

SCARCOST Experiments in the UK Coastal Research Facility

**Data on scour around a detached rubble mound
breakwater**

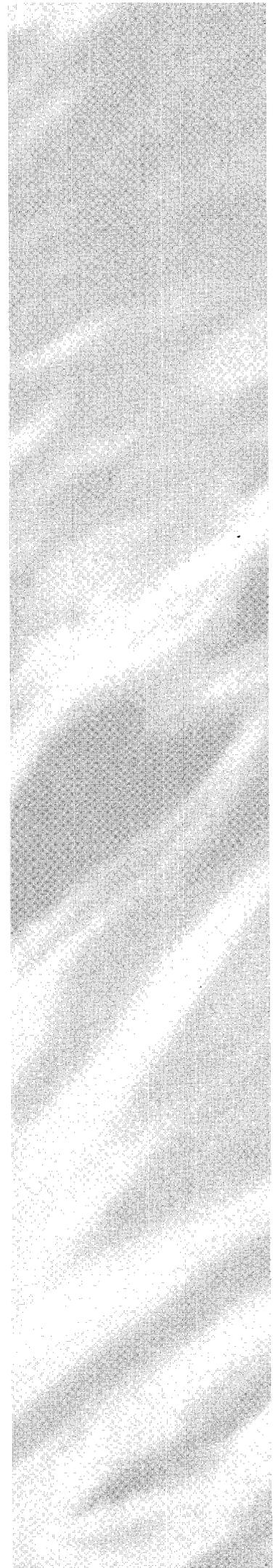
**J Sutherland
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**Report TR 98
December 1999**



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Contract

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Summary

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Data on scour around a detached rubble mound breakwater

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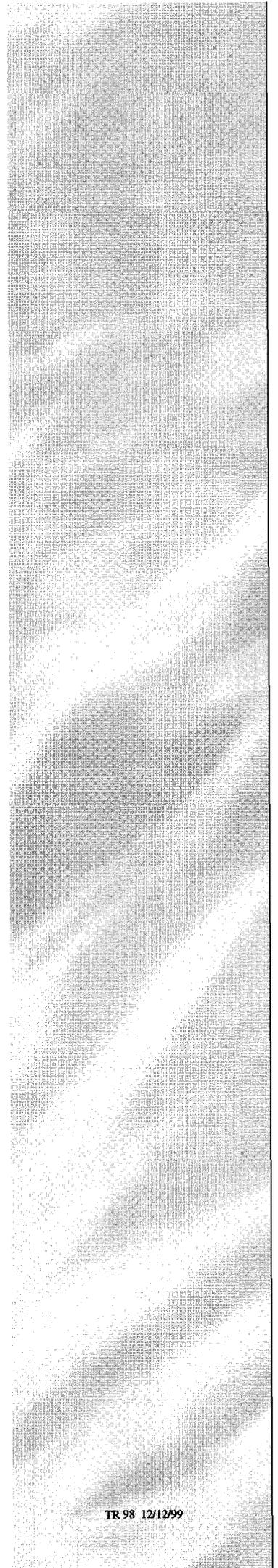
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A number of experiments on the scour and deposition around a single detached offshore rubble mound breakwater have been performed in the UK Coastal Research Facility (UKCRF) as part of the EU-funded project Scour Around Coastal Structures (SCARCOST; 1/9/1997 – 31/8/2000). The breakwater was situated near the centre of an initially flat 20cm deep sand bed, which extended for approximately 25m in the longshore direction and 6m in the cross-shore. The water depth at the breakwater was 30cm. The breakwater was 0.4m high with 1:2 (V:H) front and rear slopes and a crest width of 0.15m. It was constructed with 2 to 3 armour layers over a rock core and had a 4m long uniform central section and semicircular roundheads which extended for a further 0.9m each. At the offshore side of the sand bed was a smooth 1:20m concrete slope which extended for 4m down to a water depth of 0.5m. At the inshore end of the sand bed was a 1:6 absorbing flint beach to dissipate the incident wave energy.

A total of approximately 30,000 (average period) waves was run for each test case (with the exception of a short storm test being for the last case). The test conditions are listed in the following table with H_{m0} = incident wave spectral significant wave height (m), T_p = incident wave spectral peak period (s), α = incident offshore wave angle (degrees), U = free surface longshore current velocity (m/s) and P = width of scour protection layer (m) and N_{waves} the number of average-period waves in the experiment.

Test	H_{m0}	T_p	α	U	P	N_{waves}
1 or A	0.1	2.8	0	0	0	30000
5 or B	0.1	2.8	20	0.1	0	30000
3 or C	0.1	2.8	20	0	0	30000
6 or D	0.1	2.8	20	0	0.5	30000
2 or E	0.12	1.5	20	0	0.5	3000

The time-development of scour was measured by profiling along 10 lines a total of 6 times each during the experiment. The final bed profile was determined by profiling at almost 50 lines at the end of the experiment. This was taken to be close to the equilibrium scour depth that would be reached. The waves and currents were determined by measuring with wave gauges and Acoustic Doppler Velocimeters (ADV) at a large number of points around the structure and at some points away from the structure. Arrays of wave gauges in front of and behind the structure were used to determine its reflection characteristics.



Summary continued

This report describes the background to the experiment, presents details of how it was conducted and shows some of the results. The data takes up 7 CDs and the structure of the summary CD is described with information about the contents of the different directories. Further analysis of the data on the summary CD should be undertaken using this report. The data will become publicly available 6 months after the end of the project and may be obtained from the first author on payment of a handling charge for copying and distributing the CD.

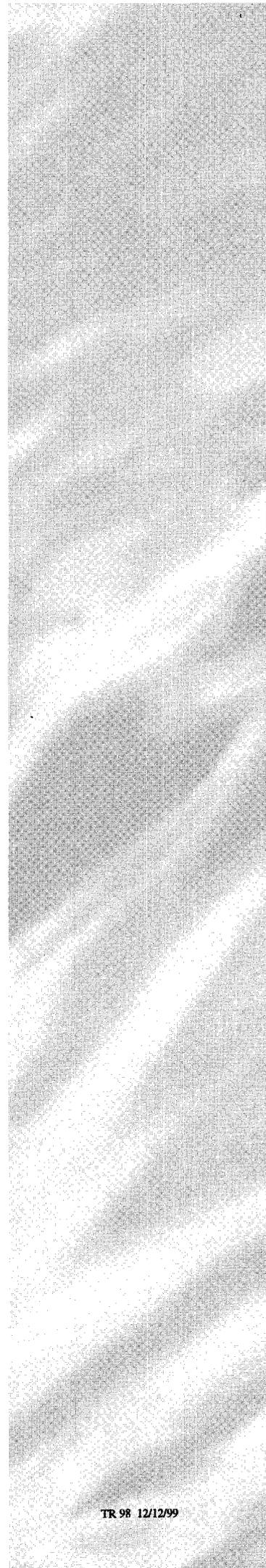
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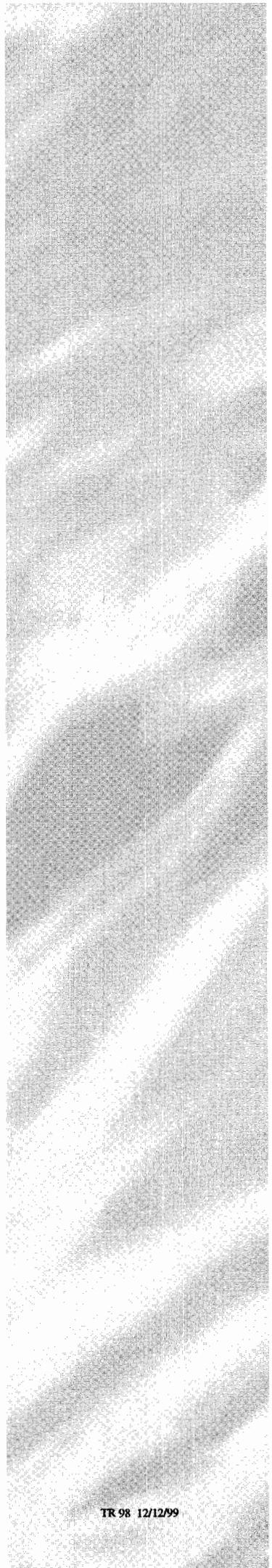
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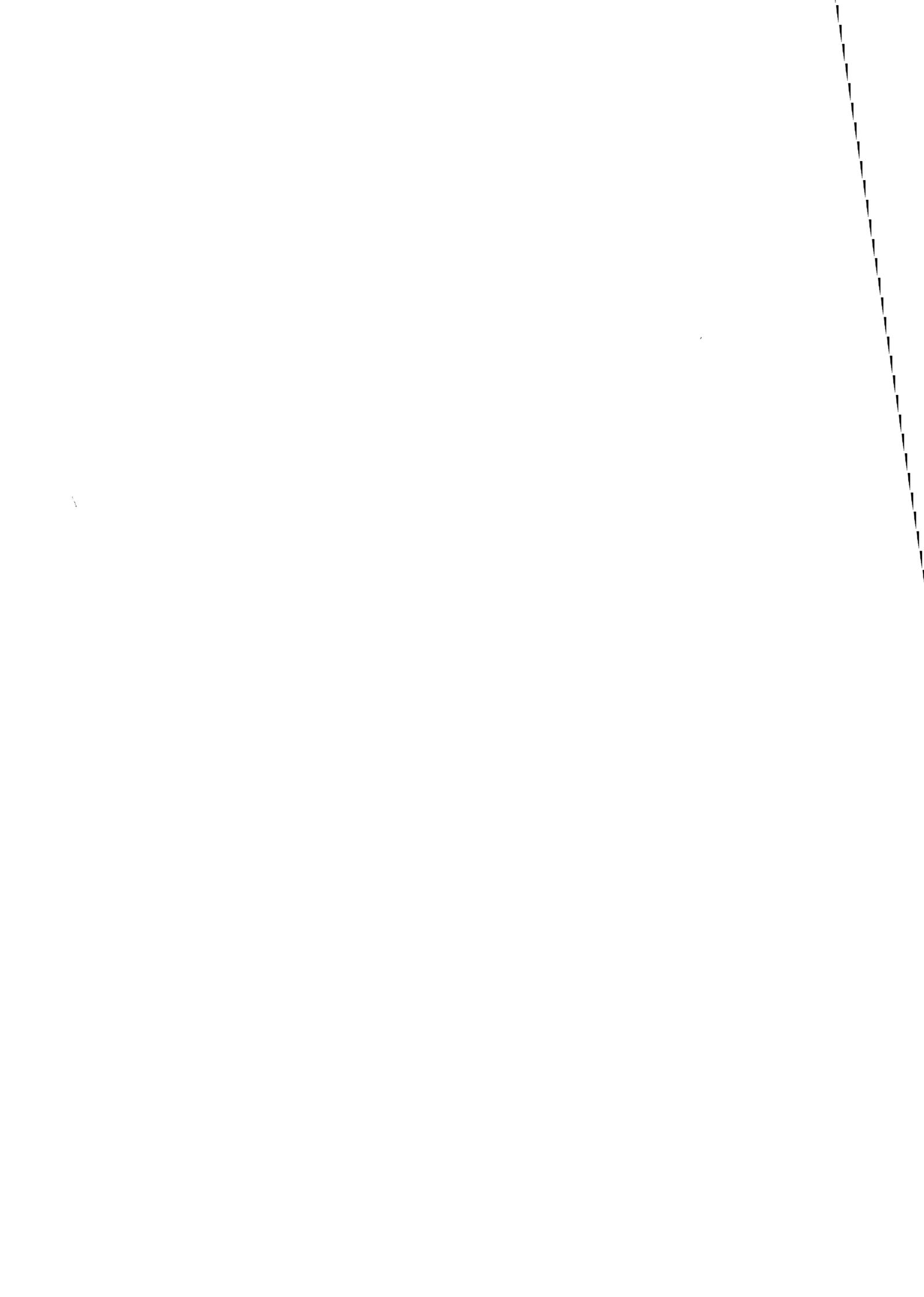
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1. INTRODUCTION

1.1 Previous tests and scour predictions

A number of experiments have been made on scour around breakwaters, as summarised by Sumer and Fredsøe (1999a, b). They include bedload and suspended-load tests and are mainly for 2-D toe scour rather than 3D scour at the end of the structures. The only in-depth investigation of 3D scour at the end of rubble mound breakwaters (RMBs) is Fredsøe and Sumer (1997). They conclude that the maximum scour and deposition due to streaming around the head of a RMB depend on the Keulegan-Carpenter number, KC , defined as:

$$KC = \frac{u_m T_p}{B}$$

with u_m the maximum wave velocity (defined as $\sqrt{2}\sigma_u$ with σ_u the velocity standard deviation) T_p the peak period and B the width of the breakwater at its base. The maximum scour, S and the maximum deposition depth, D , can then be determined from the empirical relationships:

$$\begin{aligned} S/B &= 0.04[1 - \exp(-4\{KC - 0.05\})] \\ D/B &= 0.04[1 - \exp(-3.5\{KC - 0.05\})] \end{aligned}$$

The areas where the scour and deposition occur are indicated in their paper. Scour also occurs when there are breaking waves plunging over the sloping curved shoulder of the RMB. The scour depth here is governed by a breaking wave number $T_p(gH_s)^{0.5}/h$ where g = gravitational acceleration, H_s is the incident significant wave height and h the water depth. The maximum scour depth is given by

$$\frac{S}{H_s} = 0.01 \left(T_p \frac{\sqrt{gH_s}}{h} \right)^{1.5}$$

Sumer and Fredsøe (1997 and 1998) deal with scour at the heads of vertical, impermeable breakwaters and groups of vertical piles. In all cases the tests were conducted in wide 2D flumes. Some vertical wall experiments were done with currents as well as waves and some with an angled wall.

Powell and Whitehouse (1998) summarise our present knowledge about 2D scour in front of seawalls, as does Whitehouse (1998) about scour generally. Both references present the isoparametric plots of Powell and Lowe (1994) for sand and shingle beaches. These give S/H_s as a function of h/H_s and H_s/L_m , with L_m the mean wavelength. The results are given after 3,000 waves, which is probably not a large enough number for the sand beach to have reached equilibrium (although shingle beaches tend to equilibrium after 3000 waves, Powell and Lowe, 1994). The plots show that the maximum scour is approximately equal to the significant wave height in the range $0.03 < H_s/L_m < 0.04$. Also, for sand beaches, the maximum scour occurs when h/H_s is about 1.5, so the incident waves are very close to breaking.

Fowler (1992) reviewed the recommended equations for toe scour given by Song & Schiller and Jones and proposed his own equation:

$$\frac{S}{H_o} = \left(22.72 \frac{h}{L_o} + 0.25 \right)^{1/2}$$

Where H_o is the deep water unbroken wave height. The equation fits the results well except when the toe of the seawall is at mean water level. Fowler (1993) presents some example calculations. The equation above presumably supercedes the equation in Hughes and Fowler (1991).

McDougal et al (1996) proposed a new equation for scour using their data from SUPERTANK seawall tests in a large-scale 2D flume. It includes grain size and is:

$$\frac{S}{H_o} = 0.41m^{0.85} \left(\frac{L_o}{H_o} \right)^{1/5} \left(\frac{h}{H_o} \right)^{1/4} \left(\frac{H_o}{d_{50}} \right)^{1/3}$$

Where m = the initial plane beach slope and d_{50} = median diameter of the sand. McDougal et al note that the results of scour tests depend on the initial beach profile so making equations like the above difficult to apply generally. The waves here were shoaling and breaking in front of the structure.

Silvester (1977), Xie (1981 and 1985), Irie and Nadaoke (1984) and Hsu and Silvester (1989) performed experiments with regular waves and vertical walls and all these papers are summarised in Silvester and Hsu (1997). The pattern of island crests and troughs formed by the 3D standing waves when there is oblique incidence is well described. Partial nodes are formed at $L^*/4, 3L^*/4, \dots$ from the structure where $L^* = L/\cos\theta$ with L = wavelength of the incident waves and θ = angle of incidence. The horizontal velocities change from being parallel to the structure at the structure to being ellipsis to being perpendicular to the structure at the partial nodes.

The scour patterns formed by sediment moved in suspension and in bedload are quite different. The suspended sediment in a flume is transported by the drift current from the partial nodes, where it was lifted into suspension, to the areas of lower horizontal velocity where it is deposited. The bedload moves towards the partial nodes, driven initially by the steady streaming in the boundary layer described by Longuet-Higgins (1953) for perfect reflection (and no reflection). Carter, et al (1973) showed how the region of reversed flow (opposite to the streaming caused by the progressive incident wave) varies with the reflection coefficient. However, the dominant driving mechanism under non-linear waves, after ripples have formed, is the asymmetrical vortex shedding on each side of the ripples described by Seaman and O'Donoghue (1996).

The pattern of nodes and anti-nodes formed when irregular waves reflect from a vertical wall is much less distinct than the pattern generated by regular waves. Each frequency has its own wavelength so the different waves rapidly become out of phase and within a few wavelengths of the structure no nodal pattern can be detected (Hughes, 1992). The effect of a sloping wall is to reduce the reflection coefficients and to introduce phase shifts between the incident and reflected waves at the structure toe. These factors both affect the magnitudes and positions of the velocity maxima and minima in front of the structure (Hughes and Fowler, 1995 and Sutherland and O'Donoghue, 1998a,b & 1999). Experimental relationships for the reflection coefficient and phase shift spectra are provided for simple structures.

The above set of papers and the books by Whitehouse (1998) and Hoffmans and Verheij (1997) will serve as a useful introduction to the study of scour around breakwaters and give an indication as to the experiments that have previously been performed. All wave basin mobile bed tests (and all flume tests except those conducted in the largest facilities) suffer to some extent from scale effects. Scale effects in the physical modelling of seabed scour are summarised by Sutherland and Whitehouse (1998) and morphodynamic modelling in wave basins is discussed in Sutherland (1999).

1.2 Aims

The aims of these tests were set by the SCARCOST project and are to:

1. Investigate time-development of scour.
2. Determine equilibrium scour depth and extent.

3. Measure pore pressures in the top 100mm of the bed (University of Oxford).
4. Study influence of breaking waves on scour.
5. Perform studies on counter measures against scour.
6. Examine the transition from 2D to 3D scour.

1.3 Deliverables

The outputs from this project are listed below. The first 3 were set by the SCARCOST project, whereas the others have come out of the additional measurements that were performed during the tests.

1. Description of the physical processes involved.
2. Data related to scour processes.
3. Graphs illustrating quantities related to scour processes.
4. Statistics, spectra and time series of surface elevations away from and around the breakwater.
5. Statistics and time series of velocity components around the breakwater.

1.4 Experimental setup

A number of experiments on the scour and deposition around a single detached offshore rubble mound breakwater have been performed in the UKCRF (UK Coastal Research Facility; Simons et al, 1995) as part of the EU-funded project Scour Around Coastal Structures (SCARCOST; Summer et al, 1998). The breakwater was situated near the centre of an initially flat 20cm deep sand bed, which extended for approximately 25m in the longshore direction and 6m in the cross-shore. The water depth at the breakwater was 30cm. The breakwater was 0.4m high with 1:2 (V:H) front and rear slopes and a crest width of 0.15m. It was constructed with 2 to 3 armour layers over a rock core and had a 4m long uniform central section (trunk) and semicircular roundheads which extended for almost 0.8m each. At the offshore side of the sand bed was a smooth 1:20m concrete slope which extended for 4m down to a water depth of 0.5m. At the inshore end of the sand bed was a 1:6 absorbing flint beach to dissipate the incident wave energy.

1.5 Experimental programme

A total of approximately 30,000 (average period) waves was run for each test case (with the exception of a short storm test being for the last case). The tests were numbered according to the experimental plan drawn up before the tests were started. The tests appear in Table 1 in the order they were performed. The tests are also identified by a letter, which is how they are referred to in Sutherland et al (1999a). The test conditions are listed in the Table 1 with H_{m0} = incident wave spectral significant wave height (m), T_p = incident wave spectral peak period (s), α = incident offshore wave angle (degrees), U = free surface longshore current velocity (m/s) and P = width of scour protection layer (m) and N_{waves} the number of average-period waves in the experiment.

Table 1 Experimental programme

Test	H_{m0}	T_p	α	U	P	N_{waves}
1 or A	0.1	2.8	0	0	0	30000
5 or B	0.1	2.8	20	0.1	0	30000
3 or C	0.1	2.8	20	0	0	30000
6 or D	0.1	2.8	20	0	0.5	30000
2 or E	0.12	1.5	20	0	0.5	3000

The time-development of scour was measured by profiling along 10 lines a total of 6 times each during the experiment. The final bed profile was determined by profiling at almost 50 lines at the end of the experiment. This was taken to be close to the equilibrium scour depth that would be reached. The waves and currents were determined by measuring with wave gauges and Acoustic Doppler Velocimeters (ADV) at a large number of points around the structure and at some points away from the structure.

Arrays of wave gauges in front of and behind the structure were used to determine its reflection characteristics.

Preliminary results can be found in Sutherland et al (1999a). Some of the summary results will be put on the SCARCOST web pages at <http://www.isva.dtu.dk/scarcost/scarcost.html> and will become publicly available.

2. EXPERIMENTAL SETUP

2.1 Wave basin

The experiments were conducted in the UK Coastal Research Facility (the UKCRF) a 57m by 27m wave basin at HR Wallingford (see <http://www.hrwallingford.co.uk/facilities/crf>). A plan view of the setup is shown in Figure 1. The central working area is 36m (alongshore) by 22m (cross-shore). The basin has 72 wave paddles, each 0.5m wide along the eastern side of the basin. The water depth at the paddles was 0.5m for all tests. The longshore current recirculation system comprises of 4 reversible 400mm axial flow pumps, each with a maximum capacity of $0.3\text{m}^3\text{s}^{-1}$. There are 40 0.5m wide inlet flumes each controlled by its own undershot weir at the North and South ends of the basin for inlet and outlet respectively. These allow an accurate cross-shore distribution of longshore current to be generated.

A 1:20 smooth concrete slope was used to decrease the water depth to 0.3m over a flat sand bed. The sand bed was approximately 25m by 6m by 0.2m deep. At the onshore (western) side of the sand bed was a 4m wide split-flint spending beach with a 1:6 front slope for absorbing the incident wave energy. The low front slope was meant to minimise reflections from the beach within a relatively small area. The basin, beach, breakwater and instrument positions were determined by a total station survey.

There was about 5m of flat concrete skim at the north end where the currents were introduced to allow the currents to smooth out before they flow over the sand. At the down stream end there was a sediment trap, a pit about 0.4m deep and 0.5m wide in the longshore direction, with a shallower trap (0.1m deep by 1.25m in longshore direction) at its downstream (South) end. The longshore length of the sediment trap was sufficient to allow sediment to settle from the surface to the bed before it was swept past the trap. The length was greater than hU/w_s , with h = depth, U = depth averaged current and w_s = settling velocity of the sediment. Here $h = 0.3\text{m}$ (from MWL to top of sediment trap) the maximum U is about 0.10m/s and $w_s \approx 0.025\text{m/s}$. Sediment collected in the traps was re-circulated using 4 pumps. Most of the water was separated from the sand in 4 hydrocyclones at the upstream end. The excess water was returned to the downstream end to prevent excess currents building up in the basin. The design of the sediment recirculation system is described in more detail in Sutherland, et al (1999b) and the recirculation system, sand bed, breakwater and spending beach are shown in plate 1.

2.2 Breakwater

The breakwater centre was half way across the sand bed in the cross-shore and 2m to the south of the centre of the basin. The breakwater had a 4m long straight central section (the trunk) and semicircular heads (or roundheads) which extended for almost 0.8m each beyond the trunk. It was constructed with 1:2 front and rear slopes and extended down to the concrete floor of the basin (0.5m below mean water level) to prevent it becoming destabilised by scouring. The breakwater had a core of small stones that extended up to MWL with 0.10m of armour stone above it. Its freeboard was 0.10m and the water depth at its toe was 0.3m (for the flat bed). The breakwater cross-section is shown in Figure 2. Plate 2 shows the breakwater and the bed profiling system. The start of each roundhead is marked by a vertical metal pole on the breakwater cross-shore centre line. These extended above the top of the breakwater and served as fixed points for defining the local co-ordinate system. The origin of the local co-ordinate system was taken as the average of the positions of the fixed points.

2.3 Co-ordinate system

The UKCRF has a basin co-ordinate system with x along-shore, y across-shore and z vertical with its origin at mean water level at the south-west corner of the basin as shown in Figure 1. The basin co-ordinates are referred to as (x_b, y_b, z_b) . In addition to this a local co-ordinate system was used for measurements around the breakwater (x_l, y_l, z_l) . In the long-shore and cross-shore directions the zeros were at the mid-point of the breakwater, with increasing (positive) numbers towards the northern end and the eastern side of the UKCRF for long-shore and cross-directions respectively (as for basin co-ordinates). Decreasing (negative) numbers are towards the southern end and western side. The origin for the vertical co-ordinate was the level of the flat sand bed, as represented by the average level of the concrete lip of the bed at the top of the 1:20 beach. The transformation from basin co-ordinates to local co-ordinates (in metres) is:

$$x_l = x_b - 16.05$$

$$y_l = y_b - 5.40$$

$$z_l = z_b + 0.30$$

The profiler (see Section 2.7) measured cross-shore positions from the offshore (eastern) profiler rail, with cross-shore co-ordinates increasing from 0 moving inshore. Increasing the profiler cross-shore co-ordinate corresponds to decreasing the basin cross-shore co-ordinate. The profiler cross-shore co-ordinate, x_p , may be converted to local breakwater co-ordinate, x_l using the equation

$$x_l = 3.12 - x_p$$

with all figures in metres (a value of 3.15m was used in Sutherland et al. 1999b). The profiler measures the bed level below the profiling rails (so all elevations are negative numbers, in millimetres). The average elevation of the concrete lip (averaged over all positions at the start of Tests 1, 5, 3 and 6) was -637mm , with a standard deviation of 6mm. To convert from corrected profiler elevation to bed level in breakwater co-ordinates use the equation:

$$z_l = z_p + 0.637$$

with all figures in metres. Note that the profiler output is in millimetres.

The local co-ordinates are shown in Figure 3, which also shows the measured rubble mound breakwater outline (RMB) outline, the target RMB outline (Target RMB) the positions of the hydrodynamic measurements (ADV), the repeated scour profiles (Scour repeat) and the local wave gauges (Wave gauges).

2.4 Wave gauges

Eight wave gauges were positioned away from the structure to provide measurements of the wave field. These are shown as dots in Figure 1. In addition to these gauges there were 3 arrays of inshore wave gauges around the structure. An array of 7 wave gauges offshore of the structure was used to measure incident and reflected waves and was usually positioned in front of the breakwater centre (at $y_l = 0$) as shown in Figure 3. The inshore and offshore limits of the array are shown by 2 dots in front of the breakwater in Figure 1. On occasions the array was moved along the breakwater to measure at different longshore positions so that the reflection coefficient at different distances from the breakwater end could be measured. An array of 4 wave gauges behind the structure was used to measure transmission (shown by a single dot in Figure 1). A short wave gauge was positioned close to each of the Nortek 3-component Acoustic Doppler Velocimeters (ADVs). Table 2 gives the positions of the fixed wave gauges deployed (in basin co-ordinates then local co-ordinates) and the "Grey cable number", the Prosig Dats channel number and the name of the position for all wave gauges. The grey cable number identifies the channel in

the analysis by HRWaves. The Dats channel number identifies the channel in the Matlab analysis of time series.

