f_r;

$S_i(f_i)$ is the total incident wave energy which is dependant on the wave frequency of the incident wave f_i.

The calculation involves division by $\sin^2(kx)$, and hence becomes singular when $kx = n\pi$, $n = 0,1,2...$ This occurs because a cross spectrum calculation cannot distinguish direction when the recording stations are separated by integer multiples of half a wave length. Hence for a given probe spacing the results of a reflection analysis calculation are only valid over a limited range of frequencies. In practice it is wise to keep well away from the singular points so the normal practice is to set the frequency range by:

$$0.2\,\pi \le kx \le 0.8\,\pi \text{ and hence } \sin^2(kx) \ge 0.35$$

This reduces to a relationship for the valid range of x :

$$0.1L_s \le x \le 0.4L_s \text{ where } L_s \text{ is the local wavelength.}$$

The problems inherent in working at the upper and lower frequencies of the input wave spectrum where the spectral density becomes small are dealt with by limiting the valid frequencies to the range where the input spectral density is greater than 10% of the maximum. Equating this range to the valid calculation range given above allows the probe spacing appropriate to the spectrum to be computed.

It must be appreciated that this analysis technique assumes that energy is not shifted from one frequency band to any other. In some situations however, an incident long period may well give rise to a number of smaller and much shorter waves. If these short waves reflect, the analysis may calculate a greater coefficient of reflection for the high frequency short waves than is due to the incident waves of that frequency. For example, where waves break at or on the test slope, low frequency waves may reflect partially as high frequency waves. In these circumstances some measurements may suggest low values of C_r at the lower frequencies and high at the high values of C_r, frequencies. This shift of energy from low frequencies will probably only occur when long waves are of sufficient steepness to break, and not when long waves of relatively low steepness are present.

The HR method has recently been checked against the method of Davidson, Plymouth University, with extremely good agreement. The main differences were in the manner in which they reject data contaminated by singularities. Both methods were used to analyse waves reflected from armoured slopes in the same wave flume at Wallingford. These methods were compared by Allsop et al (Ref 3), and showed close agreement over the range tested, with regression coefficients r^2=0.97, suggesting that any error in C_r is likely to be less than 2-5%.

References

1 Gilbert, G and Thompson, D M (1978). Reflections in Random Waves, the Frequency Response Function Method. HR Wallingford Report IT 173.

2 Kajima, R (1969). Estimation of an Incident Wave Spectrum under the Influence of Reflection, Coastal Eng in Japan, Vol 12.

3 Allsop, N W H, McBride, M W and Colombo, D (1996). The reflection performance of vertical walls and 'low reflection' alternatives: results of wave flume tests. Paper 3.4 to 3rd MCS Workshop, Emmeloord, publn University of Hannover.

Appendix 6

Compact Disc index

Appendix 6 Compact Disc index

Seabed slope	***Structure***	***Data collected***	**CD No.**
1:50	Calibration	Wave measurements	0 , 1
	1: 2	Wave measurements	1 , 2 , 3 , 7
		Wave pressures	
		Wave reflections	
		Overtopping volumes	
		Overtopping wave by wave	
		Solitary wave measurements	
		Overtopping velocities	
		Overtopping wave heights	
	1: 4	Wave measurements	3, 4, 5, 6
		Wave pressures	
		Wave reflections	
		Overtopping volumes	
		Overtopping wave by wave	
	1: 4 + Extension	Wave measurements	6, 8, 9
		Run-up/run-down measurements	
		Wave reflections	
	1:4 + crest	Wave measurements	13
		Overtopping velocities	
		Overtopping wave heights	
	1:2 bermed	Wave measurements	14
		Run-up/run-down measurements	
		Overtopping velocities	
		Overtopping wave heights	
	1:2 + crest	Wave measurements	13
		Overtopping velocities	
		Overtopping wave heights	
	1: 2 + Extension	Wave measurements	8, 9
		Run-up/run-down measurements	
		Wave reflections	
	1: 2 Armoured	Cumulative armour movements sm=0.02 SWL=14m	11
		Cumulative armour movements sm=0.04 SWL=14m	
		Cumulative armour movements sm=0.04 SWL=16m	
		Individual armour movements, constant wave energy	
		Individual armour movements, constant wave period	
		Cumulative armour movements, constant swell-sea	
		Wave reflections	
	Vertical wall	Wave measurements	8, 9, 10, 14
		Wave pressures	
		Wave transmissions	
		Wave reflections	

Seabed slope	***Structure***	***Data collected***	**CD No.**
1:20	Vertical wall	Wave measurements	10,11,13
		Wave pressures	
		Wave transmissions	
		Wave reflections	
		Solitary waves measurements	
	Calibration	Wave measurements	(11)
			19
	1: 2 + Crest	Wave measurements	12,13
		Wave pressures	
		Wave reflections	
		Overtopping volumes	
		Overtopping wave by wave	
		Overtopping velocities	
		Overtopping wave heights	
		Solitary wave measurements	
	1: 2 Armoured	Cumulative armour movements sm=0.02 SWL=14m	14
		Cumulative armour movements sm=0.04 SWL=14m	
		Cumulative armour movements sm=0.04 SWL=16m	
		Individual armour movements, constant wave energy	
		Individual armour movements, constant wave period	
		Cumulative armour movements, constant swell-sea	
		Wave reflections	
	1: 4 + Crest	Wave measurements	13,14
		Wave pressures	
		Wave reflections	
		Overtopping volumes	
		Overtopping wave by wave	
		Overtopping velocities	
		Overtopping wave heights	

Seabed slope	*Structure*	*Data collected*	CD No.
1: 10	1: 4 + Crest	Wave measurements	14,15
		Wave pressures	
		Wave reflections	
		Overtopping volumes	
		Overtopping wave by wave	
		Overtopping velocities	
		Overtopping wave heights	
	1: 2 + Crest	Wave measurements	15,16
		Wave pressures	
		Wave reflections	
		Overtopping volumes	
		Overtopping wave by wave	
		Overtopping velocities	
		Overtopping wave heights	
	Calibration	Wave measurements	(16)
			19?
	Vertical wall	Wave measurements	17
		Wave pressures	
		Wave transmissions	
		Wave reflections	

Seabed slope	*Structure*	*Data collected*	CD No.
1: 7	Vertical wall	Wave measurements	18
		Wave pressures	
		Wave transmissions	
		Wave reflections	
	Calibration	Wave measurements	(18)
	1: 2 + Crest	Wave measurements	19
		Wave pressures	
		Wave reflections	
		Overtopping volumes	
		Overtopping wave by wave	
		Overtopping velocities	
		Overtopping wave heights	