Table 2 Wave gauge positions, channel numbers and position names

y_b	x_b	y_l	x_l	Grey cable number	Dats channel No	Position name
11.49	16.03	6.09	-0.02	0	11	Midshore south
17.97	16.00	12.57	-0.05	1	1	Offshore south
18.06	21.75	12.66	5.70	2	2	Offshore centre
18.02	28.35	12.62	12.30	3	3	Offshore north
8.59	22.08	3.19	6.03	4	4	Inshore centre
11.59	28.59	6.19	12.54	5	5	Midshore north
4.00	22.13	-1.40	6.08	6	6	Inshore east (Lee-side)
6.99	22.07	1.59	6.02	7	7	Inshore East (in front)
-	-	-	-	8	8	ADV wave probe West
-	-	-	-	9	9	ADV wave probe Centre
-	-	-	-	10	10	ADV wave probe East
4.28	16.13	-1.12	0.08	17	18	Lee-side East
4.16	16.13	-1.25	0.08	18	19	Lee-side Centre
4.09	16.02	-1.31	-0.03	19	20	Lee-side South
4.09	16.24	-1.32	0.19	20	21	Lee-side North
6.44	16.14	1.04	0.09	21	22	Directional array 1
6.64	16.14	1.24	0.09	22	23	Directional array 2
7.00	16.15	1.60	0.10	23	24	Directional array 3
7.32	16.15	1.92	0.10	24	25	Directional array 4
6.74	15.95	1.34	-0.10	25	26	Directional array 5
6.74	16.34	1.34	0.29	26	27	Directional array 6
7.06	15.85	1.66	-0.20	27	28	Directional array 7

Grey cable channels 8, 9 and 10 were connected to the wave probes approximately 0.10m inshore of the western, central and eastern ADVs respectively.

2.5 Acoustic Doppler Velocimeters

The 3 Nortek 3-component Acoustic Doppler Velocimeters (ADV) were arranged in a cross-shore line 0.5m apart, with a wave gauge beside each ADV (approximately 0,10m inshore of it). The array of ADVs and wave gauges was moved around the breakwater to measure the hydrodynamics. The positions of these measurements are shown by the squares in Figure 3, with each set of 3 cross-shore positions being one deployment location. Table 3 shows the co-ordinates of the ADVs in the deployments used. The position names are those used in column E of *admin\File database.xls*, which gives the names of the files to which they apply (in column C). Gauge 0 was to the West, gauge 2 was in the centre and gauge 1 was to the East.

Table 3 ADV positions and position names

Position	Longshore breakwater co-ordinate x_b (m)	Gauge 0 Cross-shore co-ordinate y_b (m)	Gauge 2 Cross-shore co-ordinate y_b (m)	Gauge 1 Cross-shore co-ordinate y_b (m)
P1 +1.0m	1.0	1.0	1.5	2.0
P2 +2.0m	2.0	1.0	1.5	2.0
P3 +2.5m	2.5	1.0	1.5	2.0
P4 +3.0m	3.0	1.0	1.5	2.0
P5 +3.0m	3.0	-0.5	0.0	0.5
P6 +3.5m	3.5	-0.5	0.0	0.5
P7 +3.0m	3.0	-2.0	-1.5	-1.0
P8 +2.5m	2.5	-2.0	-1.5	-1.0
P9 +2.0m	2.0	-2.0	-1.5	-1.0
P1 -1.0m	-1.0	1.0	1.5	2.0
P2 -2.0m	-2.0	1.0	1.5	2.0
P3 -2.5m	-2.5	1.0	1.5	2.0
P4 -3.0m	-3.0	1.0	1.5	2.0
P5 -3.0m	-3.0	-0.5	0.0	0.5
P6 -3.5m	-3.5	-0.5	0.0	0.5
P7 -3.0m	-3.0	-2.0	-1.5	-1.0
P8 -2.5m	-2.5	-2.0	-1.5	-1.0
P9 -2.0m	-2.0	-2.0	-1.5	-1.0
P(offshore) -5.5m	-5.5	1.0	1.5	2.0
P(offshore) -4.0m	-4.0	1.0	1.5	2.0
P(shadow) +1.0m	1.0	-2.0	-1.5	-1.0
P(shadow away) +4.0m	4.0	-2.0	-1.5	-1.0
P4b	-3.5	1.0	1.5	2.0

NOTE that some of the short wave gauges co-located with the ADVs were too short to measure the highest waves. The highest peaks extended above the tops of the gauges and the wave records are clipped. No attempt was made to correct the wave records for this phenomenon. Therefore plots of highest wave height may be misleading, but the overall spectral statistics should be relatively accurate, as the phenomenon did not occur often. This was only a problem when the gauges were in front of the structure. Moreover the range of the gauges in the directional array in front of the breakwater occasionally became saturated. In this case the gauges were long enough to cope with the range of surface elevation but the voltages produced sometimes exceeded the range of the sampling system, so the recorded voltages were clipped. This problem was corrected for the later tests but is occasionally present in the earlier tests.

2.6 University of Oxford pressure transducers

University of Oxford has designed and built an instrument package with 4 pressure transducers mounted 20mm apart on a vertical pipe. This was used to measure pore pressures in the upper layers of the seabed at 3 locations. The results were collected and analysed independently by the University and are held by the University of Oxford, Department of Engineering Science (Dr G.Sills).

2.7 Profiler

The surface elevations of the bed and the breakwater were measured using a HR Wallingford touch-sensitive point profiler. This can be seen in plate 2 and is described at <http://www.hrwallingford.co.uk/equipment/profiling/index.html>. It operates by moving along a rail in the cross-shore direction, stopping at a pre-set distance, lowering the probe until the bed is reached, registering the bed distance down from the rail, raising the probe and repeating the above process until a set distance

has been traversed. It returns cross-shore position from its (offshore) starting point and distance down from the rails, both in millimetres.

Each profile was started on the concrete edge of the sand bed, in order to produce a fixed reference point, in case the origin of the system slipped.

2.7.1 Correction of profiler results

It is necessary, because of the large distance (approx. 5.4m) that the profiler spans, to correct the raw data to account for self-induced sag in the beam. This occurs as the profiler moves across the beam. Sagging was determined by measuring the distance from the profiler's parked position down to the still water surface by using a specially designed buoyant foot. These measurements were taken at 200mm intervals in the cross-shore and at 500mm intervals in the longshore. The greatest sag occurs as the profiler moves into the centre of the beam. This results in a smaller distance being measured to the bed by the profiler around the central cross-shore region. In order to remove this effect, the distance to the measured bed must be increased by a value equal to the induced sag to provide meaningful results of scour and deposition.

2.7.2 Repeat survey profile correction

To calculate a correction value along each of the measured profiles, the data was imported into Excel and plotted. A sixth-order polynomial was then fitted to the data, as shown in Figure 4. The curves look like parabolas. An equation for sag correction was obtained for each of the measured profile lines. These corrections were applied to the repeat profiles.

2.7.3 Final bed profile correction

As there are many more profiles measured for the full survey than there are for the short survey, it is difficult to calculate a correction factor for the intermediary points. To account for sagging, Surfer was used to obtain a correction map for the entire region. Firstly, a data file was generated which consisted of the correction values for each profile calculated by the Excel spreadsheet. This was then imported into Surfer and gridded using a polynomial regression. A surfer correction map was then generated at each point in a grid with spacings of 100mm (cross-shore) and 125mm (longshore) which would correspond with the final survey points. This grid was then exported in xyz format for later subtraction and correction. A visual representation of the correction map is given in Figure 5. The fitted values obtained from polynomial regression were compared to the measured points. The largest difference was found to be less than 3mm.

To use this correction map, raw data obtained from the different final surveys was imported into Surfer and gridded to obtain a final survey map of the entire area. This data was then exported into a xyz file. The correction map xyz data was then subtracted from this final survey file to provide a corrected value. This new data was then imported back into Surfer and gridded using a simple interpolation method. These grids were then mapped to provide the final corrected contour plots.

2.8 Size distributions of beach and breakwater materials

Samples of the sand bed, armour layer and spending beach were sieved to provide size distributions. The percentage undersize is shown against size in Figure 6. The armour layer had $d_{10} = 47\text{mm}$, $d_{50} = 58\text{mm}$ and $d_{90} = 73\text{mm}$ and the sand had $d_{10} = 0.15\text{mm}$, $d_{50} = 0.24\text{mm}$ and $d_{90} = 0.33\text{mm}$. The size range of the breakwater core and the scour protection layer were defined by sieving the material twice. The breakwater core material was 6mm to 10mm gravel and the scour protection layer was sieved between 10mm and 14mm. The armour layer, core and scour protection layer were all carboniferous limestone. The armour layer specific gravity was measured as 2.71.

2.9 Structure of a test

The sand bed was flattened before each test and profiled at a cross-shore spacing of 200mm and a longshore spacing of 0.50m (with an additional profile at $x_l = \pm 2.75$). The predicted average wave period

and the number of average waves were used to calculate the length of each run. The details of the runs are shown in Table 4, assuming $T_{0,2} = 2.2s$.

Table 4 Run lengths and durations

Run No.	No. of waves	Cumulative total No. of waves	Duration of run (hour, min)	Total duration of experiment (h, m)
1	3000	3000	1h, 50m	1h, 50m
2	3000	6000	1h, 50m	3h, 40m
3	4000	10000	2h, 27m	6h, 07m
4	5000	15000	3h, 3m	9h, 10m
5	5000	20000	3h, 3m	12h 13m
6	10000	30000	6h, 7m	18h, 20m

One run of 3000 waves was done using a shorter wave period, (Test 2) so the duration was correspondingly shorter. The actual average period will differ from experiment to experiment (and from gauge to gauge) but the duration of each run was maintained at the value shown in Table 2 (except for Test 2). Moreover, the text refers to scour after 3,000 or 10,000 waves, even if the wave period, and hence the average number of waves was slightly different from the assumed values.

The surface elevations and ADVs were sampled during most runs. Three sampling and analysis systems were used, HRWaves – Spec, HRWaves – Warp and the Prosig Dats data-logger. In HRWaves – Spec the wave gauges were sampled at 8 times the peak frequency, f_p , of the spectrum. Therefore for $T_p=3s$, the sampling frequency $f_s = 8/3Hz = 2.667Hz$. A total of 4096 records were sampled giving a total sample time $T_{tot} = 512T_p$ and a spectral analysis was performed. The Nyquist frequency, $f_{Nyq} = 4f_pHz$ and 64 points were used in each Fast Fourier Transform (FFT) so there were 32 frequency bins between 0Hz and $4f_pHz$. Therefore each frequency bin had a frequency width, $\Delta f = f_p/8Hz$ and the peak frequency was at the 8th frequency band (ignoring the half band centred on 0Hz). The results are the average of 64 FFTs so there will be 128 degrees of freedom for each spectral estimate (unless the analysis was done with overlapping spectra, when there will be more degrees of freedom and a lower error). The statistics calculated are as defined by IAHR (1989). They are:

spectral peak frequency, f_p

$$\text{average period, } T_{0,2} = \sqrt{\frac{m_0}{m_2}}$$

$$\text{with } n^{\text{th}} \text{ spectral moment, } m_n = \int_0^{f_{Nyq}} S_{\eta} f^n df$$

$$\text{and spectral significant wave height, } H_{m0} = 4\sqrt{m_0}.$$

In HRWaves – Warp a 10 minute time series of surface elevations was collected at 20Hz and a zero-crossing analysis was performed. The record time was split into bursts and statistics were provided for each burst. Initially the burst length was set to 2 minutes so there are relatively few waves in each burst but in later tests the statistics are calculated for the whole 10 minutes.

In Dats all the channels were sampled at 100Hz for 10 minutes. The wave gauges were re-sampled at 25Hz at the calibration stage. Spectral analysis was performed on the surface elevation data and time-series analysis on both surface elevation and velocity data.

The 3 ADVs (and corresponding wave gauges) were moved to the positions indicated in Figure 3 during the course of runs 1 to 6. Occasionally the directional arrays of wave gauges were moved in the cross-shore direction to determine the directional wave statistics along the breakwater.

Notes were made on the sediment transport observed.

Bed profiles were measured (using 200mm spacing in the cross-shore) at 10 longshore positions (5 for Test 1 due to its symmetry) at the end of each run, to help determine the time-development of the scouring and deposition. The locations (in local co-ordinates) are $x_l = \pm 3.0m, \pm 2.75m, \pm 2.5m, \pm 2.0m$ & $\pm 1.0m$ (see Figure 3). The profiles at $\pm 1.0m$ are half way from the centre of the breakwater trunk to the start of the roundhead and will reveal the time-development of the scouring and deposition patterns away from the heads (although possibly influenced by them). The profiles at $\pm 2.0m$ are at the ends of the trunk section, whereas the profiles at $\pm 2.5m$ are about half way across the roundheads. The profiles at $\pm 2.75m$ are close to the ends of the roundheads while the profiles at $\pm 3.0m$ are on the initially undisturbed bed.

At the end of the test a full bed profile was measured, using a cross-shore spacing of 100mm and a longshore spacing that varied from 0.5m (away from the structure) down to 125mm (around the roundheads).

The bed was flattened between the tests, except between Tests 6 and 2, when a storm condition was run over the final bathymetry generated by the longer, lower waves of Test 6.

All the summary statistics and compressed time series (over 150MB) were collected onto one CD (Table 5), also described in Appendix 1 in detail. The raw data was stored on 3 CDs as described in Table 5 as is the processed data. The CDs are available from the first author on payment of a handling charge for copying and distributing the CDs. The raw data (that collected and created during the SCARCOST experiment) includes details of experimental set-up as well as the original data files. Three CDs were used to store these files: "1of3" contains results from Tests 1 and 3, "2of3" contains results from Tests 5 and "3of3" contains results from Tests 2 and 6. The processed data (files that were created after the SCARCOST physical model experiment) includes finalised file details, calibrated wave and ADV data files, statistics and characteristic measurements. 3 CDs were used to store the processed data.

Table 5 Summary of contents of the data CDs

Contents	No. of CDs	CD Names	Contents Description
Summary statistics	1	summary	Background details, time-development of scour, final bed bathymetries, incident waves, velocities, reflection characteristics.
Raw Data	3	1of3 2of3 3of3	All CDs include admin, calibration files, HR Waves Data, bed observations, RS evaluation, pump settings, Test logs, longshore current calibration and measured profiles. DAC data: 1of3 contains Test1 & Test3 2of3 contains Test5 3of3 contains Test6 & Test2
Processed Data	3	4 5 6	All CDs include admin (finalised), Batch files (m-files for Matlab), calibration and depth files and profile data which includes finalised surfer plots as well as calibrated time series and summary statistics. Spectra, spectral statistics, time-series statistics, etc.

3. TEST 1 OR A RESULTS

Test 1 (or A) is the normal-incidence test case with no pumped current or scour protection. Measured wave heights and periods are shown in Table 6. The water temperature varied from 12° Celsius to 11° Celsius from start to finish of the experiment (13/05/99 to 18/05/99 – see *admin\water depth and temp summary.xls* for daily measurements).

Table 6 Test 1 spectral wave heights and periods (from HRWaves file T131405a.spc)

Grey channel number	Longshore co-ordinate, x_l (m)	Cross-shore co-ordinate, y_l (m)	H_{m0} (m)	f_p (Hz)	T_z (s)
0	-0.02	6.09	0.103	0.31	2.20
1	-0.05	12.57	0.101	0.31	2.31
2	5.70	12.66	0.104	0.31	2.27
4	6.03	3.19	0.084	0.31	1.95
6	6.08	-1.40	0.082	0.40	1.55
7	6.02	1.59	0.091	0.35	1.70
17	0.08	-1.12	0.040	0.31	2.05
21	0.09	1.04	0.089	0.31	1.76
22	0.09	1.24	0.090	0.31	1.73
23	0.10	1.60	0.112	0.40	1.72
24	0.10	1.92	0.113	0.35	2.06

The wave height and period results show some variability, due to the presence of structures etc. Gauges 0, 24, 23, 22 & 21 form a cross-shore row of 5 gauges close in front of the structure. The variations in wave height and period are due to the partial standing wave pattern caused by reflections from the structure. Gauge 17 is behind the breakwater so the wave height is low.

The formation of ripples occurred very soon after commencement of the wave conditions (10-15 minutes). Their height and length were approximately in the order of 4cm and 10cm respectively. Sediment was clearly moved under the larger waves in which case the sand was ejected into suspension from the ripple crest. This ejection did not seem to occur for the small to medium sized waves. The sand moved generally, in a backwards/forwards motion, resulting from wave induced orbital motion.

A small quantity of sediment was moved offshore continuing the ripple shape perfectly on the concrete slope. There was virtually no loss of sediment into the spending beach or RMB. Scouring developed at the concrete lip of the spending beach, in the areas not sheltered by the breakwater, as the net sediment transport direction was offshore. The size and depth of these scour pits increased with time.

There appeared to be some indication of scour development due to wave breaking over the breakwater shoulder. In addition, ripple crests aligned themselves with the diffracted waves behind the structure as expected. This occurred up to the end point of the breakwater head. Past this location the bed was smooth and clearly not influenced by the waves. This is due to the reduced energy in the lee.

Generally most energy behind the breakwater occurred due to diffraction and overtopping, very little occurred due to transmission through the structure. Overtopping occurred with medium size waves upwards. Wave breaking on the front of the structure varied with wave steepness. A full range of breaker types occurred on the breakwater ranging from surging for smaller waves to collapsing for medium size waves and plunging for larger waves. Plunging waves always occurred over the RMB shoulder whatever the height. These observations may well be inaccurate due to the difficult in observing distinct waves forms on a RMB.

Floats and dye were observed and recorded onto video. The sequence starts at video counter setting 00:00:00(time counter). The floats were positioned and observed near the boundaries to see whether a circulation cell was set up within the basin. Generally it was observed that the floats moved backwards and forwards very slowly and showed no sign of being moved around the basin in a circular manner. Thus there are no significant basin recirculation currents.

3.1 Time-development of scour

The results for the time development of scour and deposition are shown in Figures 7 to 11. Repeat cross-shore surveys were made at 5 longshore positions starting with the flat bed and continuing, at increasing time intervals, until the near equilibrium final bathymetry. The positions of the repeated profiles are shown in Figure 3. The co-ordinates used are those of the profiling system.

Figure 7 shows the time-development of scour and deposition at longshore co-ordinate $x_l = -1.00\text{m}$. The results show a small amount of scour and deposition after 6000 waves. There is deposition at the toe of the structure after 10,000 waves and scour further away from the breakwater. This pattern remains similar for the remaining 20,000 waves of the test. The final bathymetry can be seen in plate 3, which shows this area of deposition at the toe of the breakwater near the breakwater centre. The level of deposition may even be higher at the breakwater centre.

Figure 8 shows the time-development of scour and deposition at longshore co-ordinate $x_l = -2.00\text{m}$, at the start of the roundhead. This shows the development within 3000 waves of a scour pit (armour layer $d_{50}/2$ deep) at the toe of the breakwater and the more gradual development of scour away from the breakwater. The area behind the breakwater initially shows some scouring but this is replaced by a small amount of deposition by the end of the test. Note that the volume of sediment under the profile is not preserved with time, indicating that there is longshore transport.

Figure 9 shows the time development of scour at $x_l = -2.50\text{m}$, just over half way between the start and the tip of the roundhead. Here a slightly larger scour hole develops at the toe of the breakwater, but the development is not as rapid as at $x_l = -2.00\text{m}$. The area behind the breakwater shows deposition throughout the test. The volume of sediment under the profile is not preserved with time, indicating that there is transport around the roundhead and that sediment is deposited in the more sheltered area at the rear of the roundhead.

Figures 10 and 11 show the time development of scour at $x_l = -2.75\text{m}$ and at $x_l = -3.00\text{m}$ respectively. Both show some evidence of scour in front of and deposition behind the breakwater.

3.2 Final bathymetry

A contour plot of the final bathymetry can be seen in Figure 12. This shows the area of deposition at the toe of the breakwater at its centre and a broad area of scour offshore of it. The scour pits at the offshore side of both roundheads can also be seen, as can the patterns of deposition towards the rear of the roundhead. There is no significant net scour caused by breaking over the shoulder of the breakwater. The patterns of scour and deposition are near symmetrical, as expected from the normal incidence wave case, without a pumped current.

Plates 3, 4, 5 and 6 are photographs of the final Test 1 bathymetry. The ruler in plates 3, 4 and 5 is 1 metre long. The bed is rippled throughout, except in the area behind the breakwater where the velocities were too low to mobilise the sediment. The four plates show all aspects of the final bathymetry and the photographs can be compared to the figures to illustrate the different scour and deposition features.

4. TEST 5 OR B RESULTS

Test 5 (or B) was conducted using obliquely incident waves and a pumped longshore current. The offshore angle of incidence of the irregular waves was 20°, with the longshore component of the incident wave direction being from North to South. The target significant wave height and peak period were the same as for Test 1. The target surface velocity for the pumped longshore current was 0.10ms⁻¹ from North to South so the longshore component of pumped velocity and the longshore component of the incident wave direction are the same.

Measured wave heights and periods are shown in Table 7. The water temperature varied between 12° Celsius and 15° Celsius through the experiment (24/05/99 to 28/05/99 – see *admin\water depth and temp summary.xls* for daily measurements).

Table 7 Test 5 spectral wave heights and periods (from HRWaves file T512405a.spc).

Grey channel number	Longshore co-ordinate, x_l (m)	Cross-shore co-ordinate, y_l (m)	H_{m0} (m)	f_p (Hz)	T_z (s)
0	-0.02	6.09	0.110	0.31	2.28
1	-0.05	12.57	0.109	0.35	2.29
2	5.70	12.66	0.074	0.31	2.11
4	6.03	3.19	0.088	0.35	2.10
6	6.08	-1.40	0.068	0.35	1.63
7	6.02	1.59	0.079	0.35	1.76
17	0.08	-1.12	0.038	0.31	1.94
21	0.09	1.04	0.100	0.35	1.74
22	0.09	1.24	0.101	0.31	1.74
23	0.10	1.60	0.117	0.35	1.74
24	0.10	1.92	0.105	0.35	1.85

Table 8 shows the significant wave height and average reflection coefficient, Kr_{av} , calculated using spectra from the directional array in front of the breakwater. The longshore position of the array (defined by the position of directional gauges 1, 2, 3 and 4 which have grey cable numbers 21, 22, 23 and 24) is also shown. The relative cross-shore positions of the gauges remain as in Table 2. The results show a small variability between test runs and large differences between the reflection coefficients at different longshore positions in front of the breakwater. This longshore variation is not symmetrical about the centre of the breakwater due to the oblique angle of incidence

Table 8 Test 5 incident spectral significant wave heights and reflection coefficients from directional wave analysis, including results from different positions in front of the breakwater

File	H_s (m)	Kr_{av}	Array x_l (m)
R512405b	0.117	0.62	0.0
R512405c	0.117	0.62	0.0
R512405c	0.118	0.62	0.0
R522505a	0.122	0.60	0.0
R532505a	0.121	0.55	0.0
R532505b	0.120	0.55	0.0
R542605a	0.117	0.56	0.0
R552705a	0.124	0.56	0.0
R552705b	0.113	0.56	0.0
R562805e	0.117	0.60	-1.5
R562805f	0.112	0.34	1.5
R562805i	0.113	0.40	-2.5

The ADVs measured time series of velocities at about 60 points around the breakwater and statistics were calculated for each position (see the appendices for instructions on how to locate and identify the data). The average longshore current is one of the stored statistics. Its value at the furthest point away from the breakwater during the test was -0.094ms^{-1} (negative value indicates flow to south) at $x_l = 4.0\text{m}$, $y_l = 2.0\text{m}$ and $z_l = 0.10\text{m}$. This is close to the target free-surface current of 0.10ms^{-1} .

The net sediment transport direction was again offshore, in areas not affected by the breakwater. Small ripples developed on the concrete slope. Scouring developed at the concrete lip of the spending beach, in the areas not sheltered by the breakwater. The size and depth of these scour pits increased with time, so some sand was added to this area of the bed midway through the experiment. The net direction of sediment transport was offshore in all the tests so this procedure was repeated for all subsequent tests.

4.1 Scour profiles

Figures 13 to 22 show the time-development of the scouring and deposition at the 10 standard longshore positions. The asymmetry of the scouring and deposition can clearly be seen by comparing, for example, the time development of scour at $+2.75\text{m}$ (Figure 14) and -2.75m (Figure 21). At -2.75m (downstream) there is far greater deposition than at $+2.75\text{m}$, due to the longshore movement of sand under the action of waves and currents. This is clearly illustrated in Figure 23, which is a contour shading map of the final bathymetry.

There is a greater area of significant deposition at the rear side of the upstream roundhead (at about $x_l = 2\text{m}$, $y_l = -1.2\text{m}$) than in Test 1. Moreover there is a significant scour hole at the rear side of the downstream roundhead (at about $x_l = -2.2\text{m}$, $y_l = -1.1\text{m}$) that was not present in Test 1. This is due to waves breaking over the shoulder of the breakwater. The large area of deposition that developed in front of the centre of the breakwater in Test 1 has developed instead towards the downstream (and down-wave) end of the breakwater in Test 5. There is a greater area of scour in front of the upstream end of the breakwater. This development is expected due to the oblique angle of the waves creating a non-symmetrical pattern of partial standing waves in front of the breakwater. This standing wave pattern will be quite distinct due to the relatively high reflection coefficient (0.6) and can be detected in the variation in the measured waves in front of the breakwater (Tables 7 and 8).

Plates 7 to 10 show the Test 5 final bathymetry from all 4 corners of the central area and clearly show the features illustrated in Figures 13 to 23. There is also evidence that waves breaking over the upstream

roundhead are causing some scouring in the base of the rear of the breakwater (at about $x_l = 1.6\text{m}$, $y_l = -1.1\text{m}$) as shown by the small depression of smooth sand that can be seen in plate 10.

5. TEST 3 OR C RESULTS

Test 3 (or C) used the same irregular oblique-angle waves as Test 5 (or B) but did not have a pumped longshore current. The differences between the results from Test 1 and Test 3 are due to having obliquely incident waves in Test 3. The differences between the results from Test 5 and Test 3 are due to having a pumped longshore current in Test 5. The test started with a flat bed. Measured wave heights and periods are shown in Table 9. The water temperature varied between 13° Celsius and 15° Celsius through the experiment (14/06/99 to 18/06/99 – see *admin\water depth and temp summary.xls* for daily measurements).

Ripples formed quickly and were realigned with wave crest direction. Therefore, asymmetrical ripple development occurred behind the breakwater due to the wave obliquity. Floats and dye were recorded onto video. The sequence starts at video counter setting 00:59:51.

Table 9 Test 3 spectral wave heights and periods (from HRWaves file T331606a.spc)

Grey channel number	Longshore coordinate, x_l (m)	Cross-shore coordinate, y_l (m)	H_{m0} (m)	f_p (Hz)	T_z (s)
0	-0.02	6.09	0.102	0.31	2.28
1	-0.05	12.57	0.105	0.31	2.29
2	5.70	12.66	0.072	0.35	2.11
4	6.03	3.19	0.090	0.35	2.10
6	6.08	-1.40	0.073	0.35	1.63
7	6.02	1.59	0.089	0.35	1.76
17	0.08	-1.12	0.045	0.31	1.94
21	0.09	1.04	0.094	0.35	1.74
22	0.09	1.24	0.099	0.35	1.74
23	0.10	1.60	0.088	0.35	1.74
24	0.10	1.92	0.106	0.35	1.85

The analysis of the directional reflection array of wave gauges in front of the breakwater gave an average spectral significant wave height in front of the structure of 0.115m (values between 0.113m and 0.117m) and an average reflection coefficient of 0.61 (with values between 0.58 and 0.63). These measurements were made with the directional array at $x_l = 0.0\text{m}$. Reflection analysis was also performed with the array at $x_l = 1.0\text{m}$ ($H_{m0} = 0.121\text{m}$, average reflection coefficient = 0.41) and at $x_l = 1.5\text{m}$ ($H_{m0} = 0.121\text{m}$, average reflection coefficient = 0.38). The reflections off the beach were also measured during run 6. The average incident spectral significant wave height in front of the spending beach was 0.109m and the reflection coefficient was 0.29.

Figures 24 to 33 show the time-development of scour and deposition along the 10 standard cross-shore profiles. As with Test 5, the results are asymmetric about the centre of the breakwater. This can be seen by comparing the time-development of scour at cross-section evenly spaced about the breakwater centre or by looking at Figure 34, which is a contour/shading map of the final bathymetry of Test 3. The pattern of scour and deposition is between those of Test 1 (normal incidence, no current) and Test 5 (same oblique incidence plus pumped longshore current).

6. TEST 6 OR D RESULTS

Test 6 (or D) used the same waves as Test 3 (and no pumped longshore current) so the hydrodynamics should be the same in Test 6 as in Test 3. The difference is the addition of a 0.5m wide 0.02cm deep scour protection layer right around the base of the rubble mound breakwater. The bed was flattened after Test 3 before the scour protection layer was added so that the scour protection layer stands proud of the flat bed.

Measured wave heights and periods are shown in Table 10. The water temperature varied between 13° Celsius and 14° Celsius through the experiment (24/06/99 to 30/06/99 – see *admin\water depth and temp summary.xls* for daily measurements).

Table 10 Test 6 spectral wave heights and periods (from HRWaves file T612406a.spc).

Grey channel number	Longshore coordinate, x_l (m)	Cross-shore coordinate, y_l (m)	H_{m0} (m)	f_p (Hz)	T_z (s)
0	-0.02	6.09	0.104	0.31	2.19
1	-0.05	12.57	0.108	0.31	2.29
2	5.70	12.66	0.071	0.35	2.03
4	6.03	3.19	0.095	0.35	2.03
6	6.08	-1.40	0.078	0.35	1.61
7	6.02	1.59	0.090	0.35	1.72
17	0.08	-1.12	0.046	0.35	1.87
21	0.09	1.04	0.088	0.35	1.89
22	0.09	1.24	0.094	0.35	1.75
23	0.10	1.60	0.088	0.60	1.72
24	0.10	1.92	0.102	0.35	1.95

Reflection analysis was performed at 4 positions along the breakwater. At $x_l = 0.0\text{m}$ (the centreline) significant wave heights of 0.114m and 0.116m were recorded with average reflection coefficients, Kr_{av} , of 0.56 and 0.62 respectively. At $x_l = -1.0\text{m}$, $H_s = 0.115$ and $Kr_{av} = 0.72$. At $x_l = -1.5\text{m}$, $H_s = 0.114$ and $Kr_{av} = 0.59$. At $x_l = -2.0\text{m}$, $H_s = 0.115$ and $Kr_{av} = 0.42$. These values are close to the ones measured in Test 3.

Figures 35 to 44 show the time-development of scour and deposition along the 10 standard cross-shore profiles. The extent of the scour protection layer can be picked out in the flat bed profiles. As with Tests 3 and 5 the results are asymmetric about the centre of the breakwater. Less scour and deposition is evident in these tests than in Test 3, due to the scour protection layer. However, the presence of the scour protection layer did not stop bed levels from changing in the area it covered. The level of the top of the scour protection layer drops in Figure 38 on the offshore side of the breakwater (cross-shore distances 1600mm and 1800mm). Moreover, sand piles up on top of the scour protection layer on the onshore side of the breakwater (cross-shore distances 4000, 4200 & 4400mm). In other positions (such as at $x_l = -1.0\text{m}$, Figure 40) the bed level increases above the level of the top of the scour protection due to the movement of sand.

The scour protection layer did prevent there being any significant scour around the toe of the breakwater, either in front or behind the breakwater. The areas where the scour protection layer did not prevent the bed level from decreasing were adjacent to the non-protected bed. This may be partly due to sand and protection layer falling into a scour pit at the edge of the layer and partly due to sand being winnowed up through the scour protection layer and then being transported when at the top of the protection layer. Significant areas of the scour protection layer at the up-wave (positive longshore co-ordinate) roundhead, which is exposed to more direct wave attack, became covered in sand during the experiment.

The asymmetry in the scour and deposition can be seen by comparing the time-development of scour at cross-sections evenly spaced about the breakwater centre or by looking at Figure 45, which is a contour/shading map of the final bathymetry of Test 6. This plot shows the outline of the scour protection (within contour band 30-50mm) layer round the back and the southern end of the breakwater. The outline is obscured by deposition at the southern (negative longshore co-ordinates) end of the breakwater and at the rear side of the northern roundhead. The deposition patterns and levels are similar to Test 3. The erosion of the scour protection layer can clearly be seen at the front of the breakwater along most of its northern end. In places the surface level has decreased from over 10mm above the flat bed level to greater than 40mm below this level.

7. TEST 2 OR E RESULTS

The waves generated for this condition were much steeper and more energetic and were used to represent “storm” associated scour and sediment movement. The bed profile at the end of Test 6 was utilised. As a result sediment movement was more intense. Non-uniform ripples formed in front of the breakwater. Away from the breakwater the ripples were very long-crested. With this test more intense breaking occurred at the structure and extreme waves broke before the breakwater. Some white capping was observed as waves moved onto the flat bed in front of the structure. Some overtopping of the structure occurred with this condition. Surface floats were moved inshore by the surface rollers of the breaking waves. There was little transmission through the structure with most energy in the lee resulting from the process of diffraction and overtopping. Floats and dye were observed and recorded onto video. The sequence starts at video counter setting 00:40:35.

Measured wave heights and periods are shown in Table 11. The water temperature was 15° Celsius during the experiment on 02/07/99.

Table 11 Test 2 spectral wave heights and periods (from HRWaves file T210207a.spc)

Grey channel number	Longshore coordinate, x_i (m)	Cross-shore coordinate, y_i (m)	H_{m0} (m)	f_p (Hz)	T_z (s)
0	-0.02	6.09	0.131	0.79	1.28
1	-0.05	12.57	0.136	0.71	1.29
2	5.70	12.66	0.136	0.71	1.24
4	6.03	3.19	0.120	0.71	1.13
6	6.08	-1.40	0.112	0.62	1.20
7	6.02	1.59	0.124	0.62	1.01
17	0.08	-1.12	0.050	0.62	1.01
21	0.09	1.04	0.110	0.79	1.16
22	0.09	1.24	0.136	0.79	1.26
23	0.10	1.60	0.139	0.62	1.34
24	0.10	1.92	0.139	0.54	1.34

The development of scour and deposition during the 3,000 waves of Test 2 are shown in Figures 46 to 55 for the 10 standard cross-shore profiles. Despite the severity of the waves, there were no significant bed level changes near the toe of the breakwater during the storm test. Nor were there any significant changes to the level of the scour protection layer. The changes can be seen by comparing the final bathymetry at the end of Test 2 (Figure 56) to that at the end of Test 6 (Figure 45).

The area of deposition on top of the scour protection layer at the southern end of the front of the breakwater is reduced in size and has moved nearer to the toe of the breakwater due to the shorter

wavelengths of the incident waves. There is more scouring around the southern end of the scour protection layer. The large area of scour in front of the breakwater (at around $x_l = 1.0\text{m}$, $y_l = 2.3\text{m}$) is reduced, although there is an area of scouring further North.

8. DEPTH VARIATION OF LONGSHORE CURRENT

The depth variation of the longshore current over the flat sand bed was measured, without waves, at 2 locations: (22, 4) and (22, 7.2) in (x_b, y_b) basin co-ordinates. The depth variations in mean longshore current magnitude are shown in Figures 57 and 58. The current actually flows in the negative y direction.

9. ACKNOWLEDGEMENTS

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The work was supervised by Dr RJS Whitehouse and Dr J Sutherland and the tests were performed by Mr AR Channell and Mr B Chapman, who also did the analysis. Mr B Chapman took a leave of absence from his PhD at the University of Plymouth at short notice to come to HR. Our thanks go to him, his supervisor Dr A Chadwick and to the EPSRC (the funders of his PhD) for allowing this to happen. Mr Chapman used software developed at Plymouth for much of the analysis. Its use is gratefully acknowledged.

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Figures

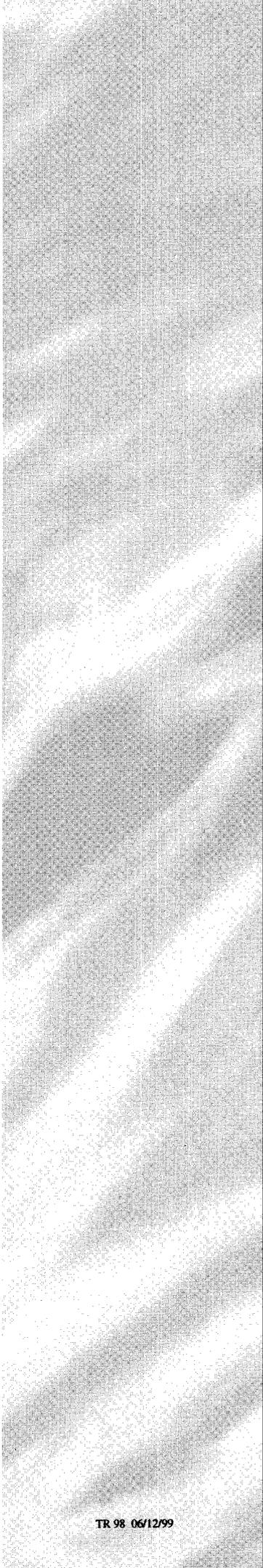
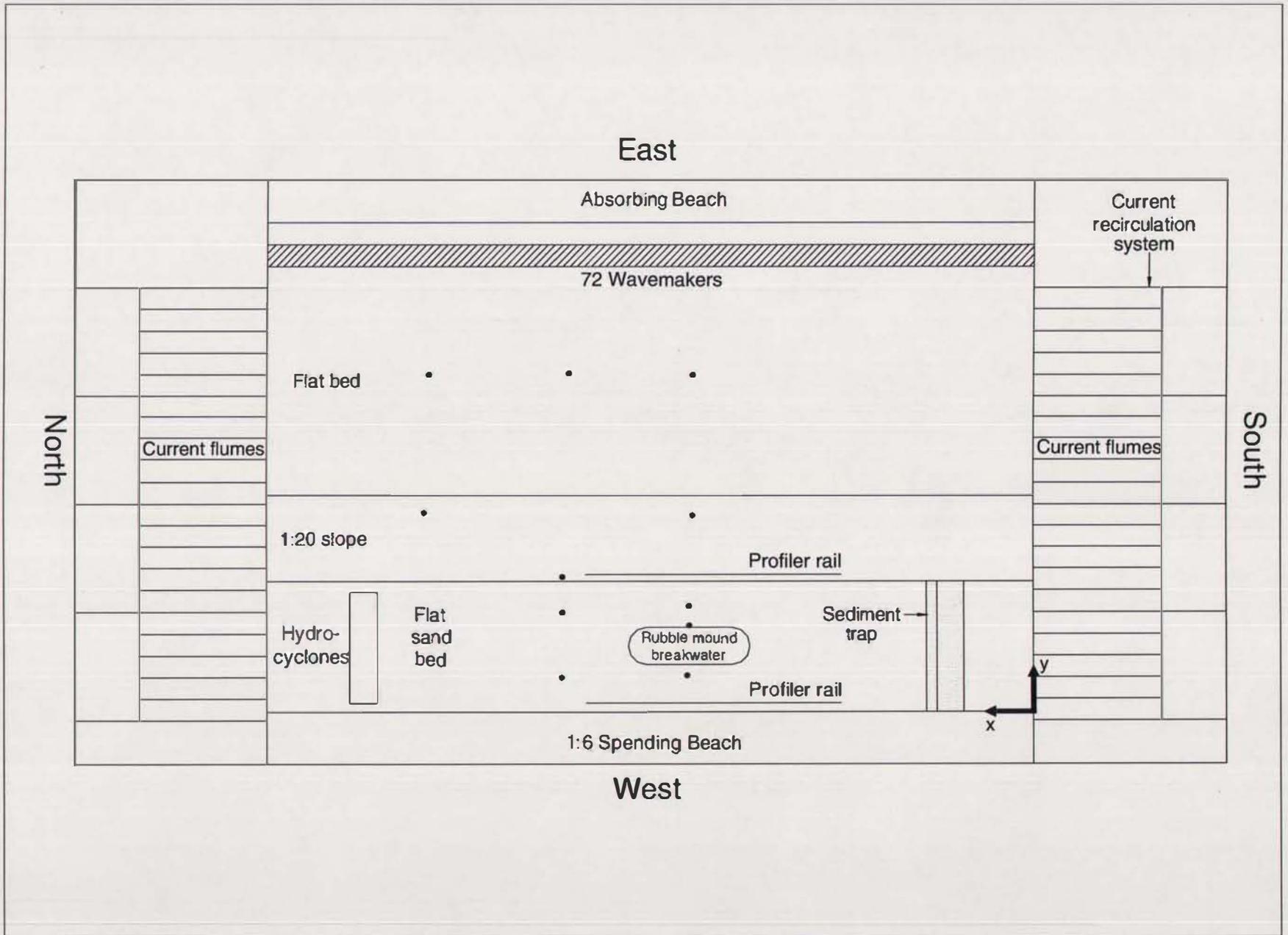


Figure 1 Experimental setup for SCARCOST tests in UKCRF



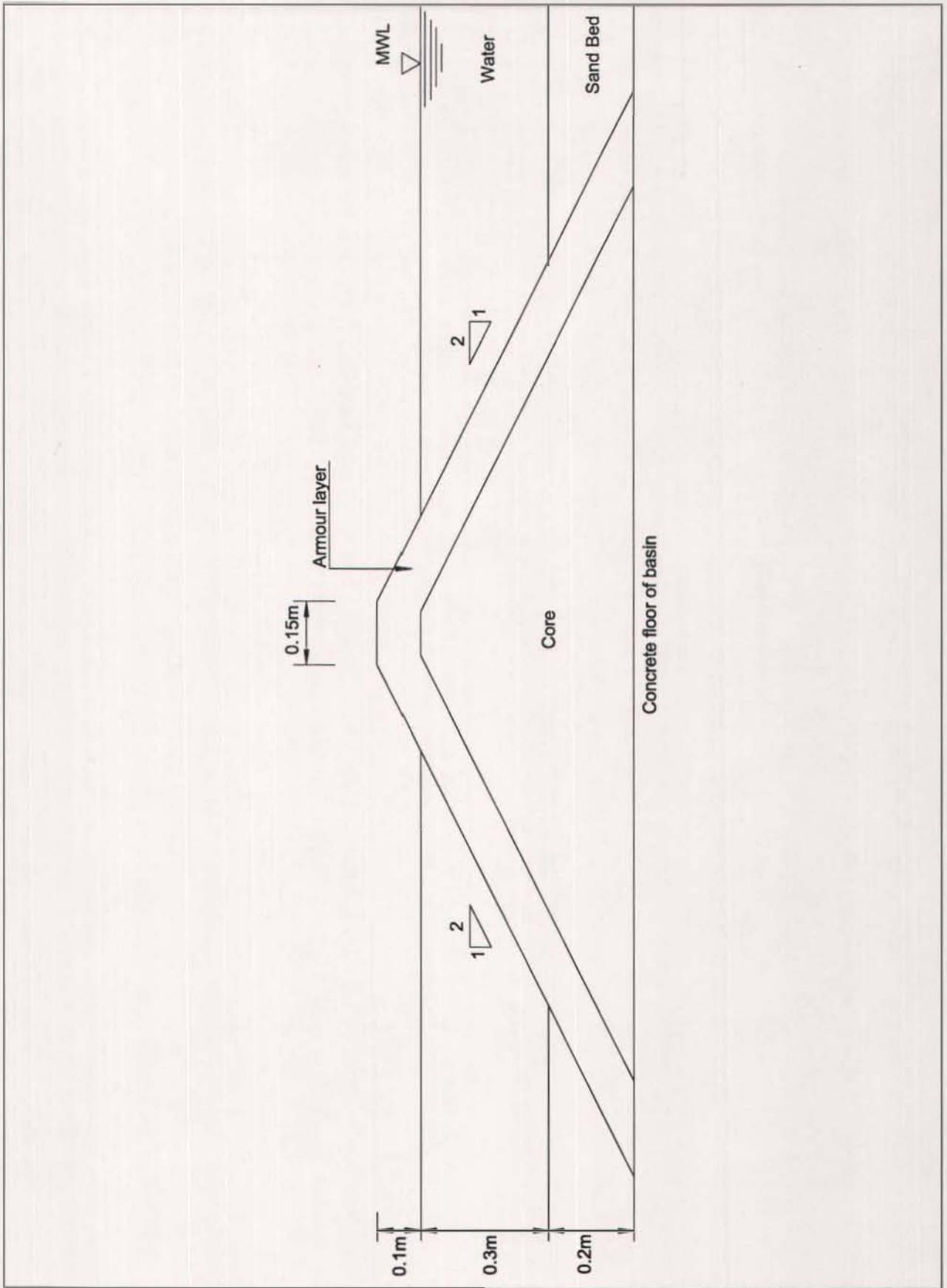


Figure 2 Breakwater cross-section

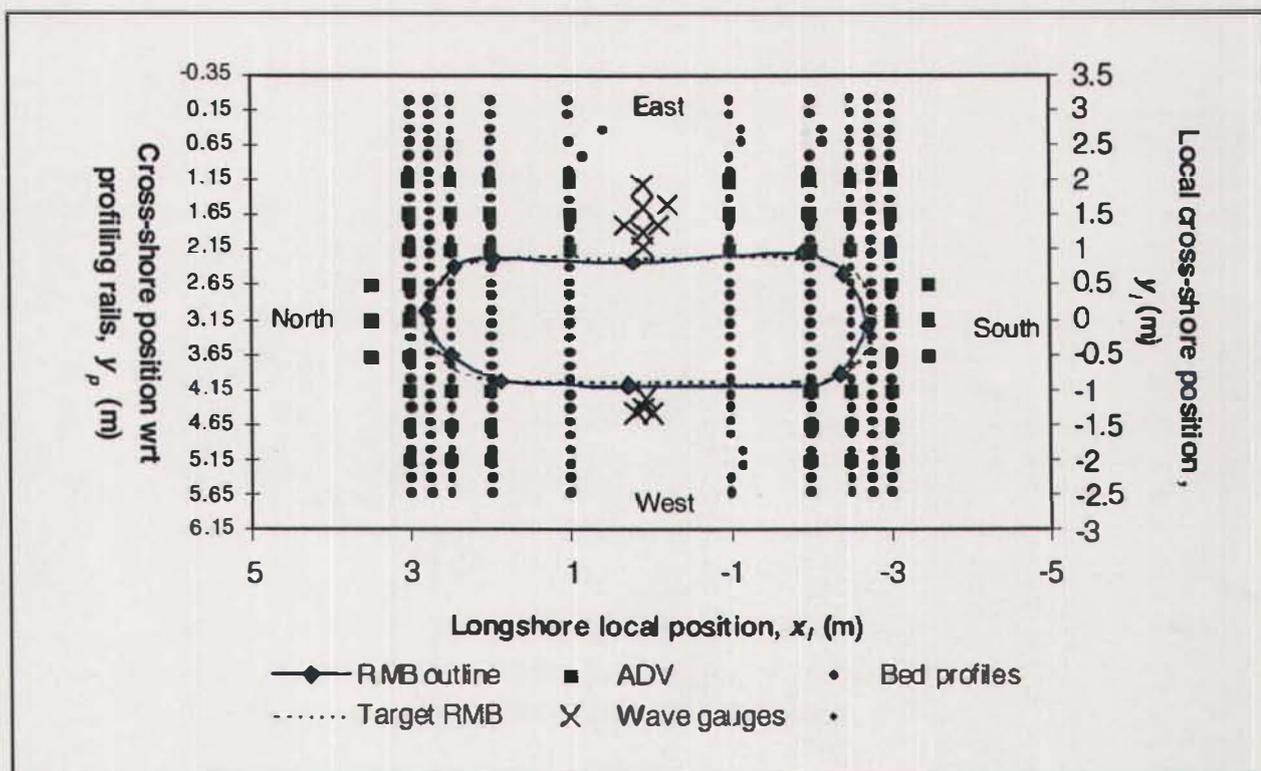


Figure 3 Local co-ordinate system, showing breakwater outline and locations of ADVs, repeat scour measurements and wave gauges close to the structure

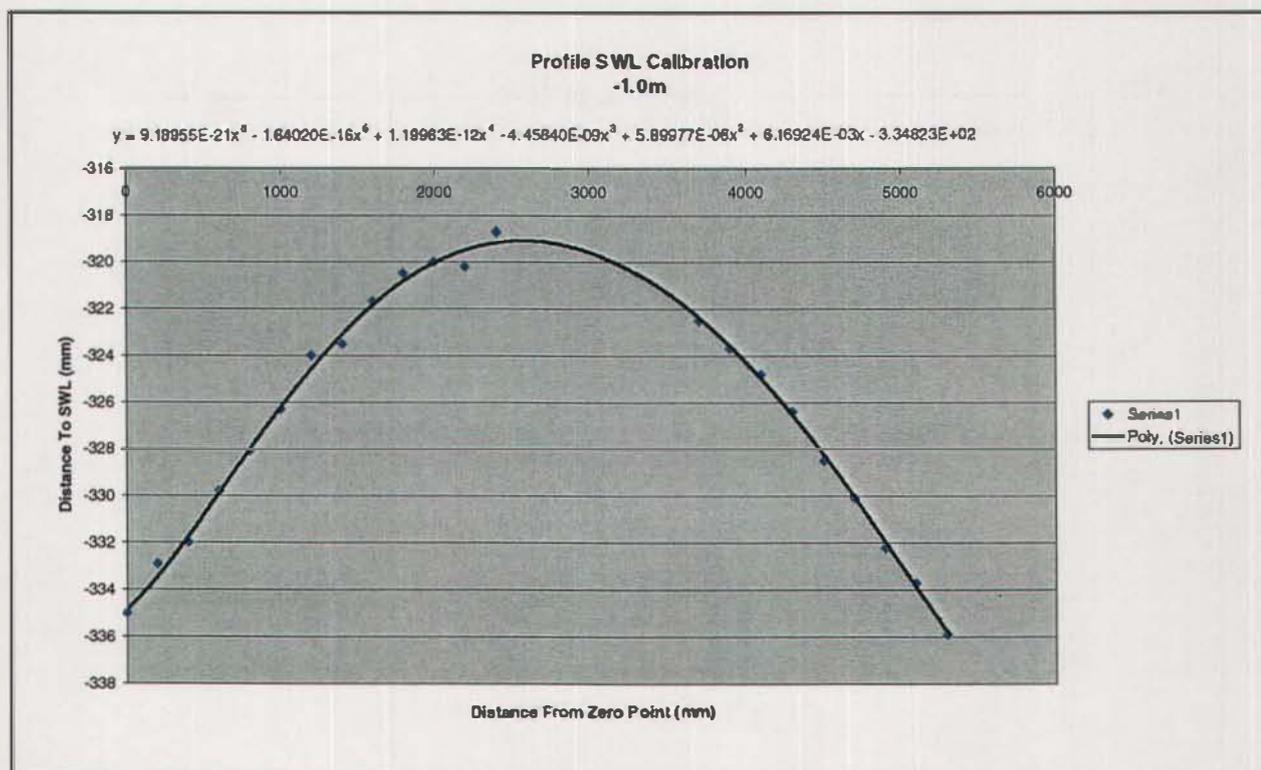


Figure 4 Correction to profiler results due to beam sag

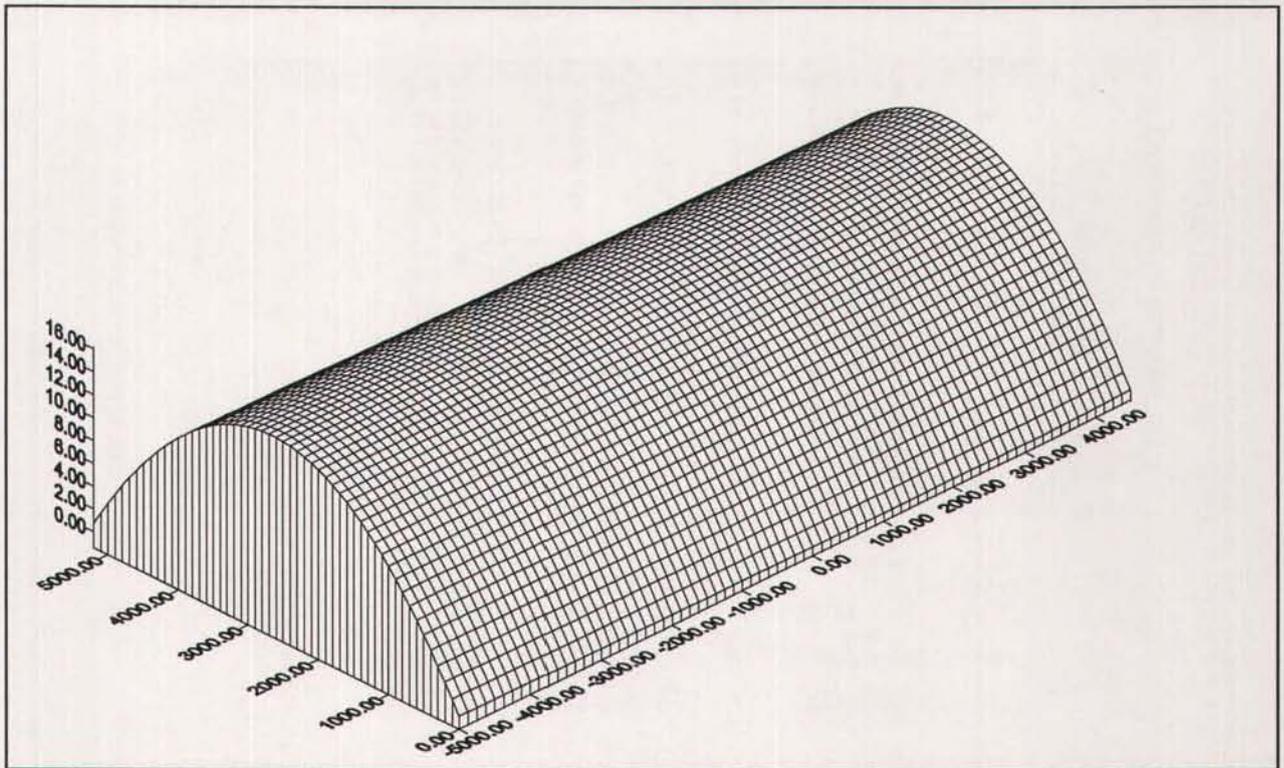


Figure 5 Correction map for final profile due to beam sag

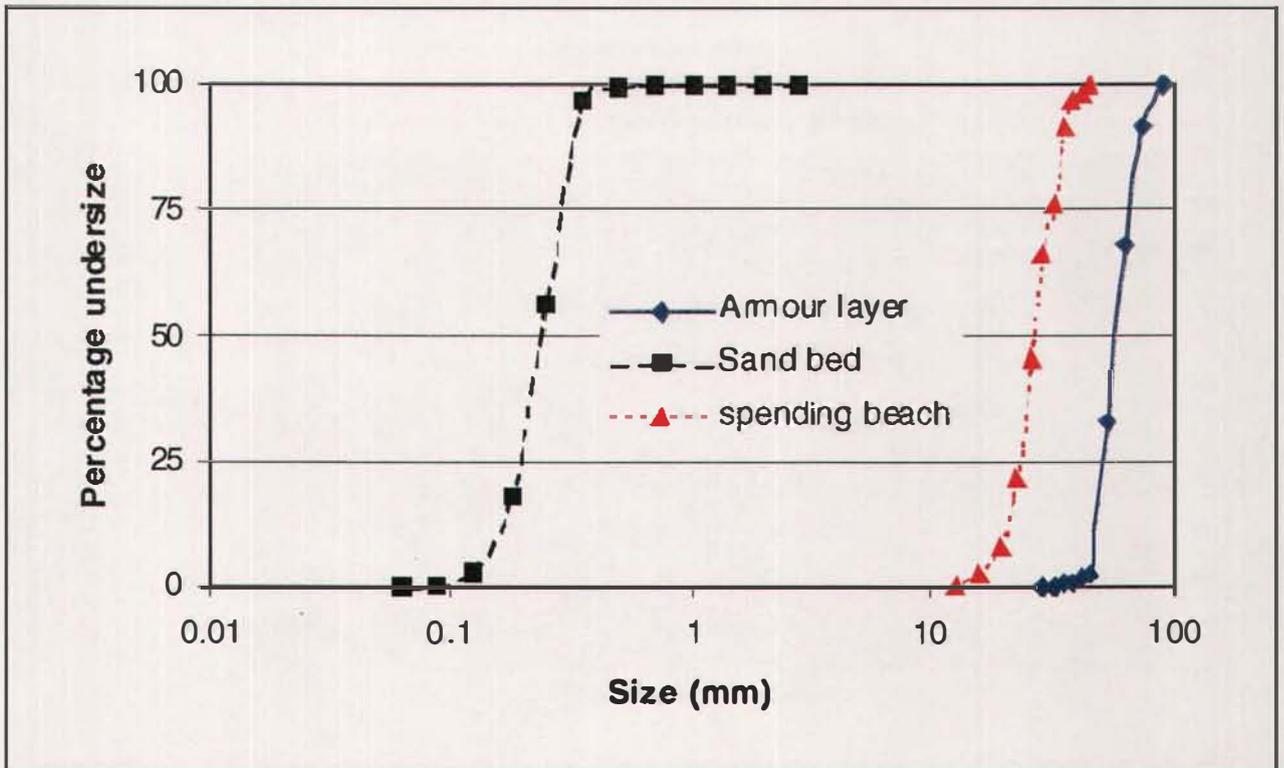


Figure 6 Size distribution of armour layer, sand bed and spending beach

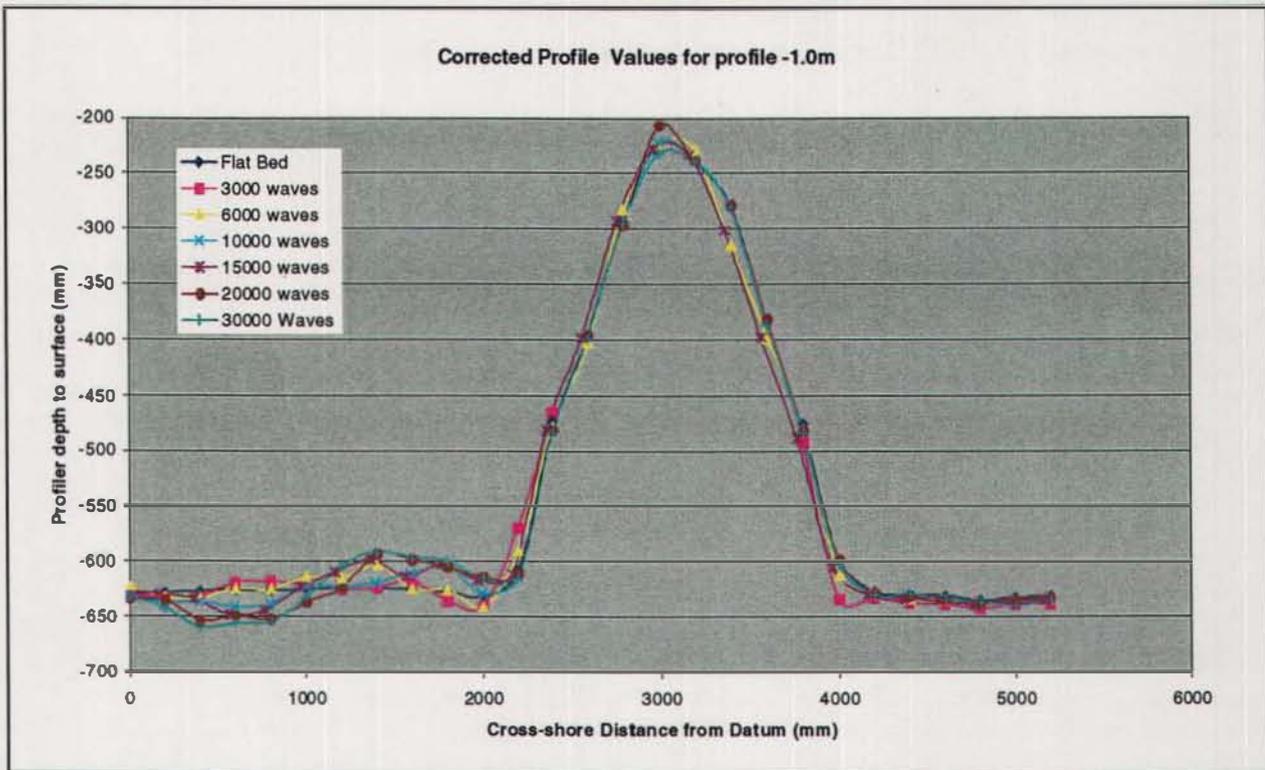


Figure 7 Test 1, time development of scour at $x_t = -1.00\text{m}$

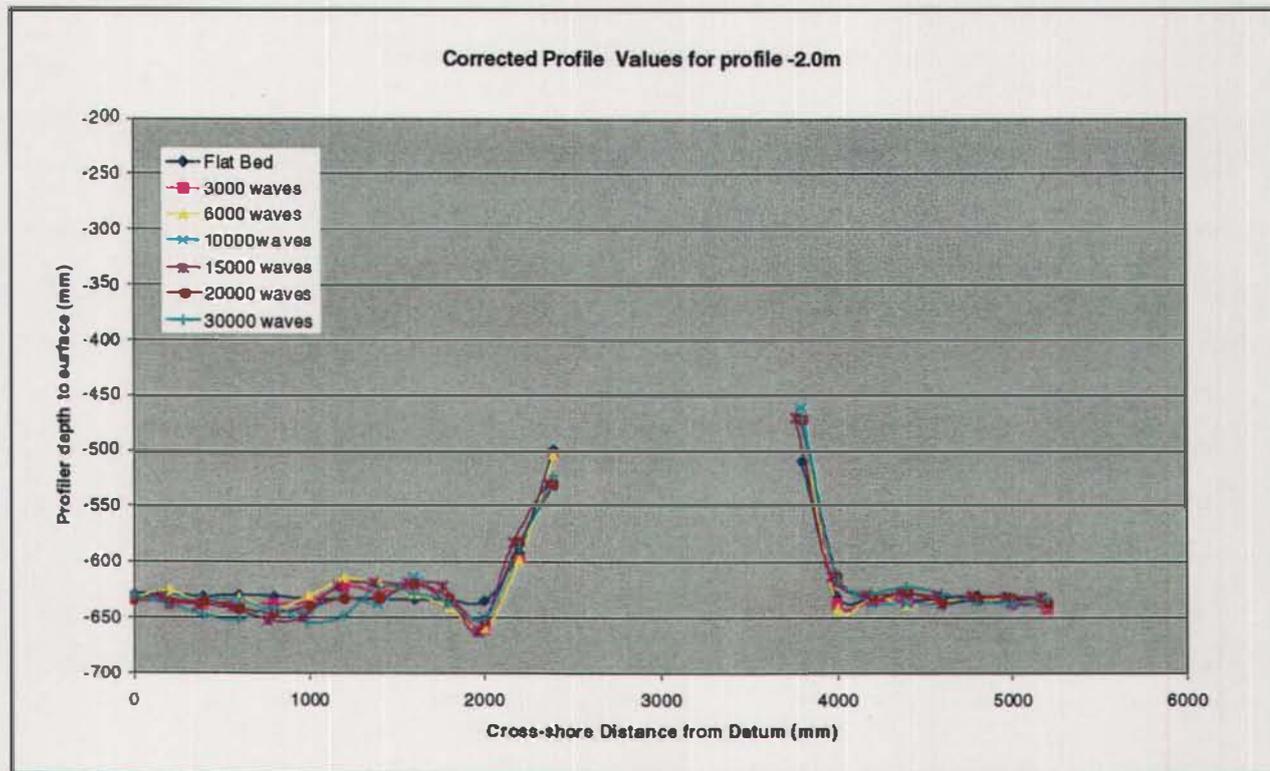


Figure 8 Test 1, time development of scour at $x_t = -2.00\text{m}$

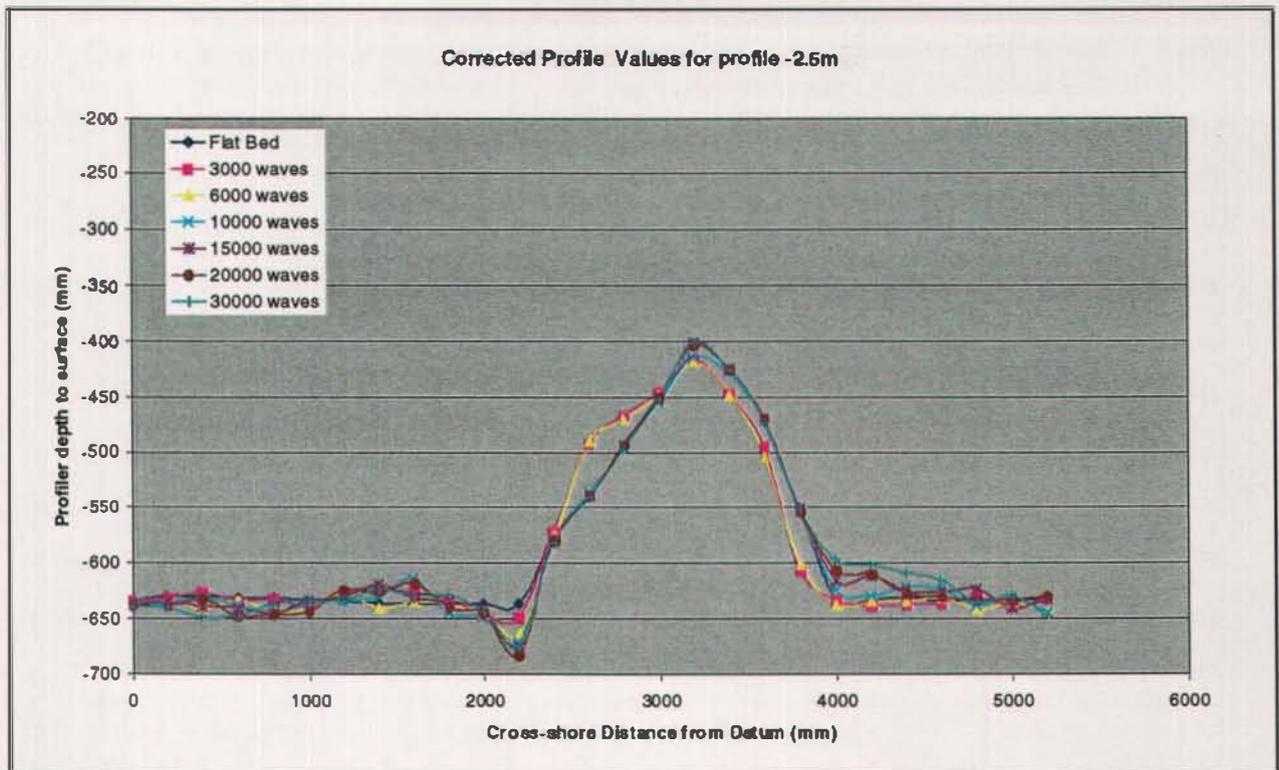


Figure 9 Test 1, time development of scour at $x_t = -2.50\text{m}$

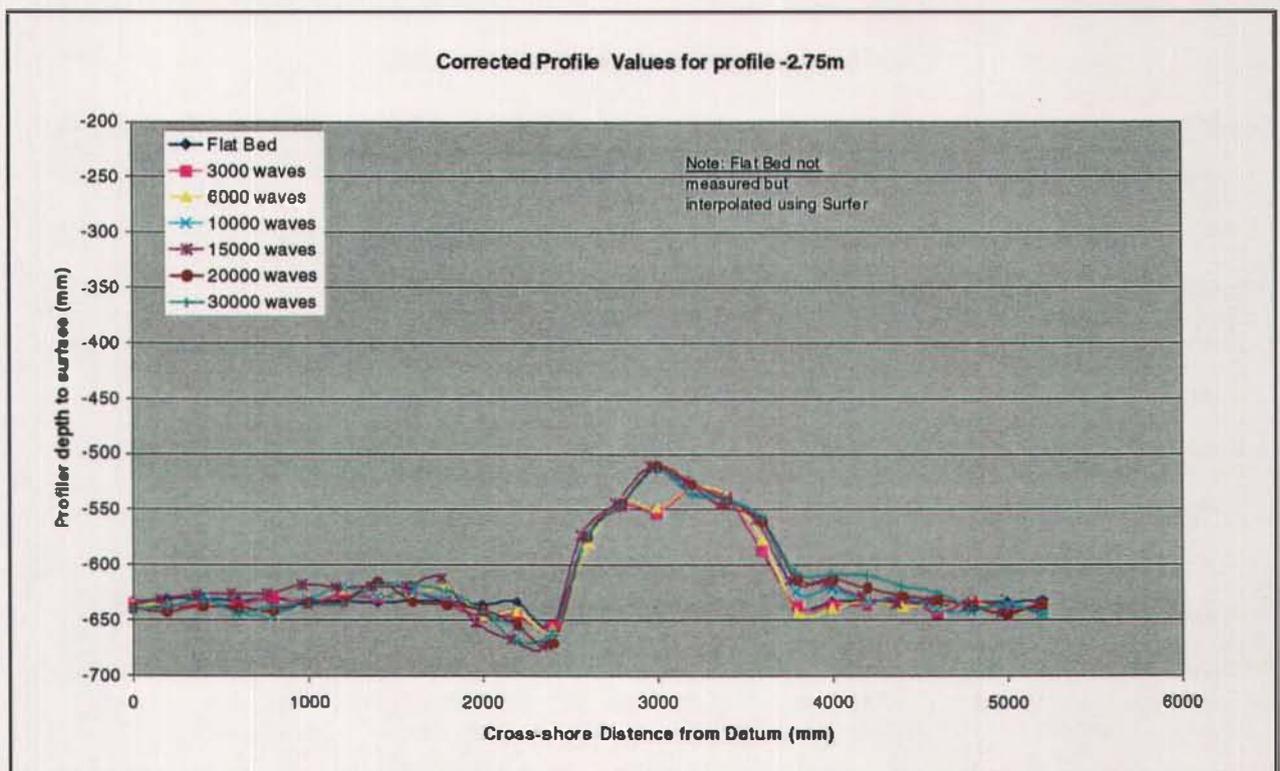


Figure 10 Test 1, time development of scour at $x_t = -2.75\text{m}$

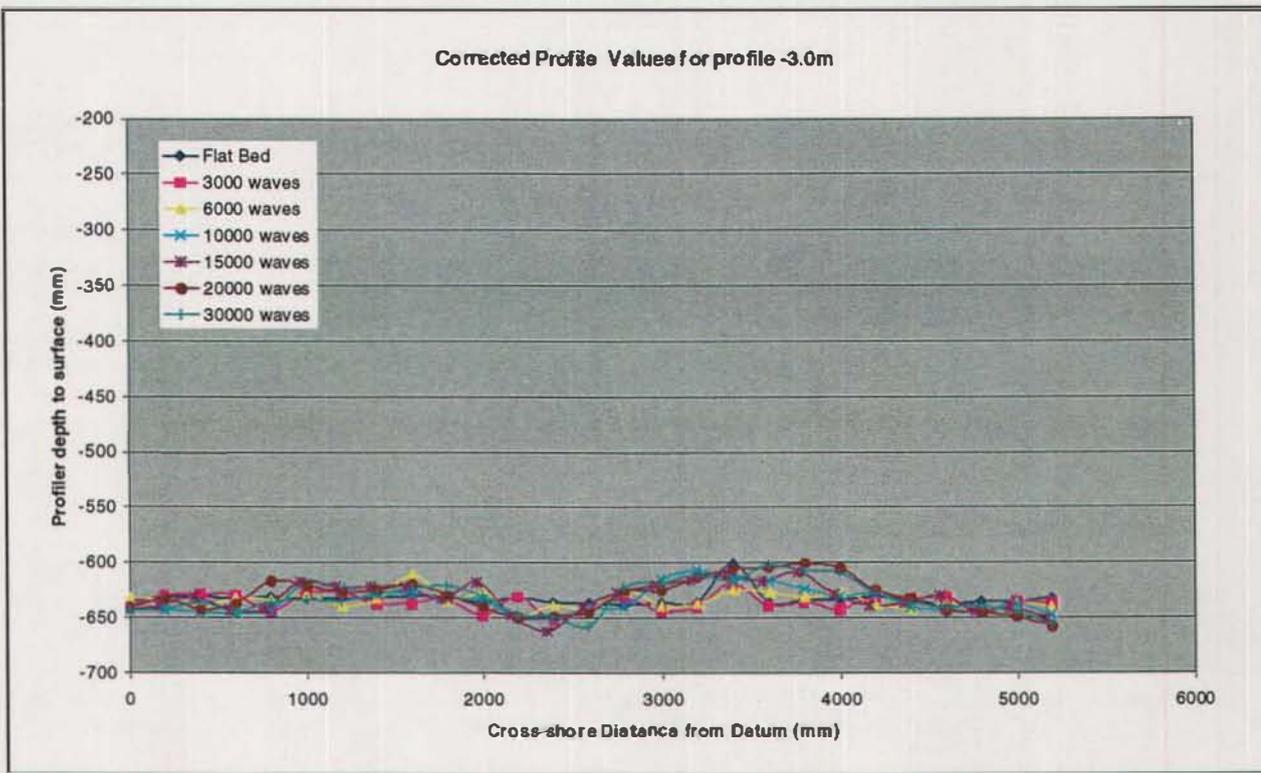


Figure 11 Test 1, time development of scour at $x_1 = -3.00\text{m}$

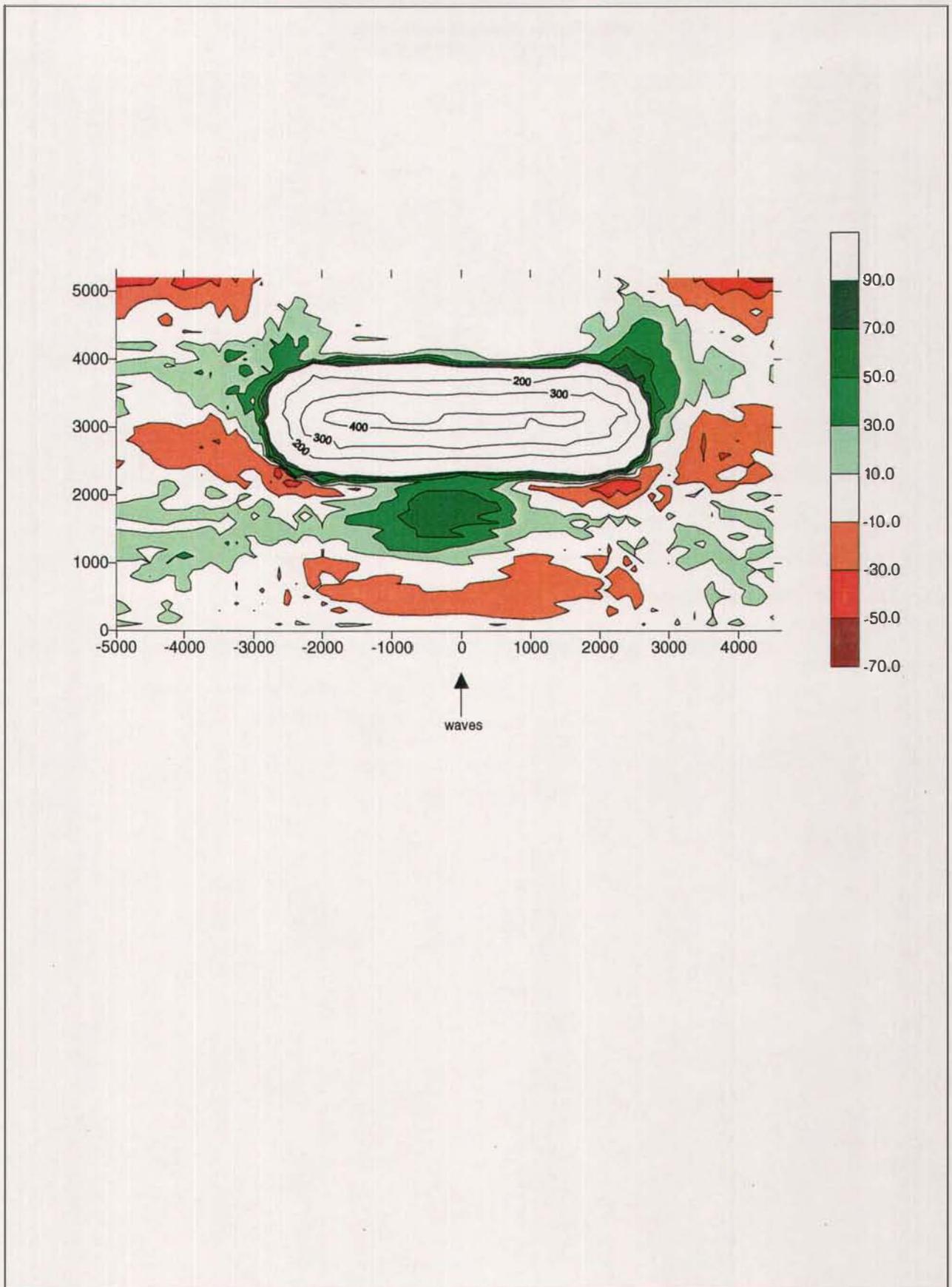


Figure 12 Test 1, final bathymetry – contour bands in millimetres

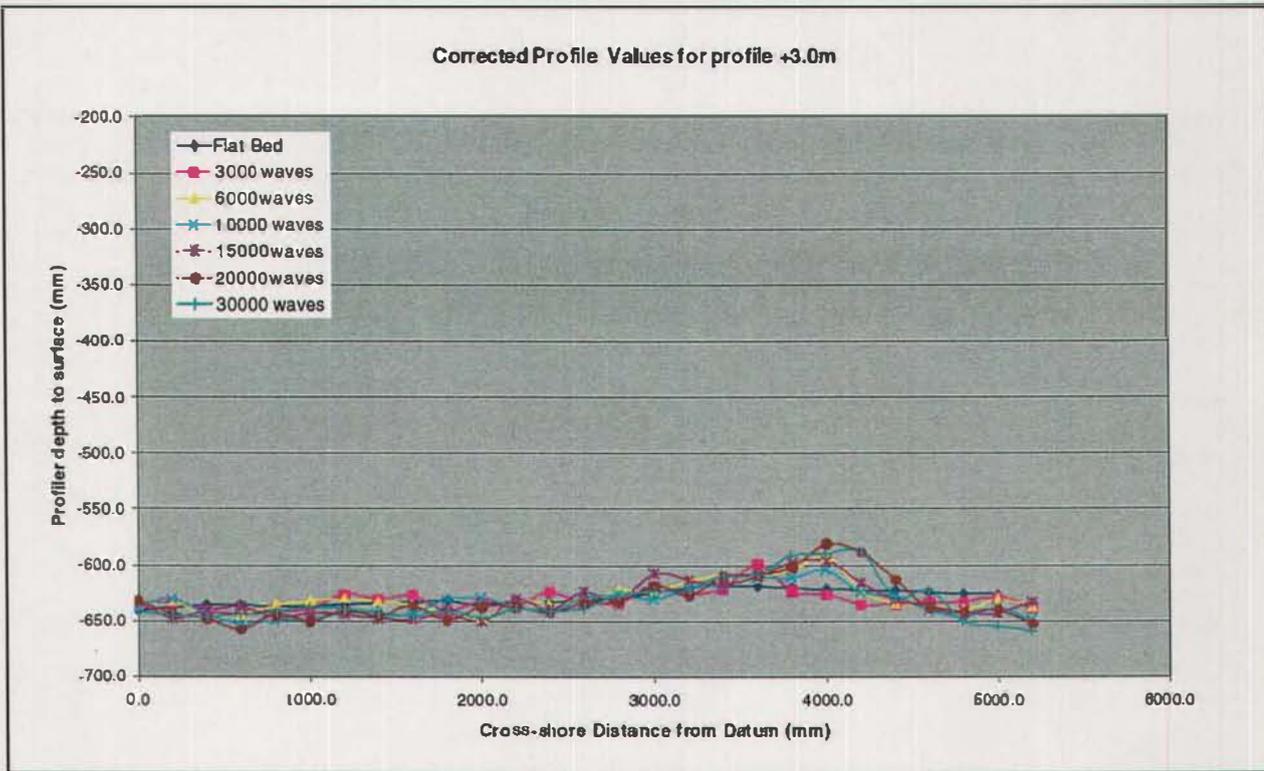


Figure 13 Test 5, time development of scour at $x_i = +3.00\text{m}$

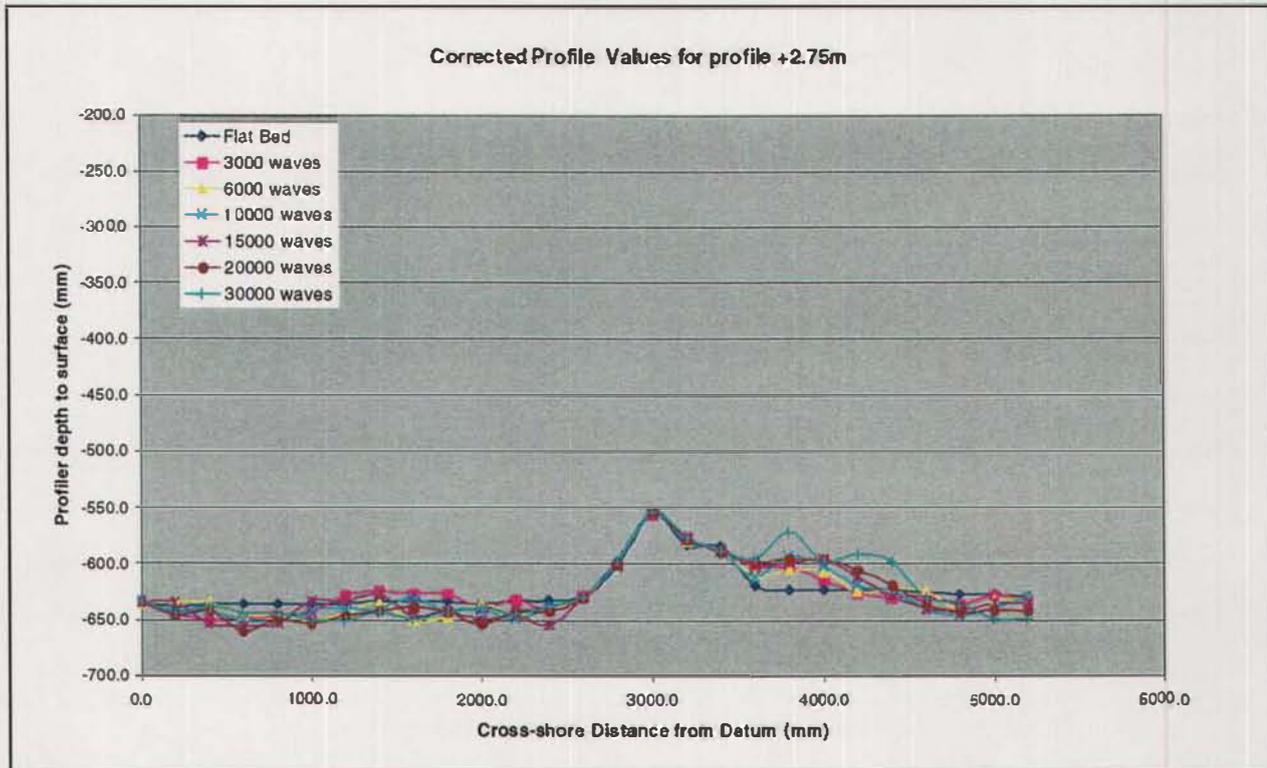


Figure 14 Test 5, time development of scour at $x_i = +2.75\text{m}$

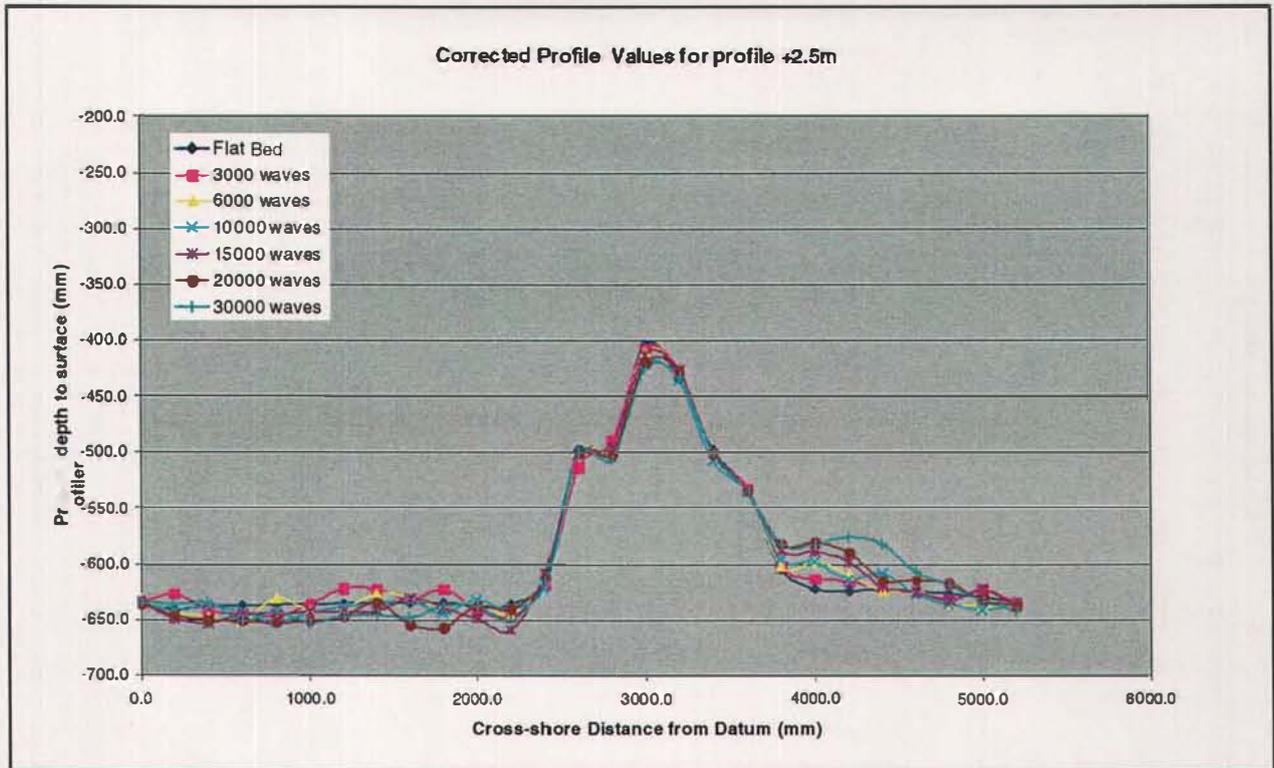


Figure 15 Test 5, time development of scour at $x_l = +2.50\text{m}$

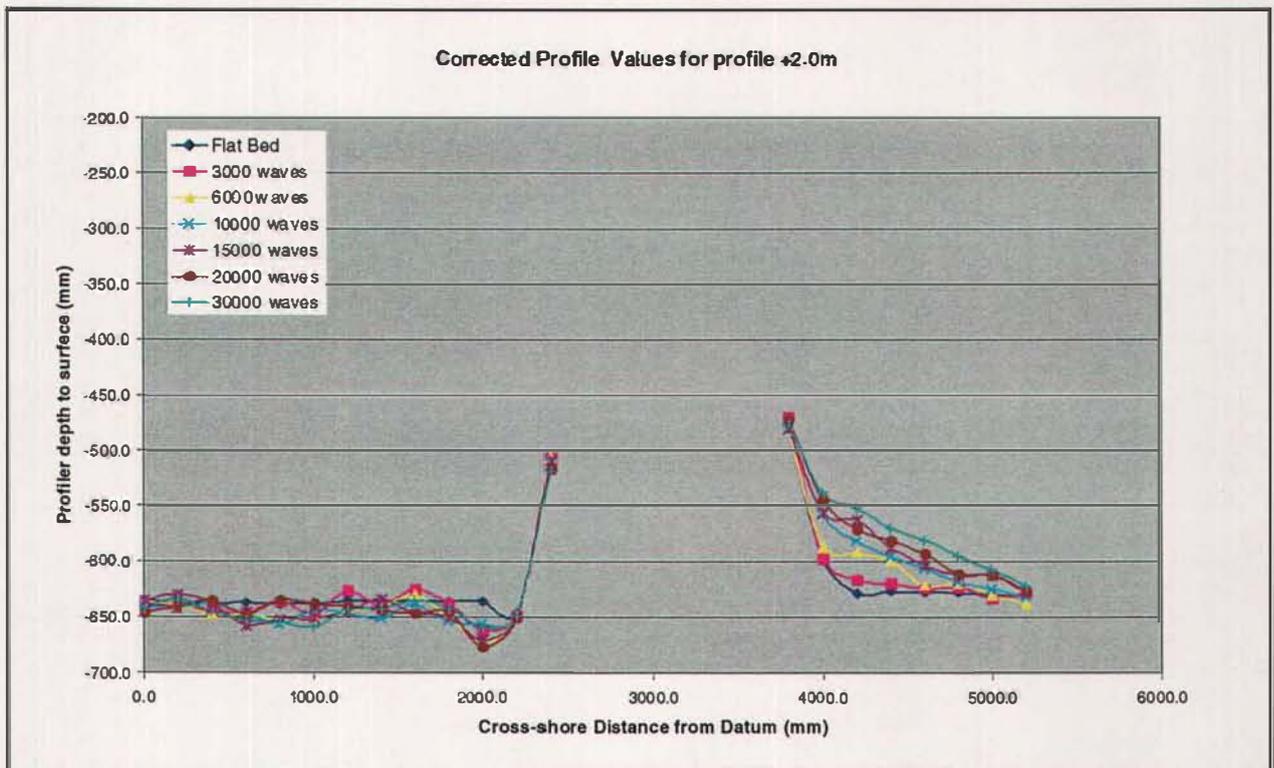


Figure 16 Test 5, time development of scour at $x_l = +2.00\text{m}$

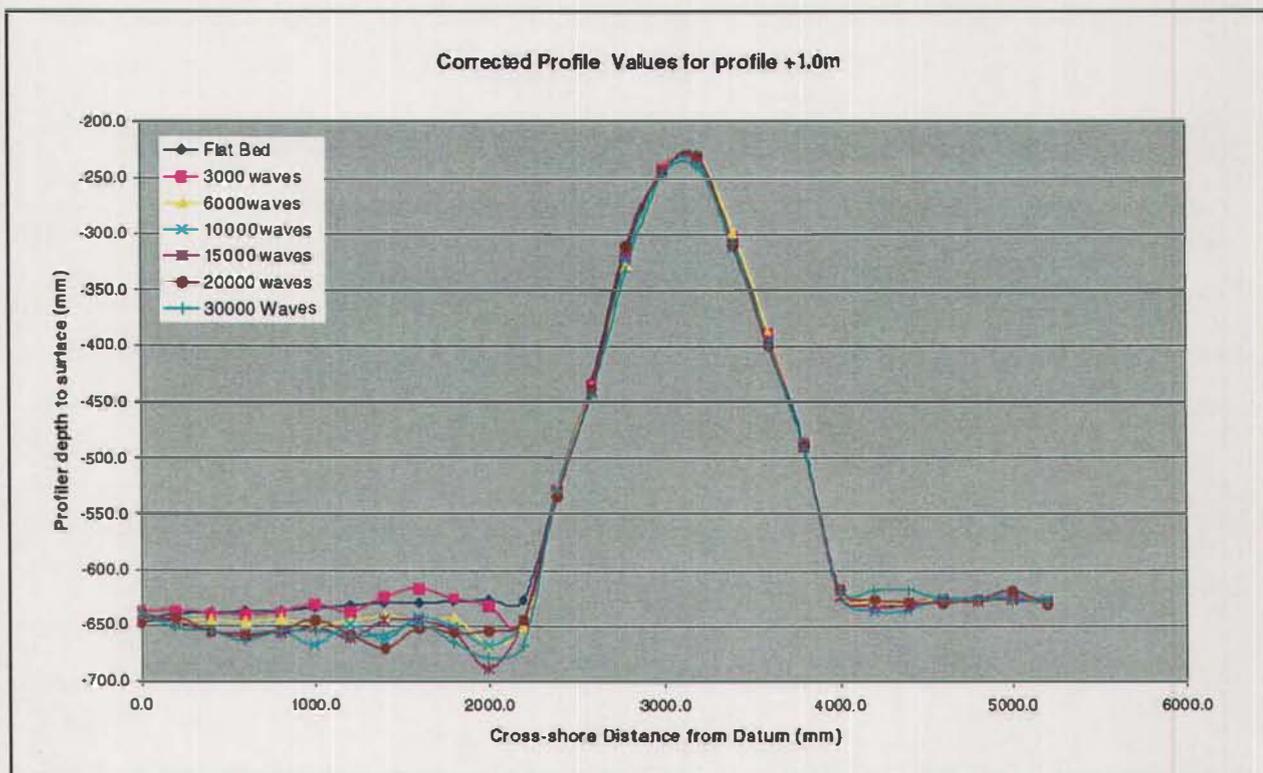


Figure 17 Test 5, time development of scour at $x_1 = +1.00\text{m}$

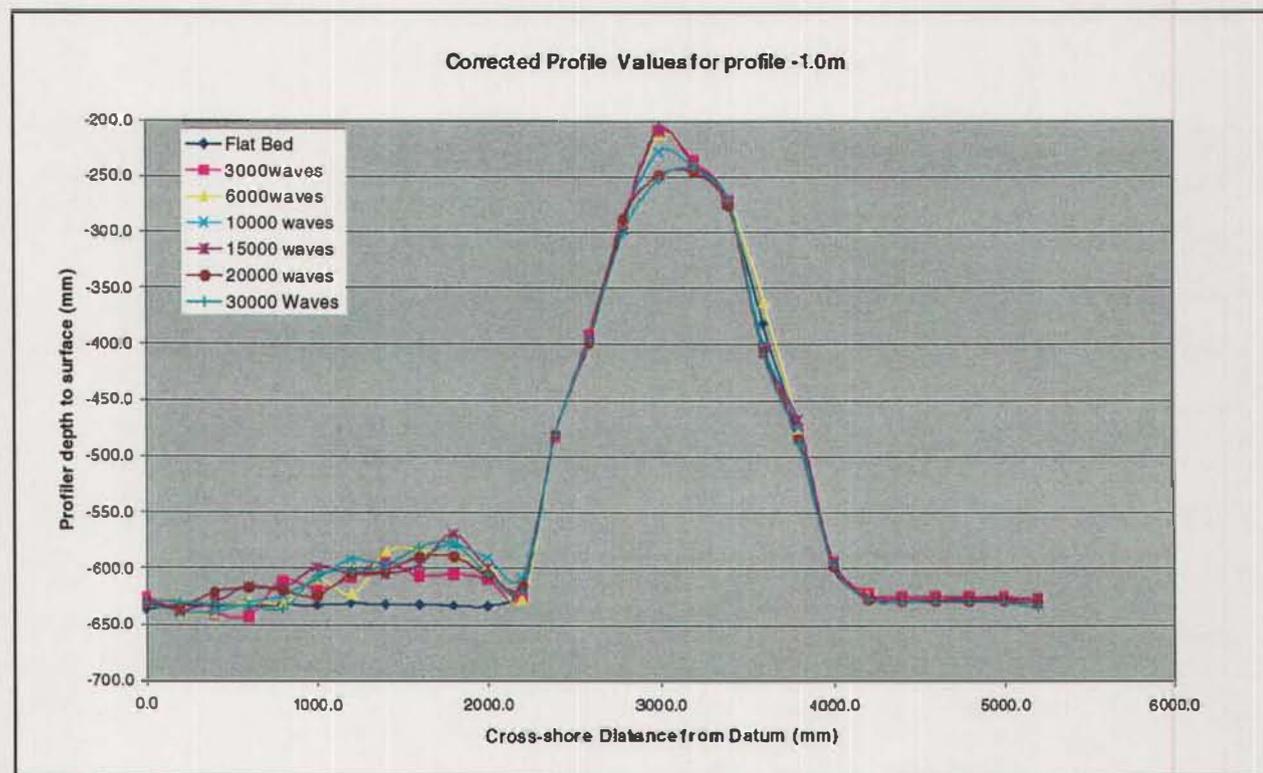


Figure 18 Test 5, time development of scour at $x_2 = -1.00\text{m}$

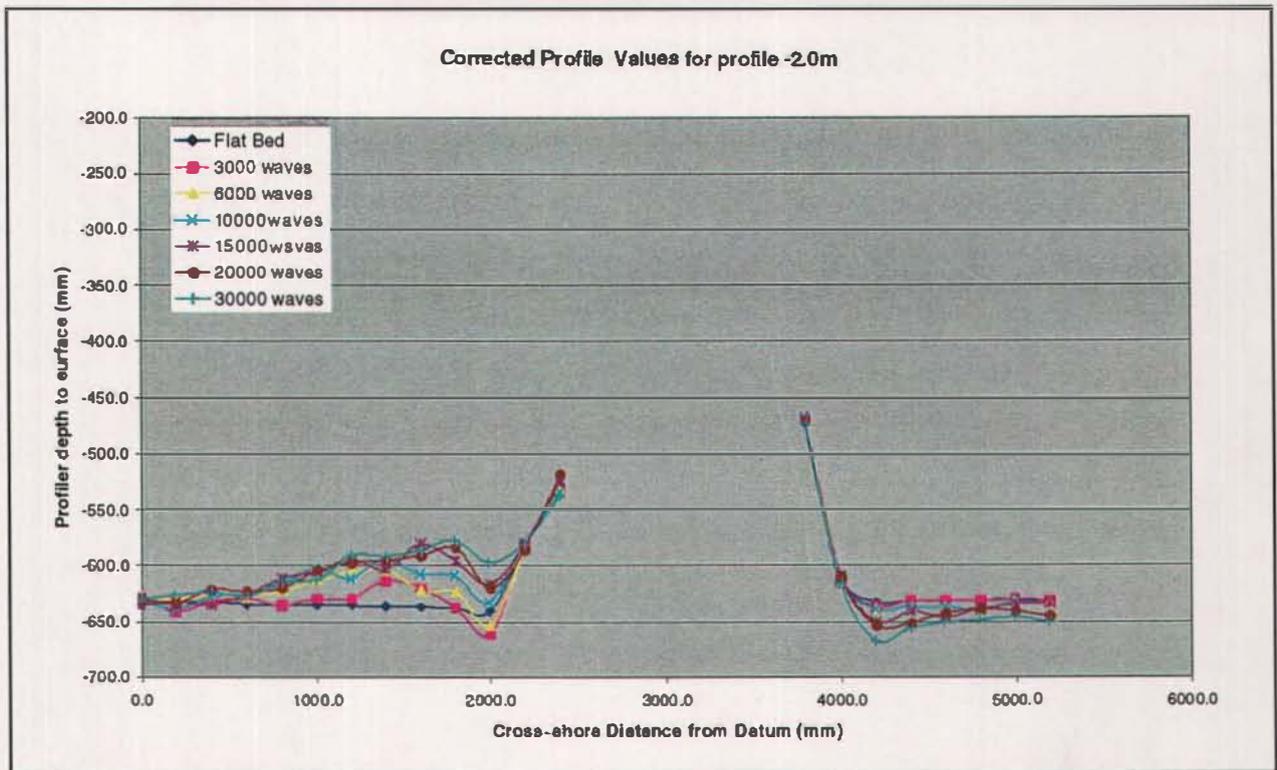


Figure 19 Test 5, time development of scour at $x_l = -2.00\text{m}$

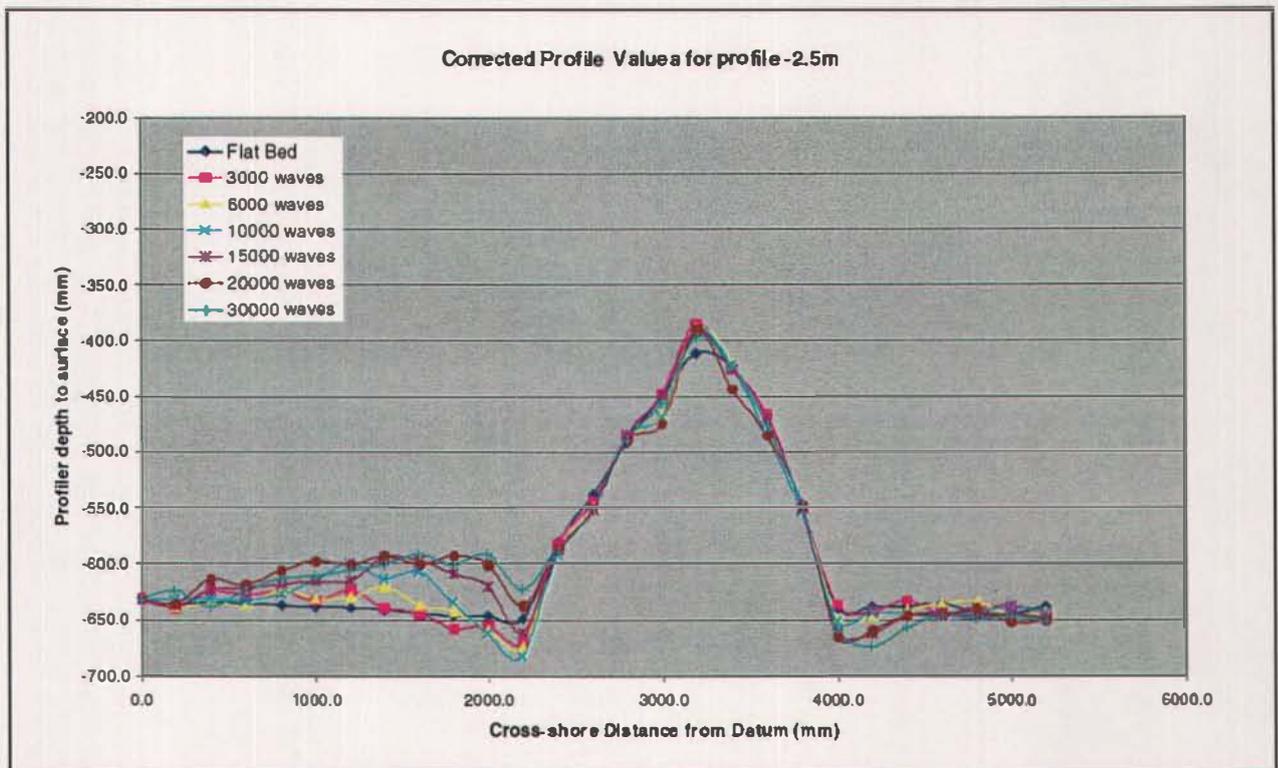


Figure 20 Test 5, time development of scour at $x_l = -2.50\text{m}$

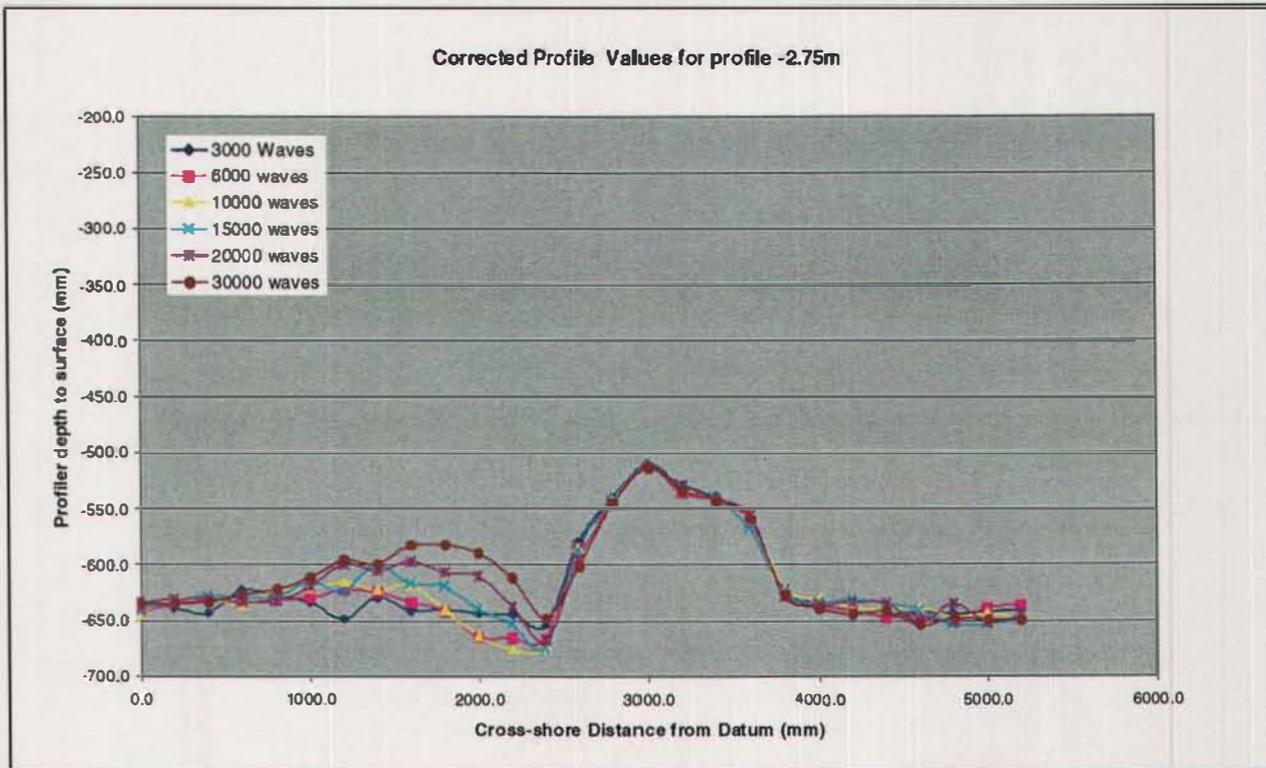


Figure 21 Test 5, time development of scour at $x_1 = -2.75m$

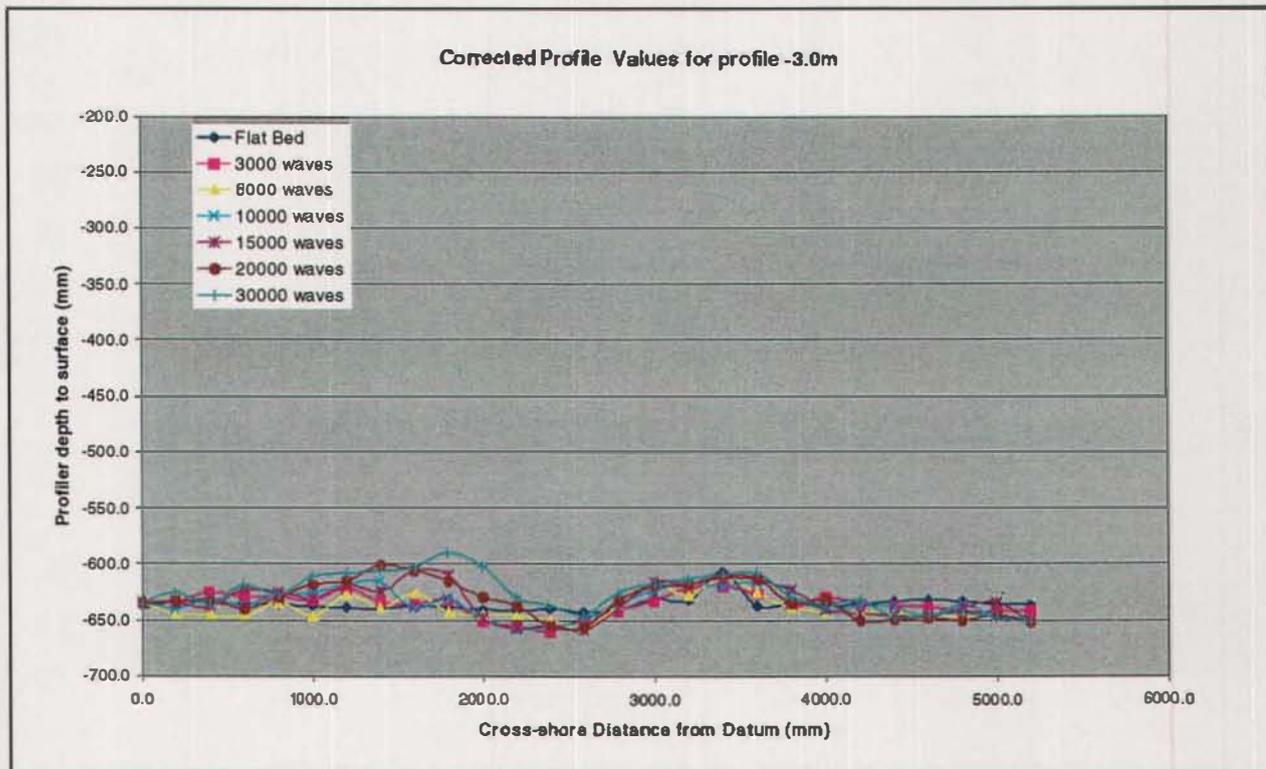


Figure 22 Test 5, time development of scour at $x_1 = -3.00m$

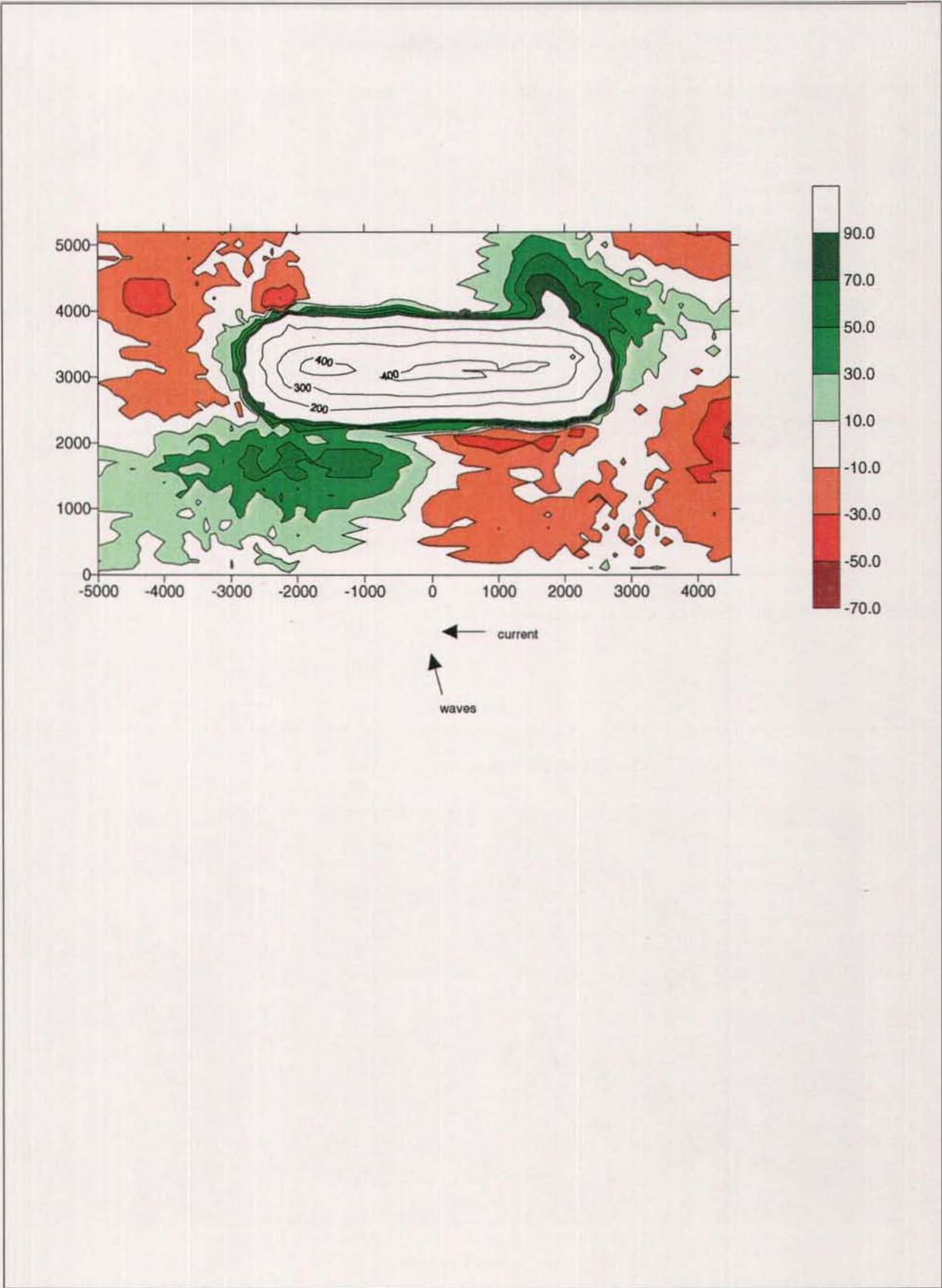


Figure 23 Test 5, final bathymetry – contour bands in millimetres

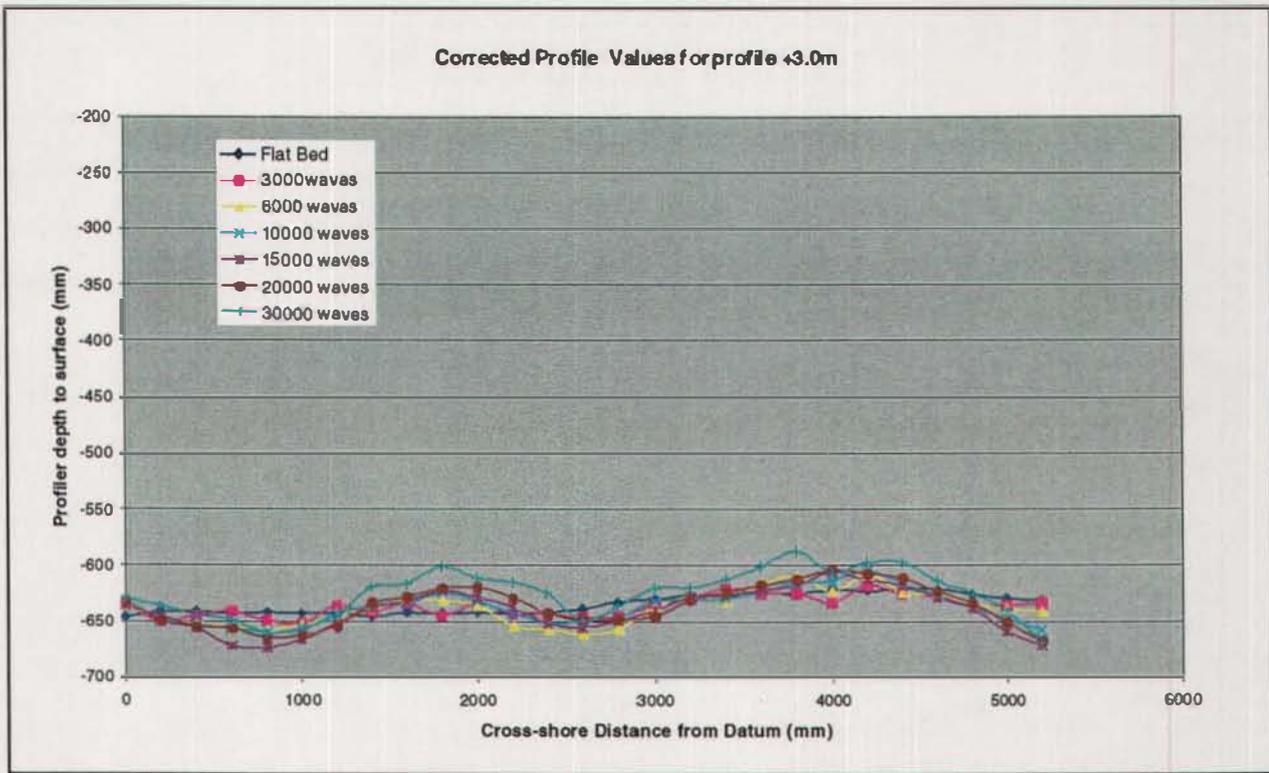


Figure 24 Test 3, time development of scour at $x_t = +3.00\text{m}$

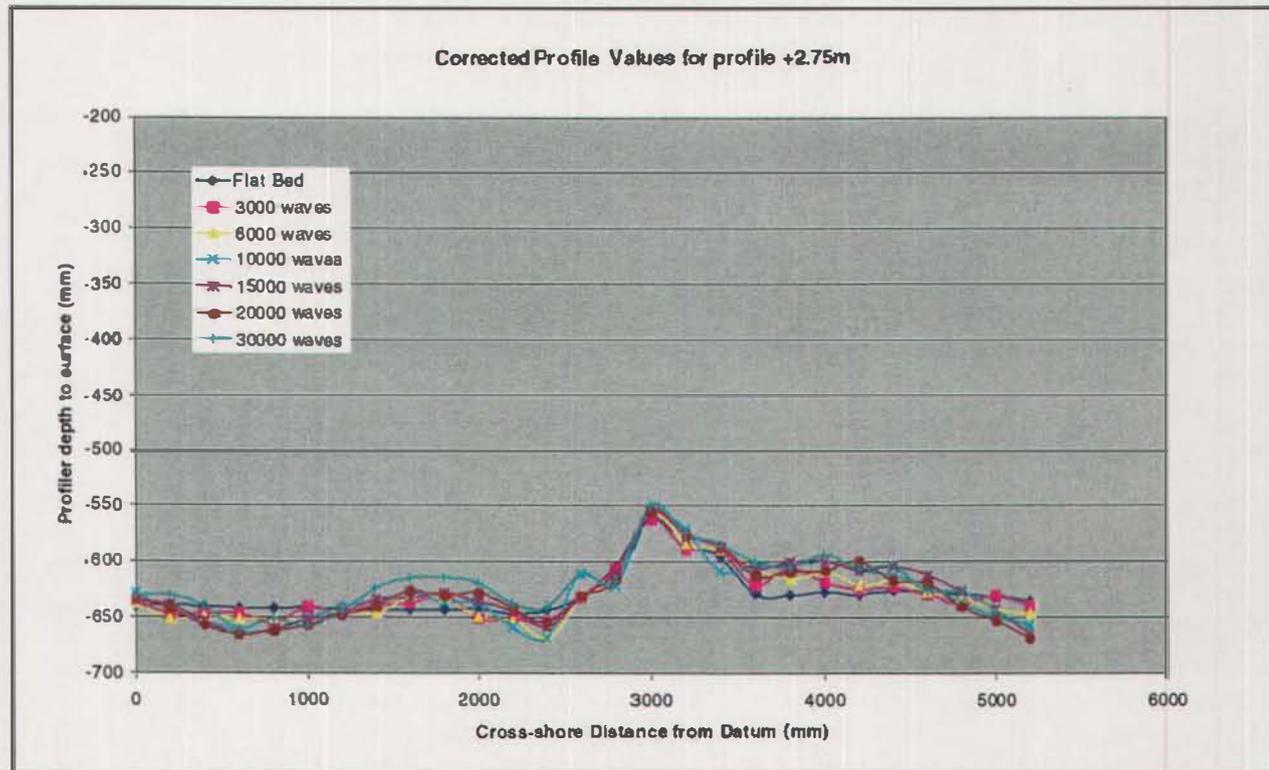


Figure 25 Test 3, time development of scour at $x_t = +2.75\text{m}$

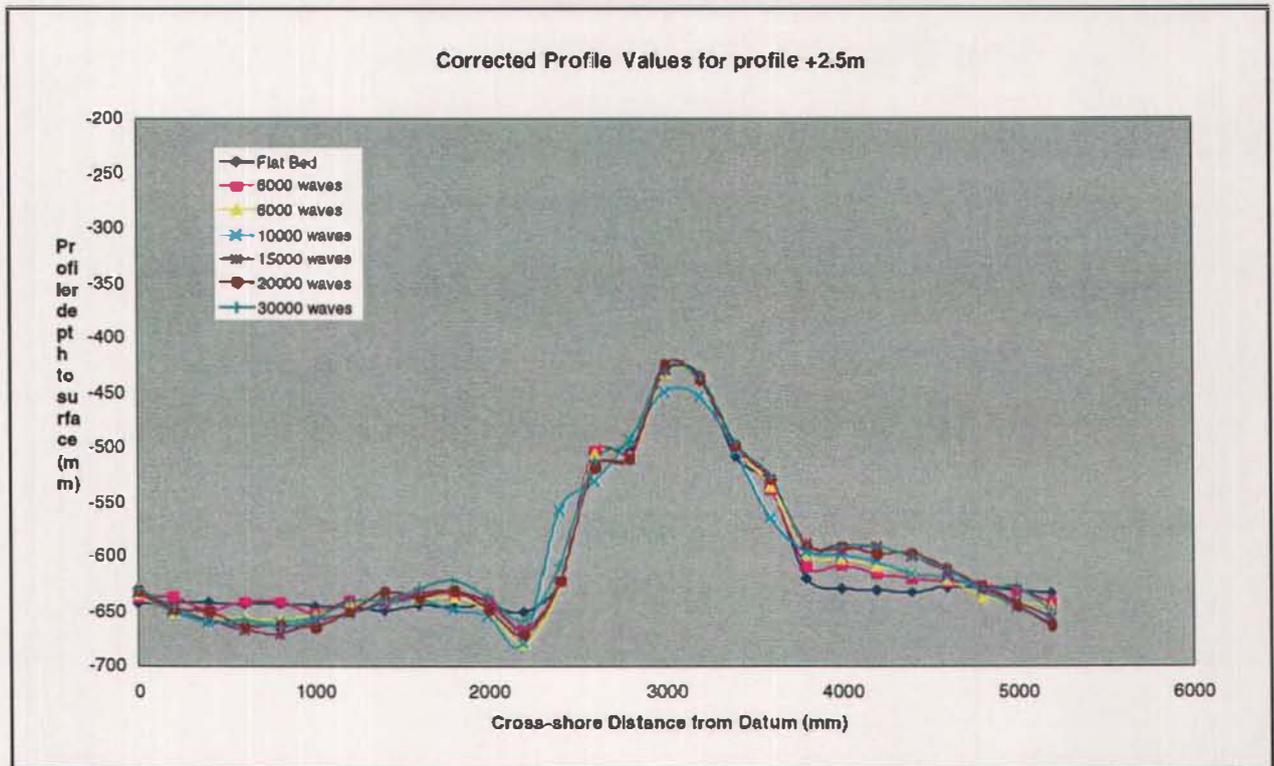


Figure 26 Test 3, time development of scour at $x_l = +2.50\text{m}$

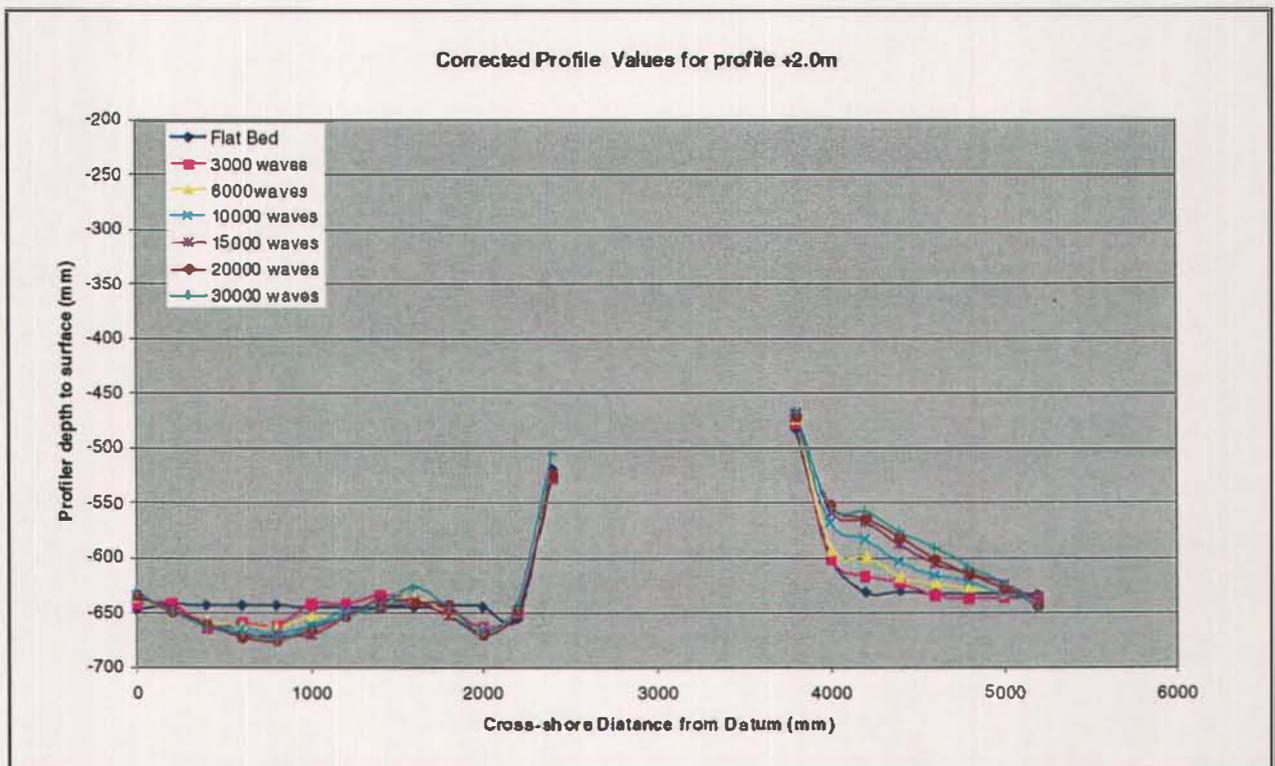


Figure 27 Test 3, time development of scour at $x_l = +2.00\text{m}$

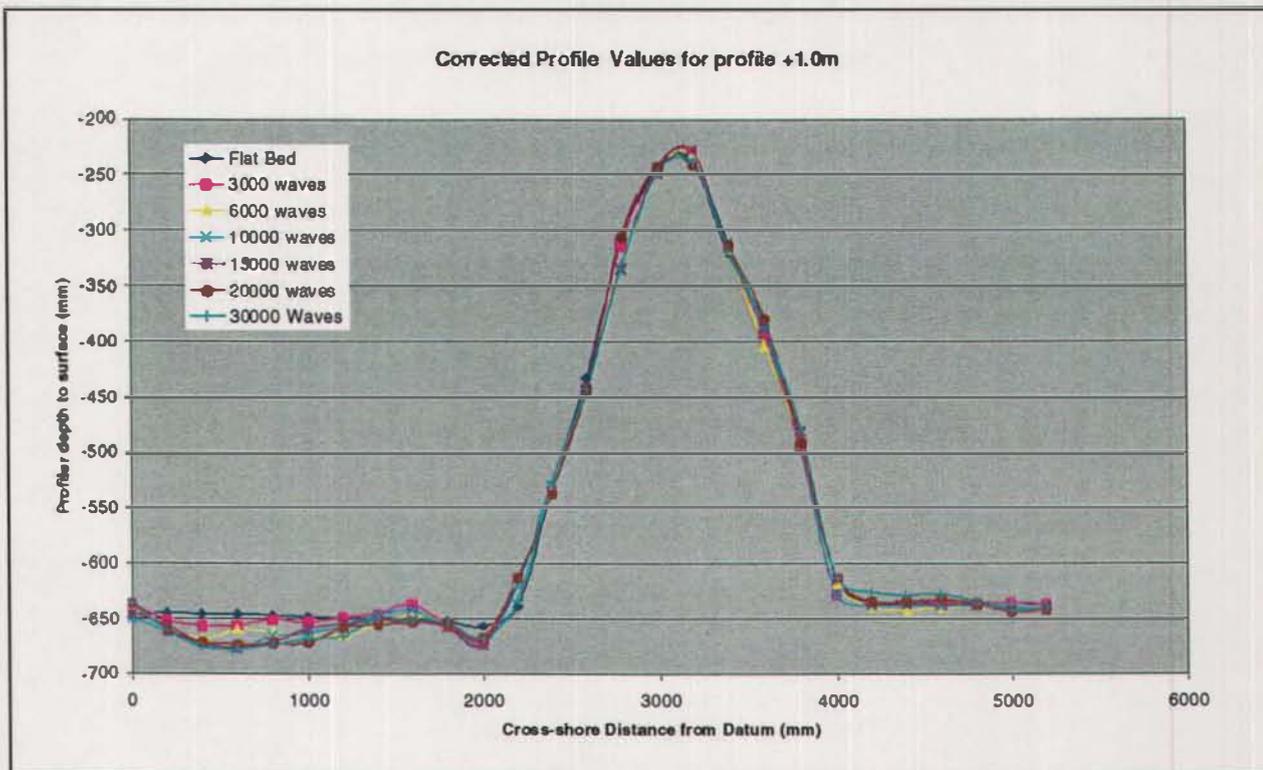


Figure 28 Test 3, time development of scour at $x_t = +1.00\text{m}$

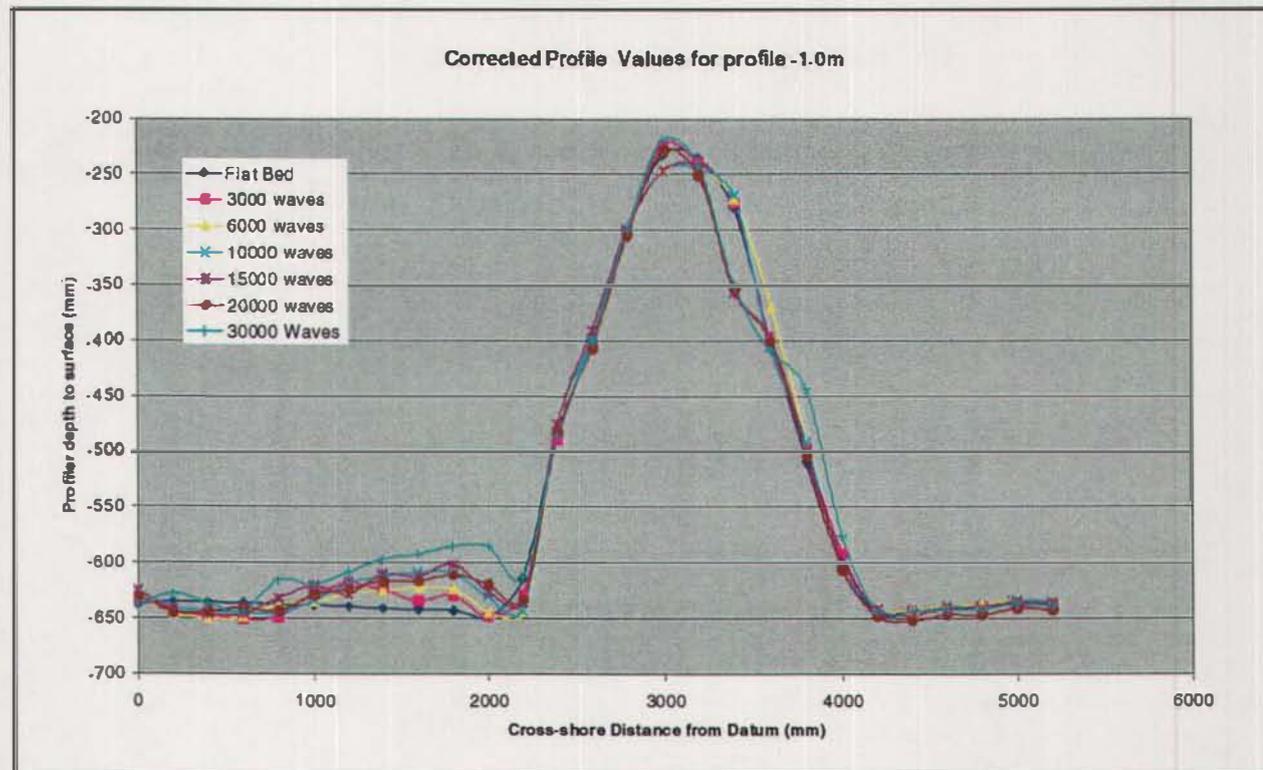


Figure 29 Test 3, time development of scour at $x_t = -1.00\text{m}$

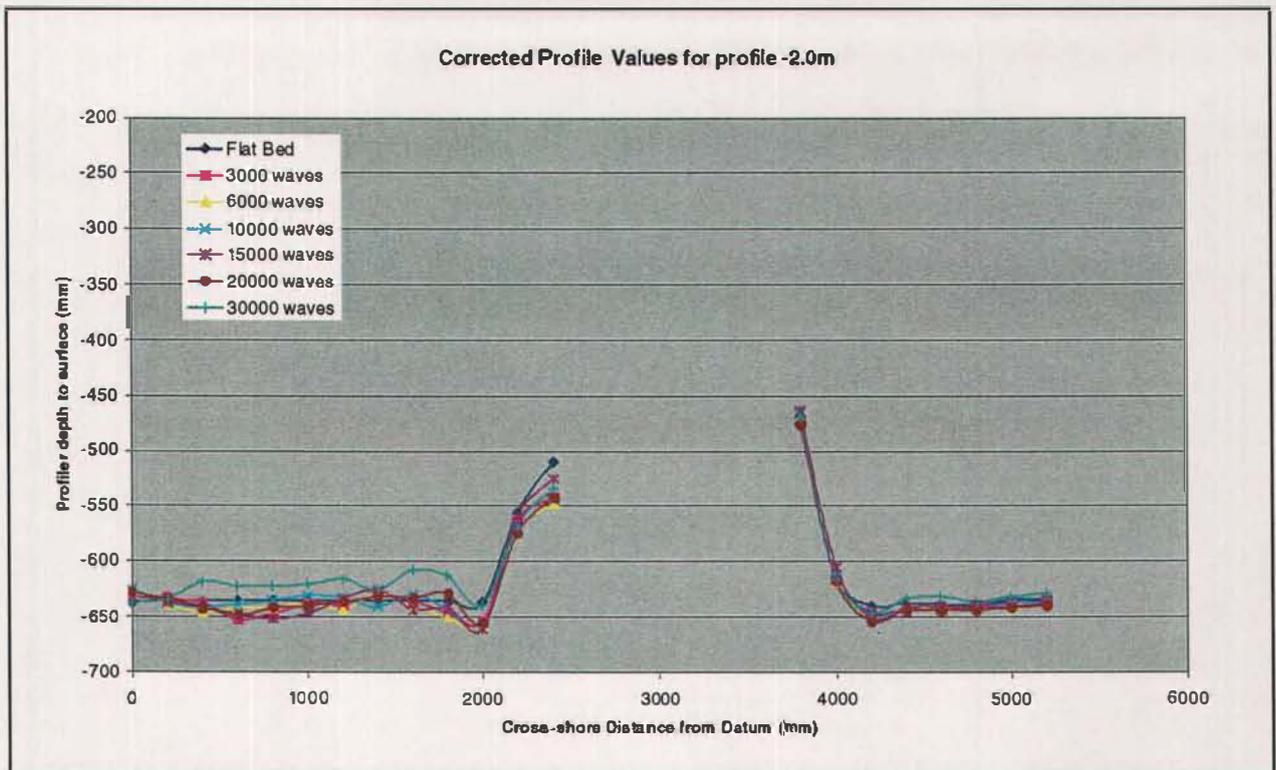


Figure 30 Test 3, time development of scour at $x_i = -2.00\text{m}$

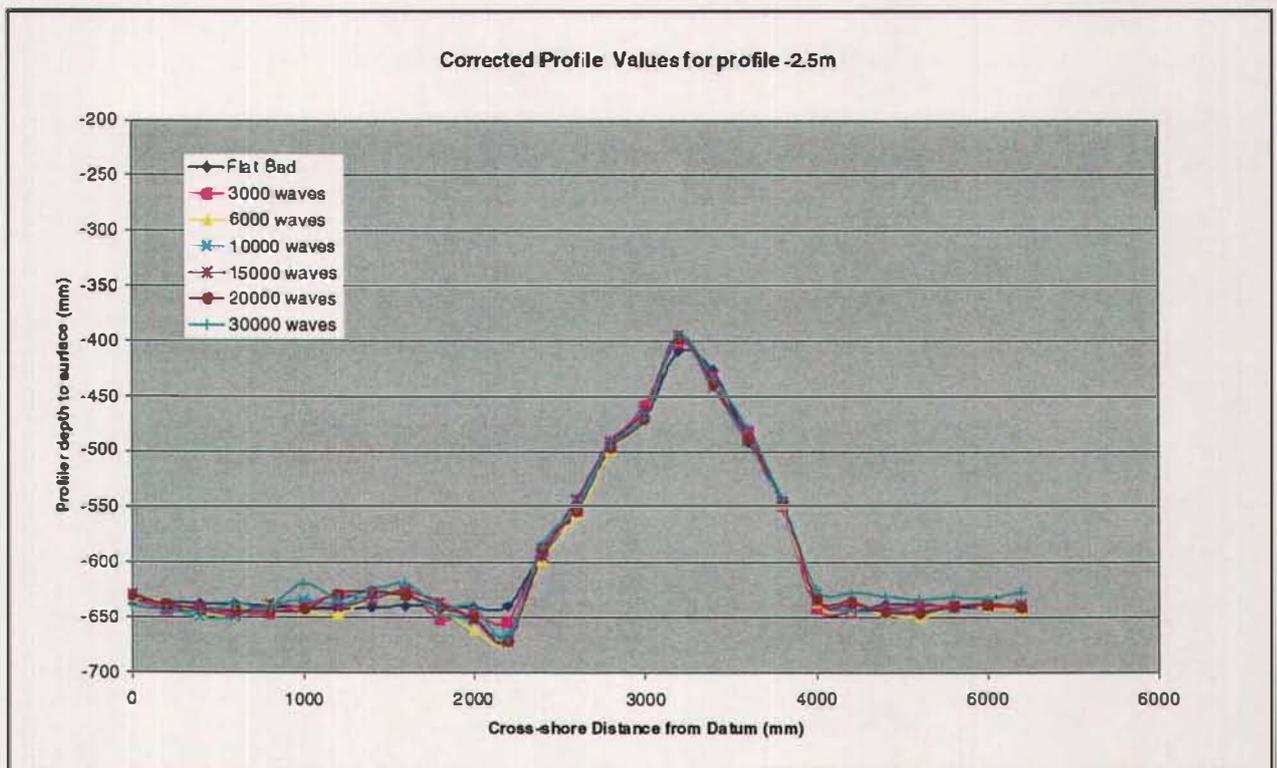


Figure 31 Test 3, time development of scour at $x_i = -2.50\text{m}$

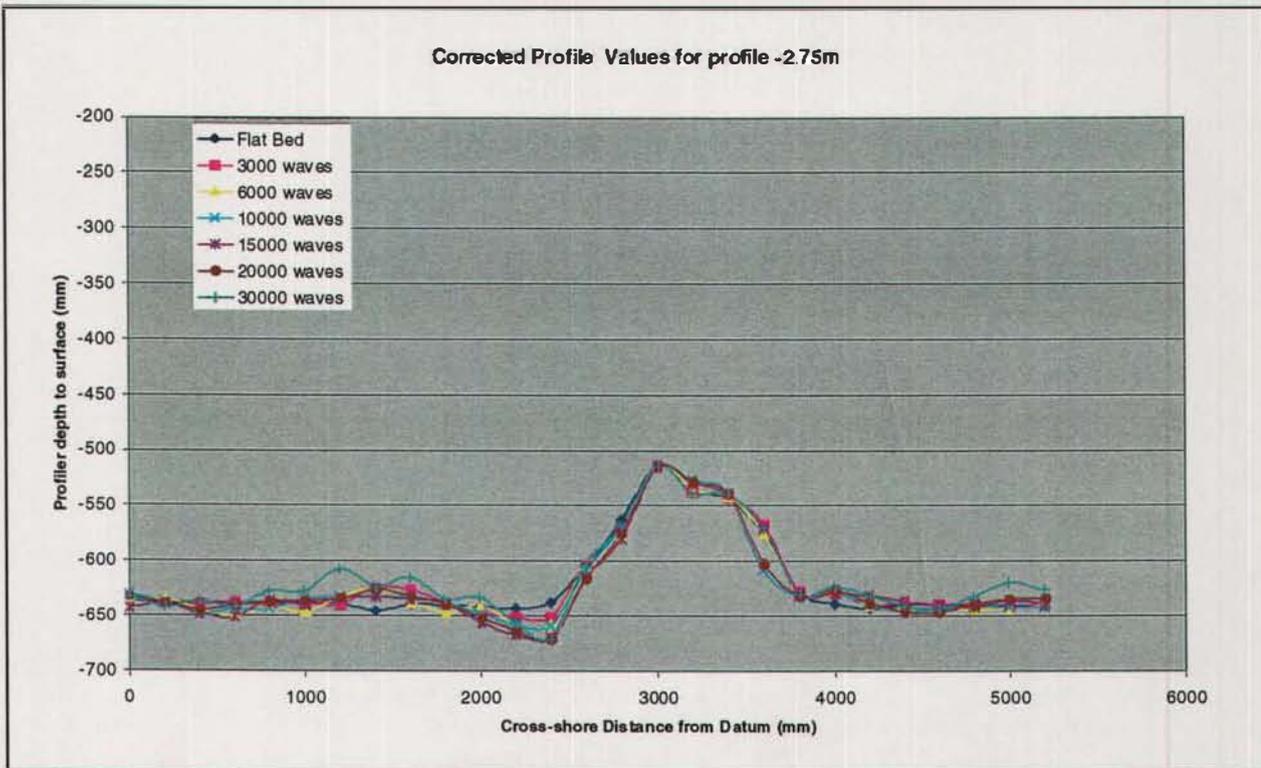


Figure 32 Test 3, time development of scour at $x_t = -2.75\text{m}$

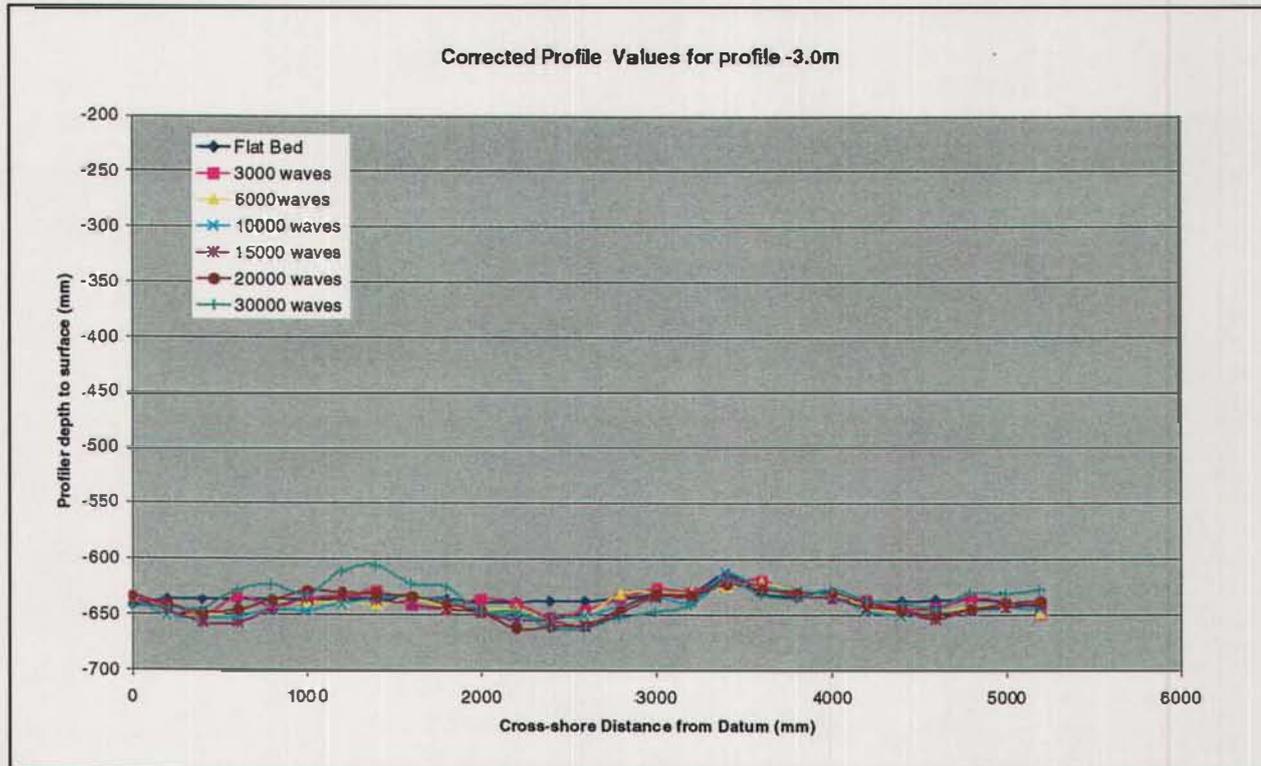


Figure 33 Test 3, time development of scour at $x_t = -3.00\text{m}$

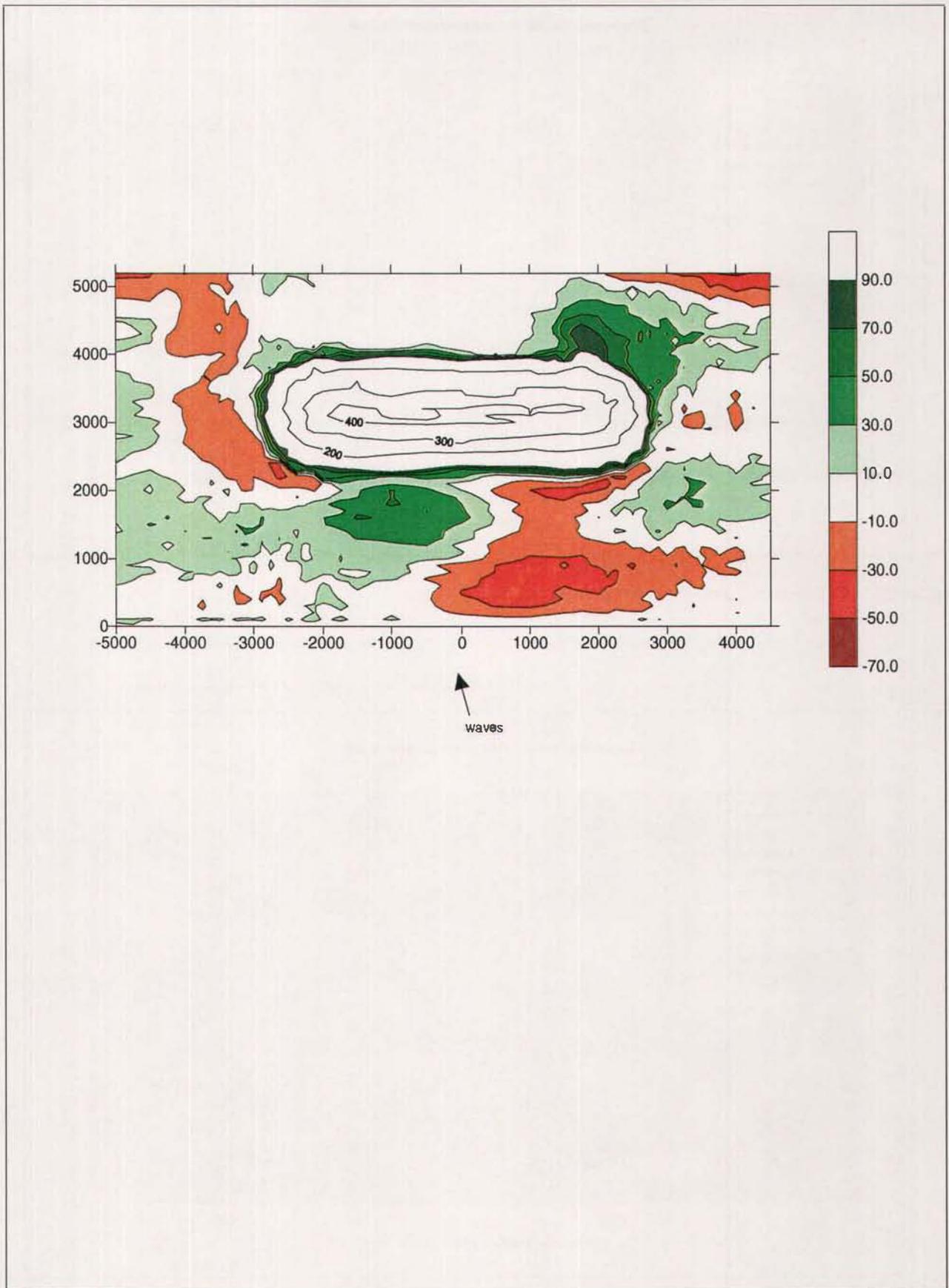


Figure 34 Test 3 final bathymetry – contour bands in millimetres

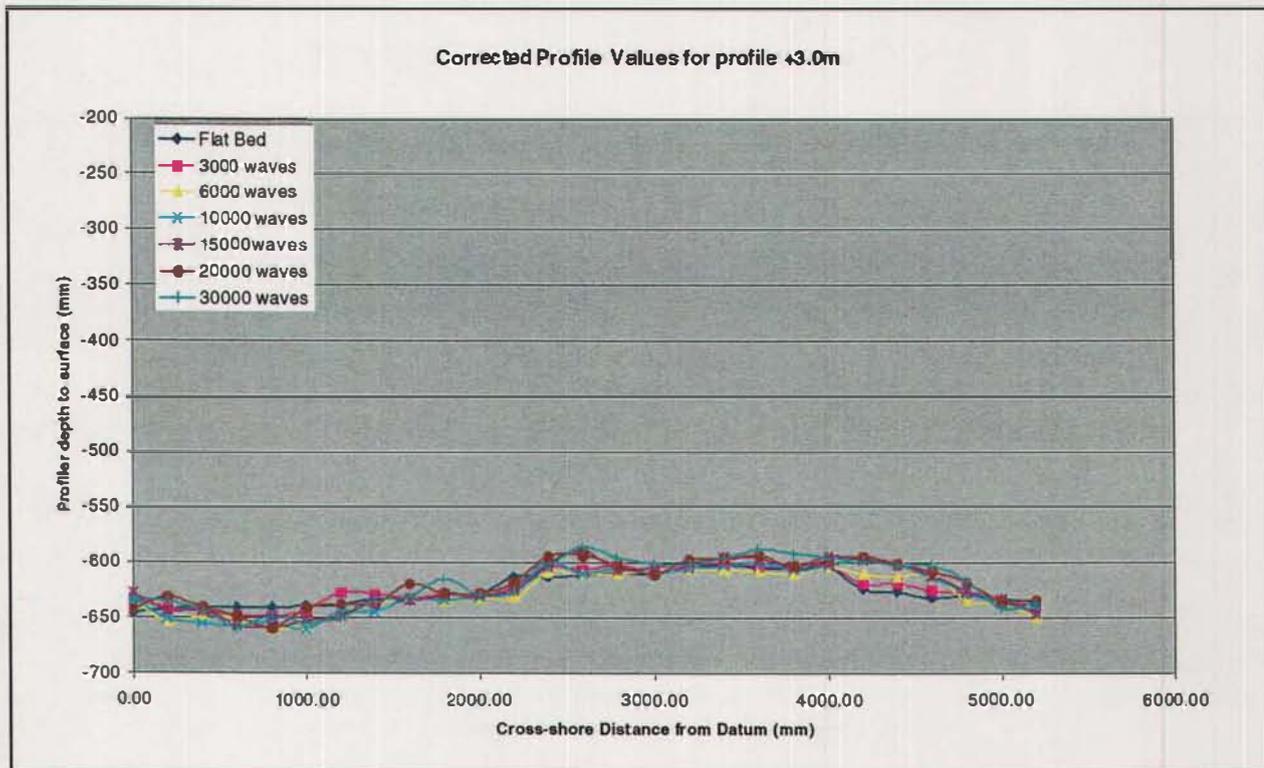


Figure 35 Test 6, time development of scour at $x_t = +3.00\text{m}$

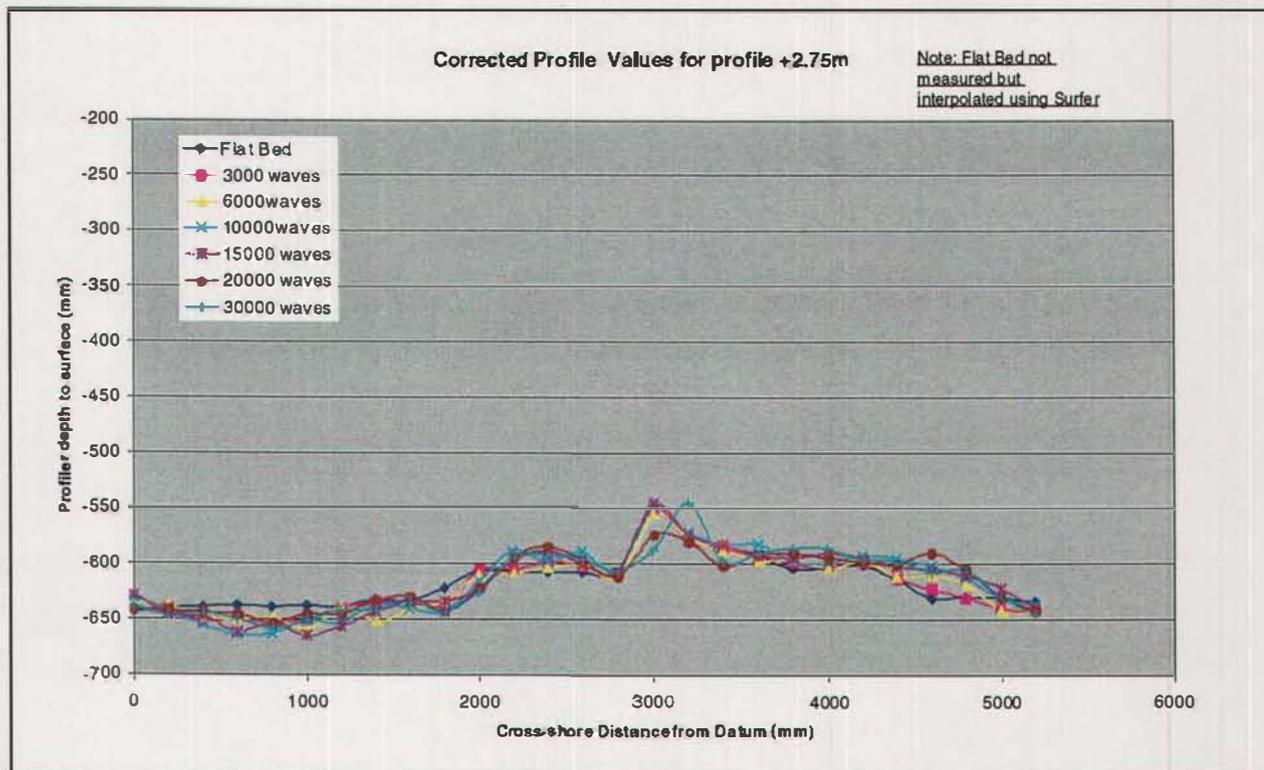


Figure 36 Test 6, time development of scour at $x_t = +2.75\text{m}$

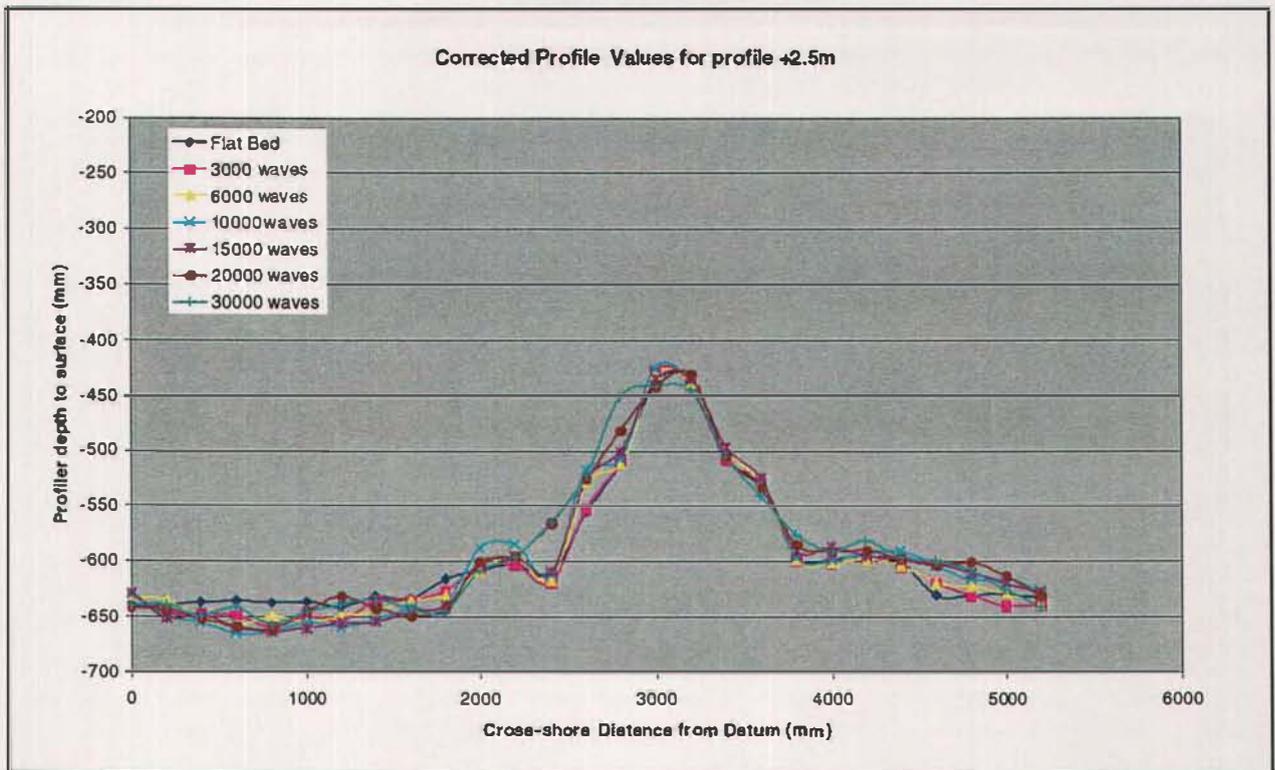


Figure 37 Test 6, time development of scour at $x_l = +2.50\text{m}$

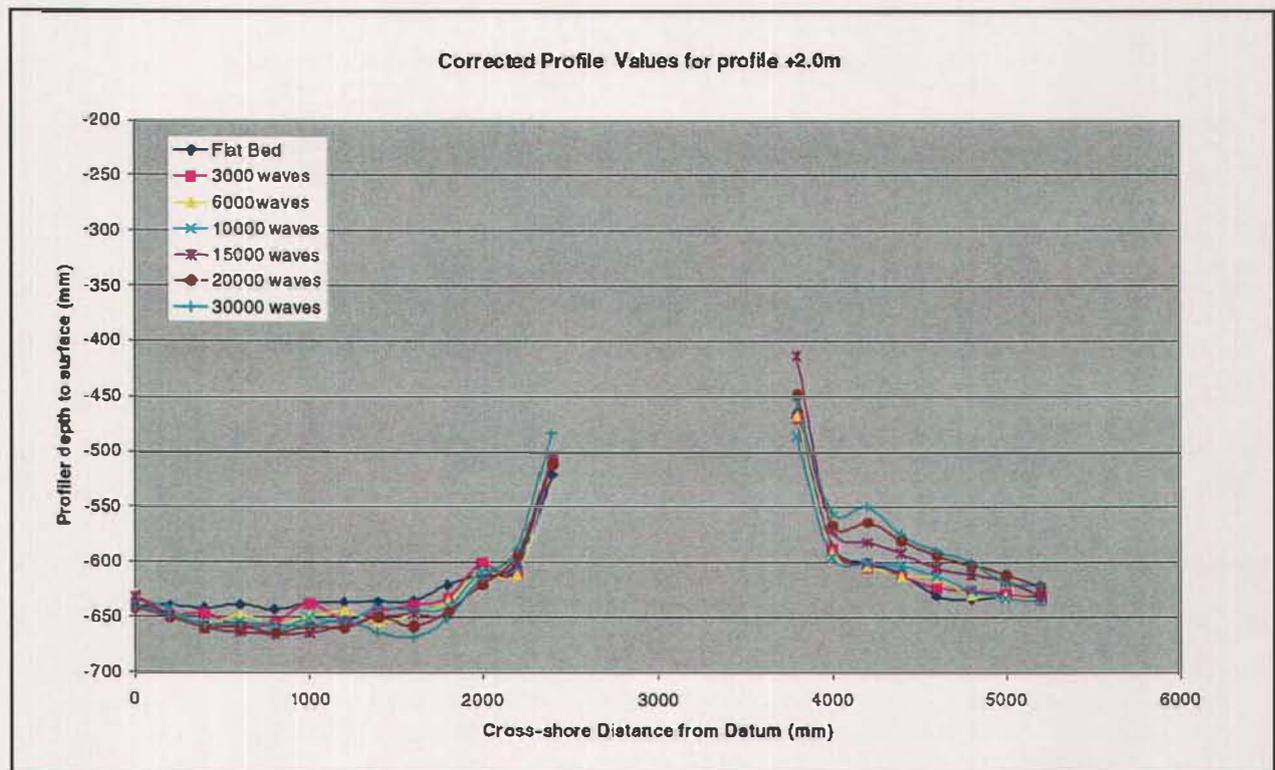


Figure 38 Test 6, time development of scour at $x_l = +2.00\text{m}$

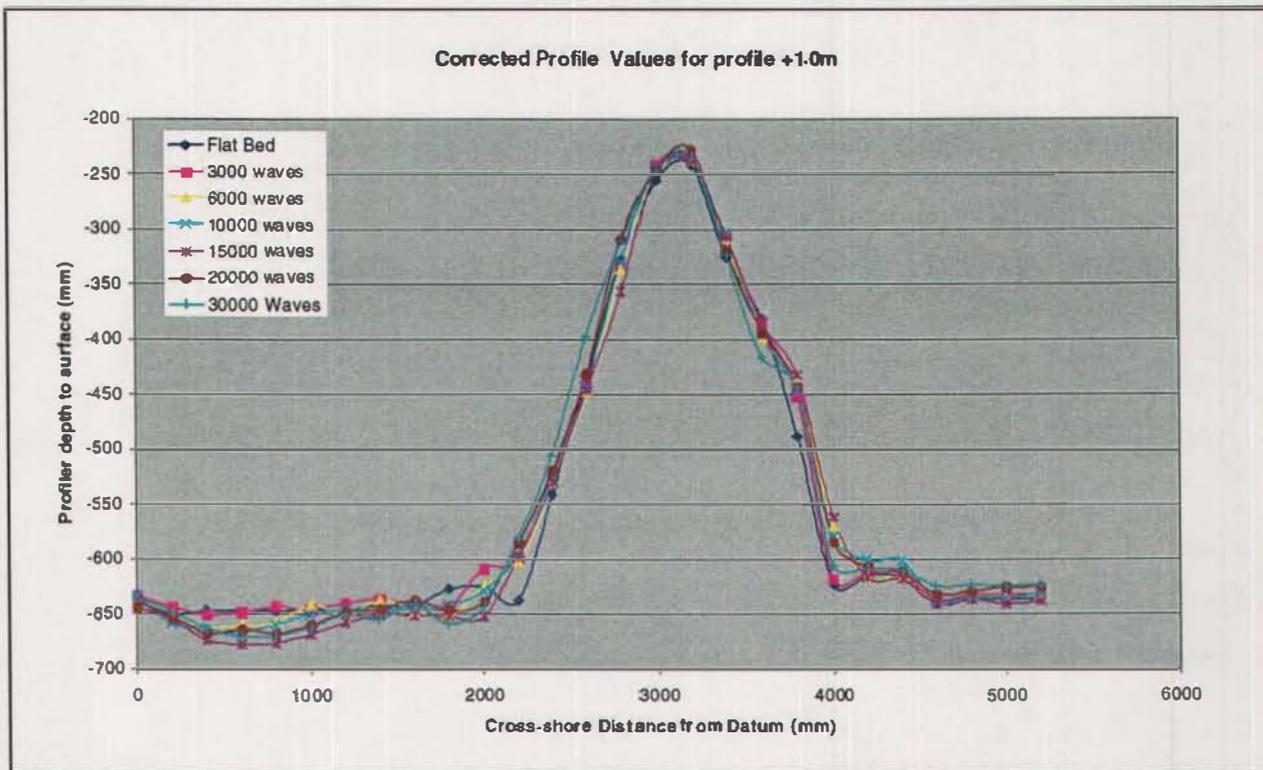


Figure 39 Test 6, time development of scour at $x_1 = +1.00\text{m}$

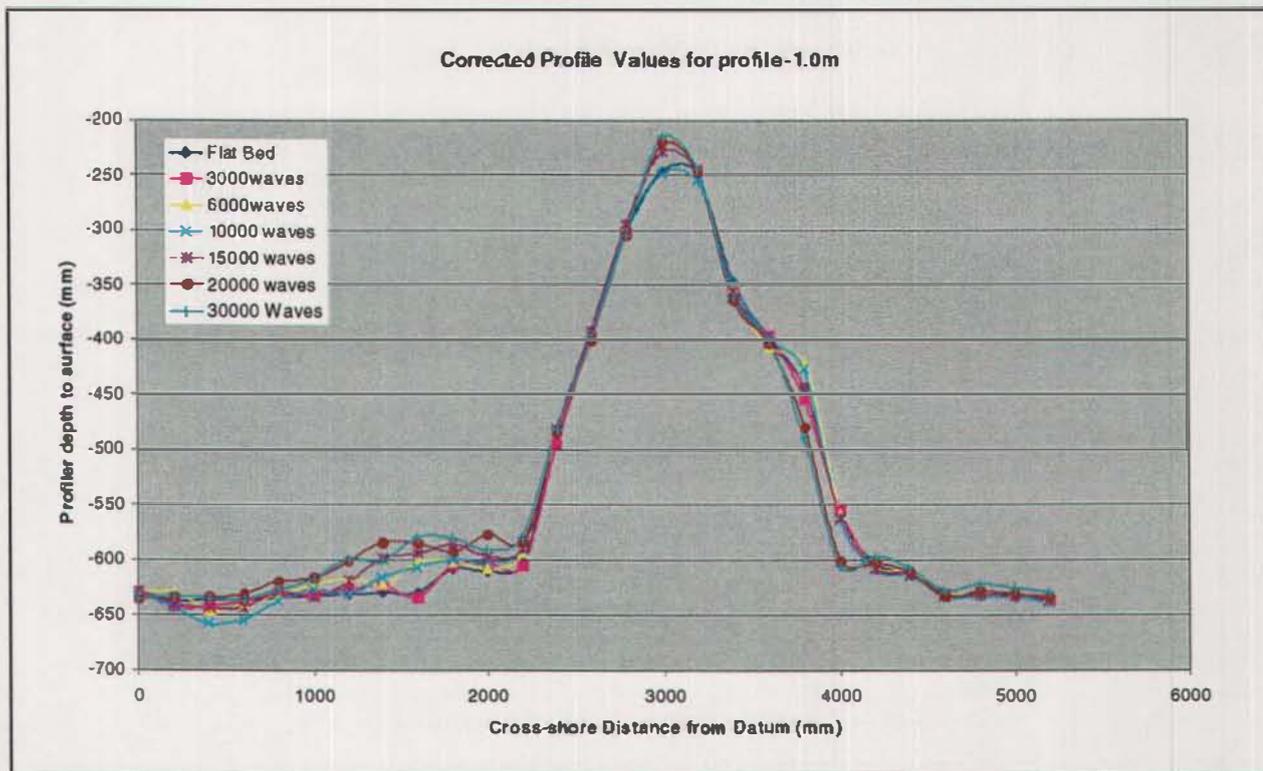


Figure 40 Test 6, time development of scour at $x_1 = -1.00\text{m}$

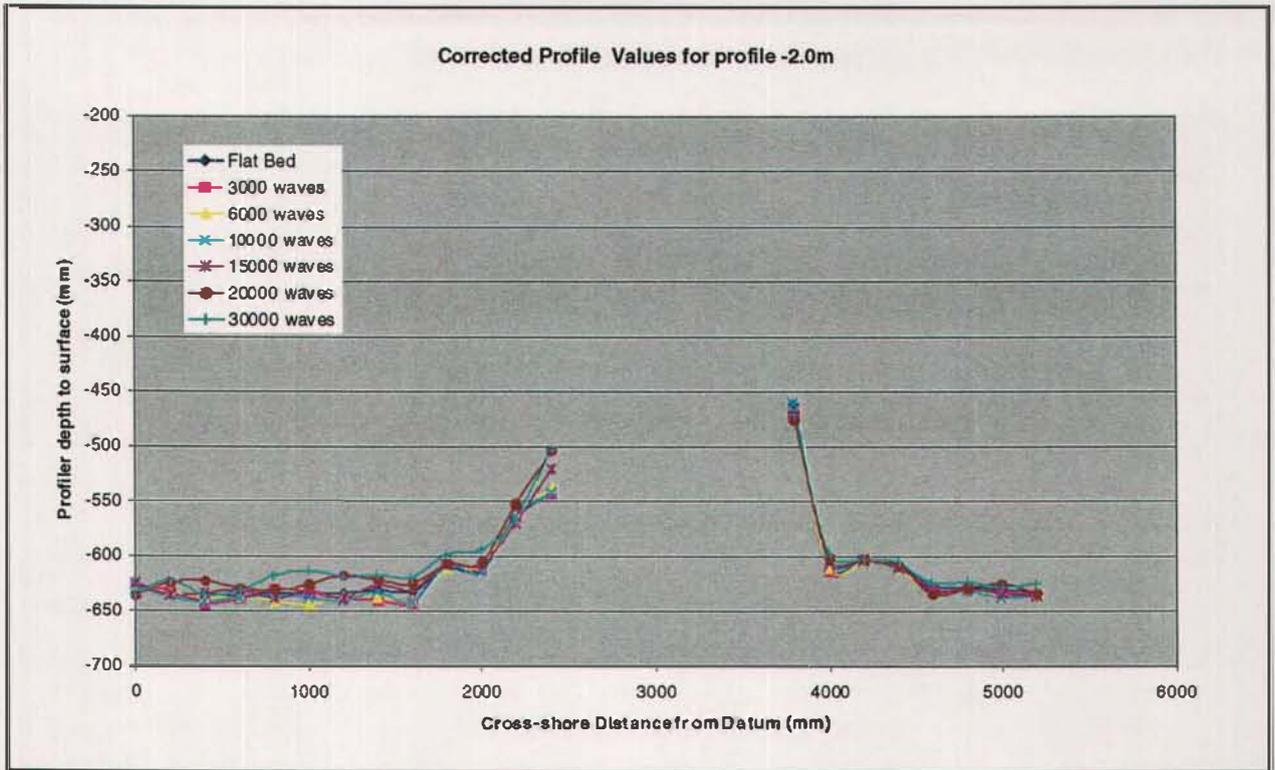


Figure 41 Test 6, time development of scour at $x_t = -2.00m$

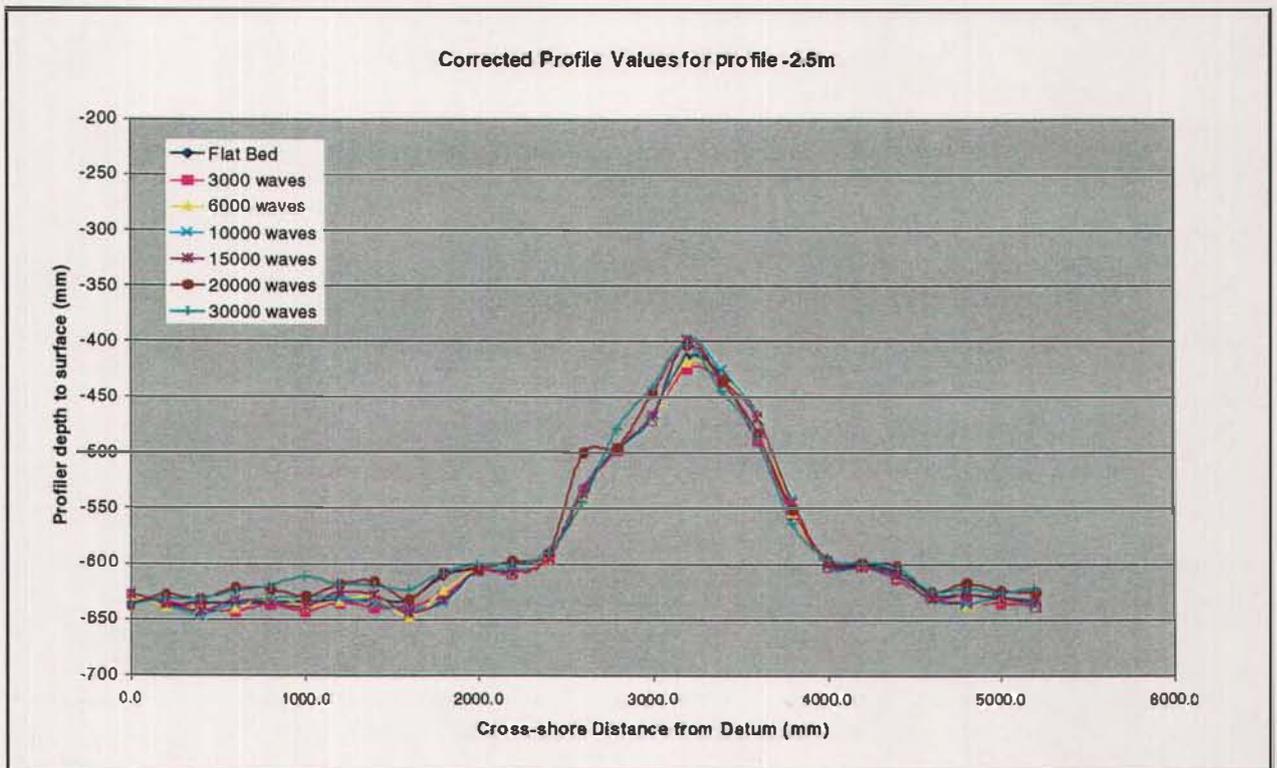


Figure 42 Test 6, time development of scour at $x_t = -2.50m$

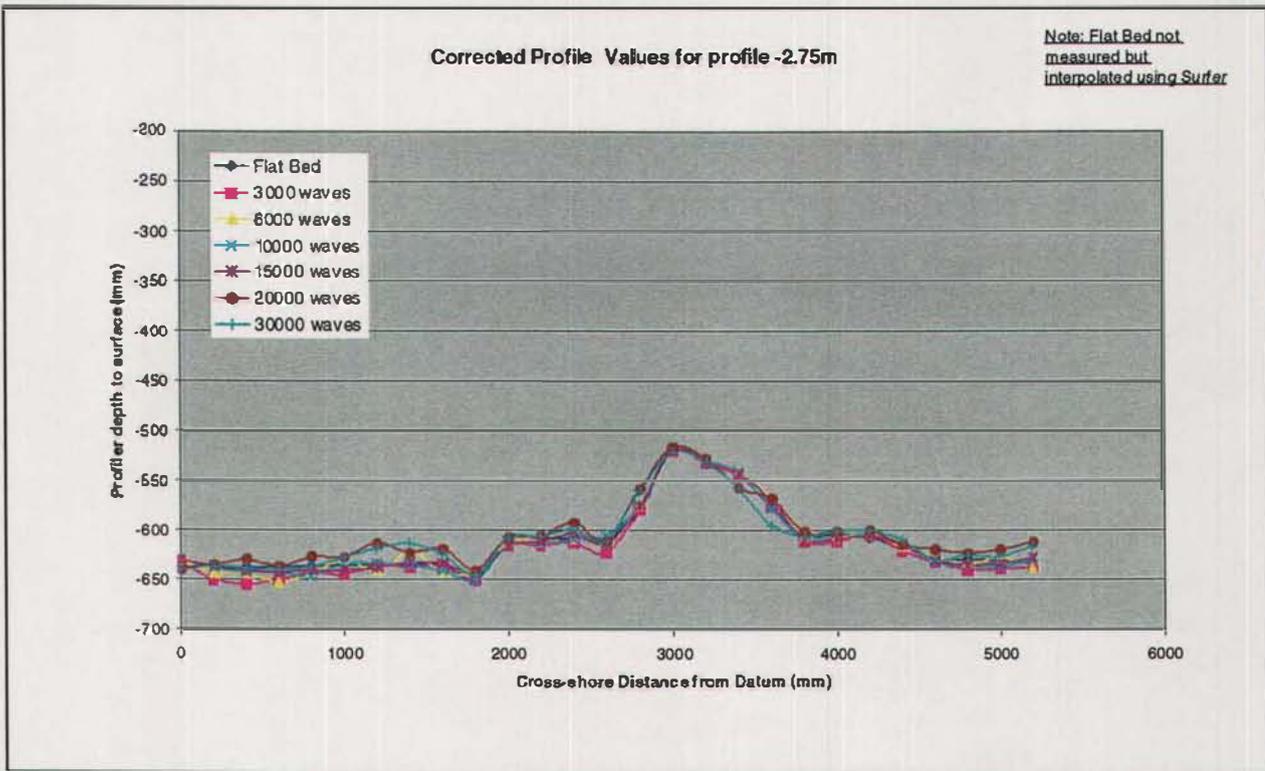


Figure 43 Test 6, time development of scour at $x_t = -2.75\text{m}$

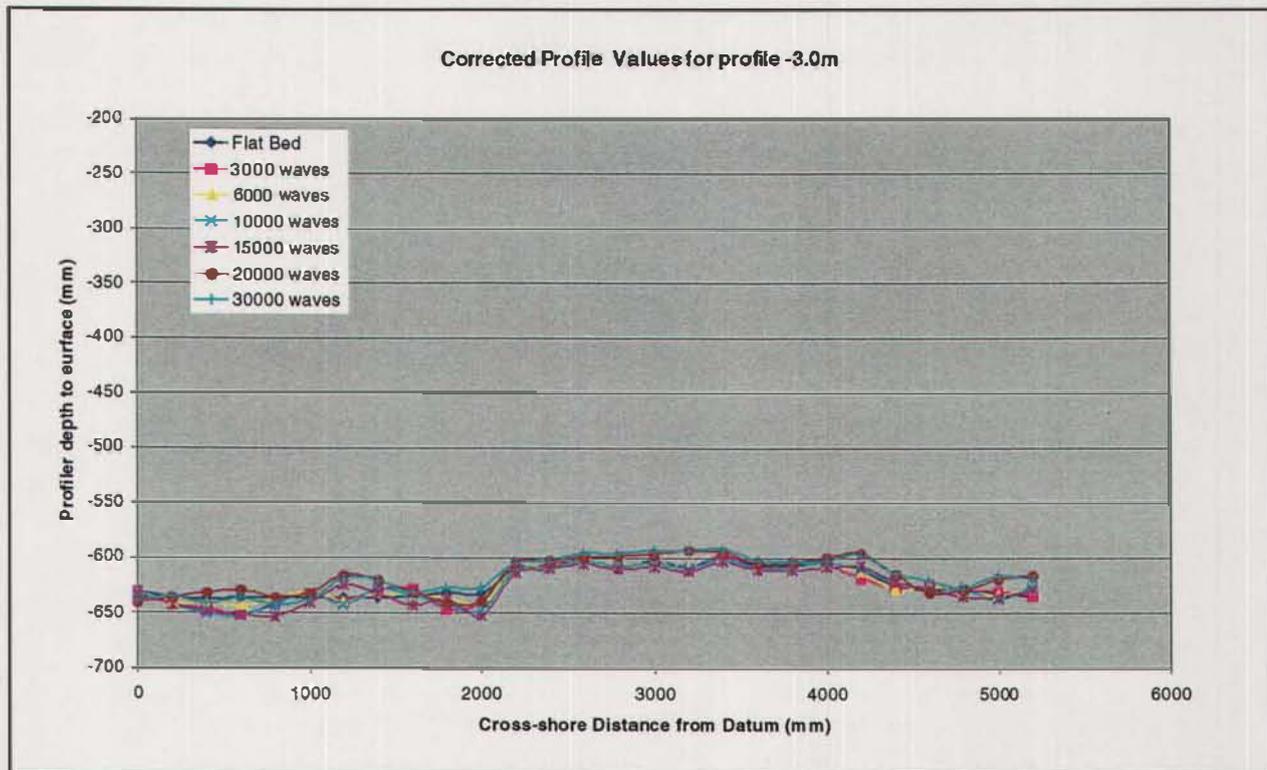


Figure 44 Test 6, time development of scour at $x_t = -3.00\text{m}$

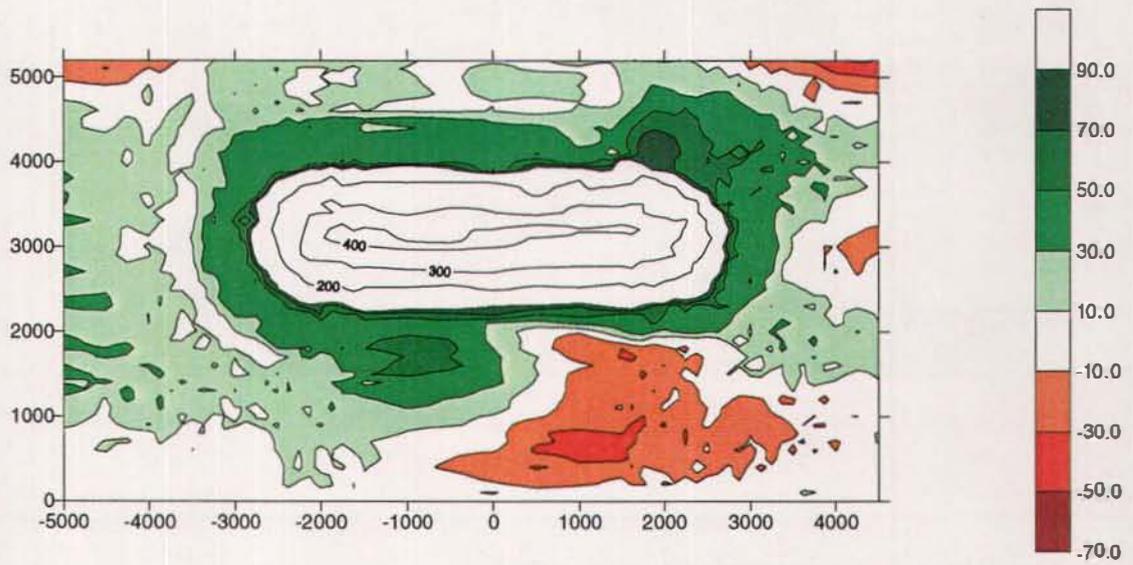


Figure 45 Test 6 final bathymetry - contour bands in millimetres

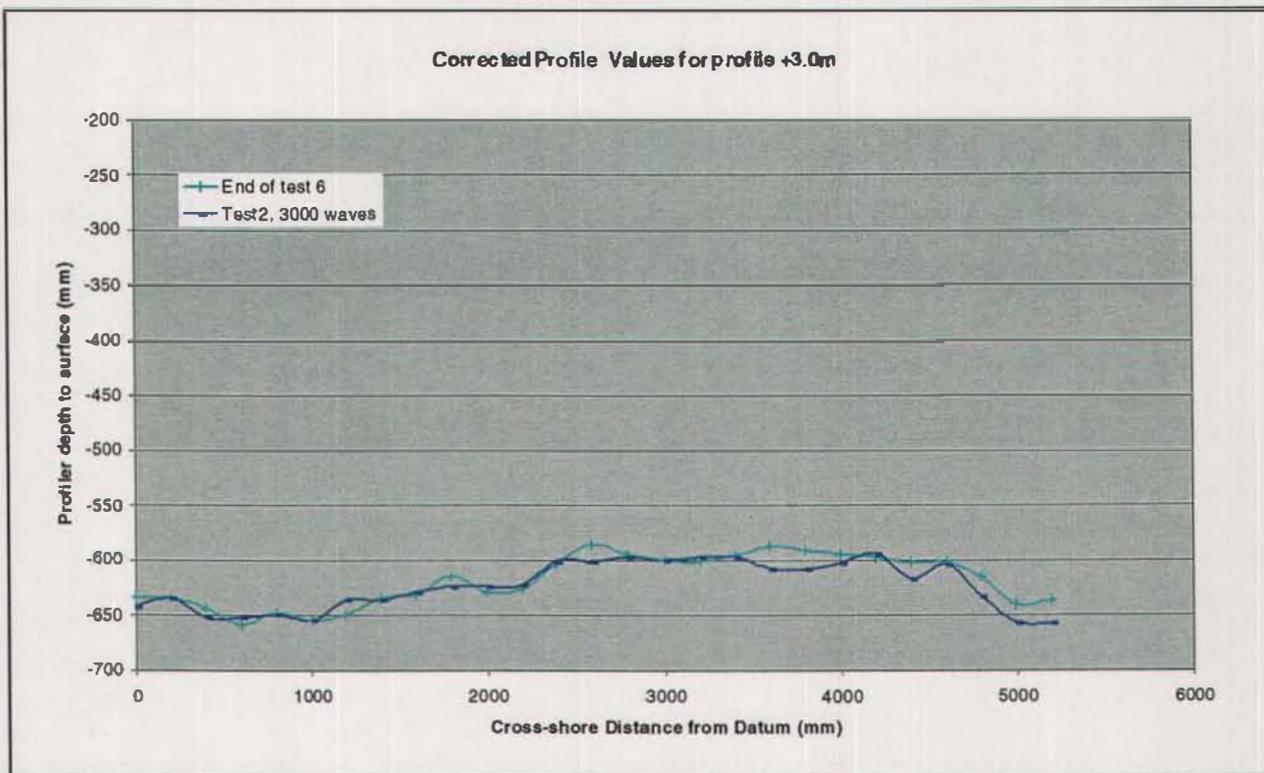


Figure 46 Test 2, time development of scour at $x_l = +3.00\text{m}$

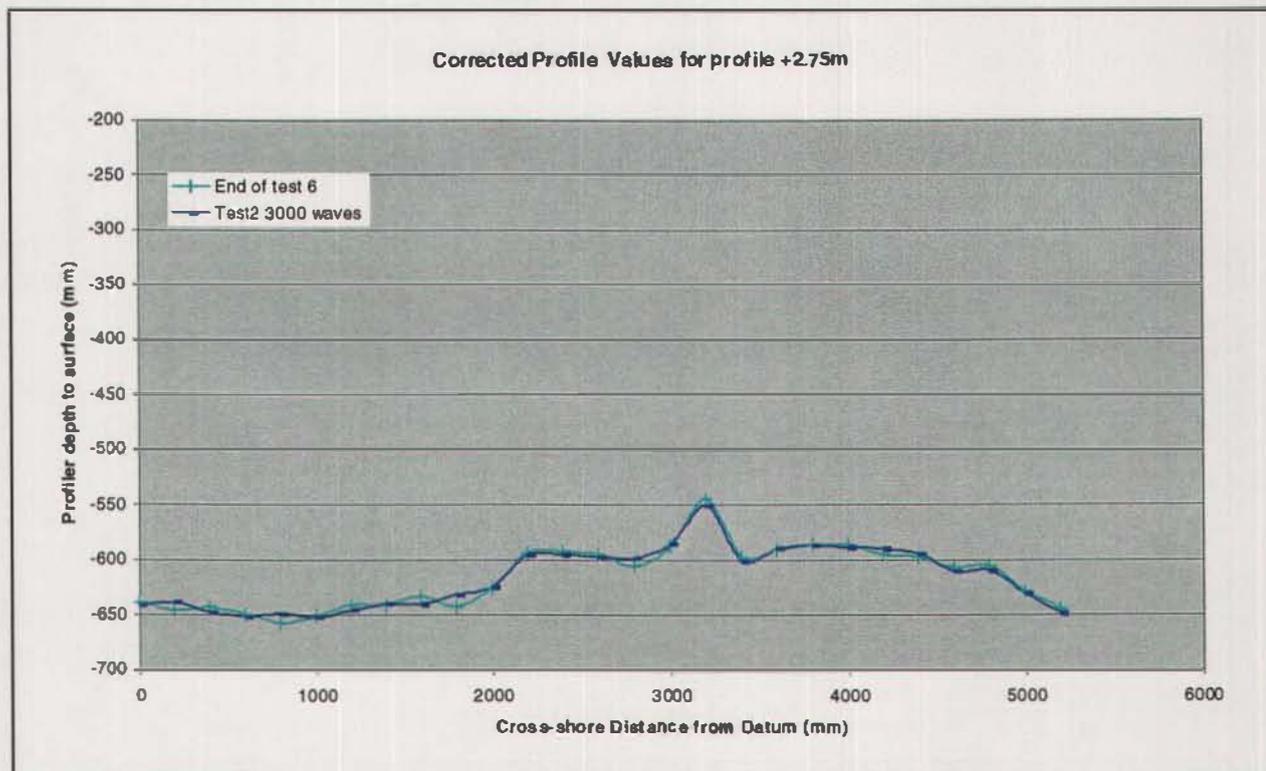


Figure 47 Test 2, time development of scour at $x_l = +2.75\text{m}$

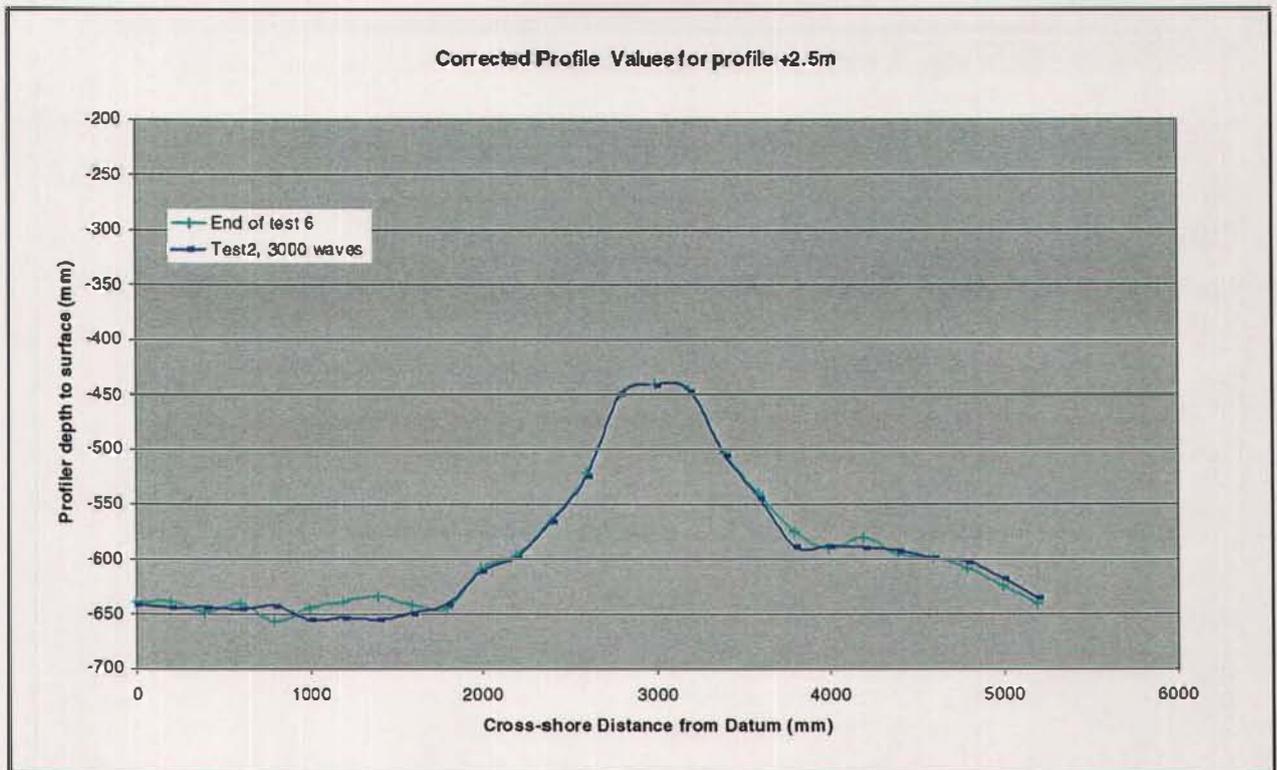


Figure 48 Test 2, time development of scour at $x_i = +2.50\text{m}$

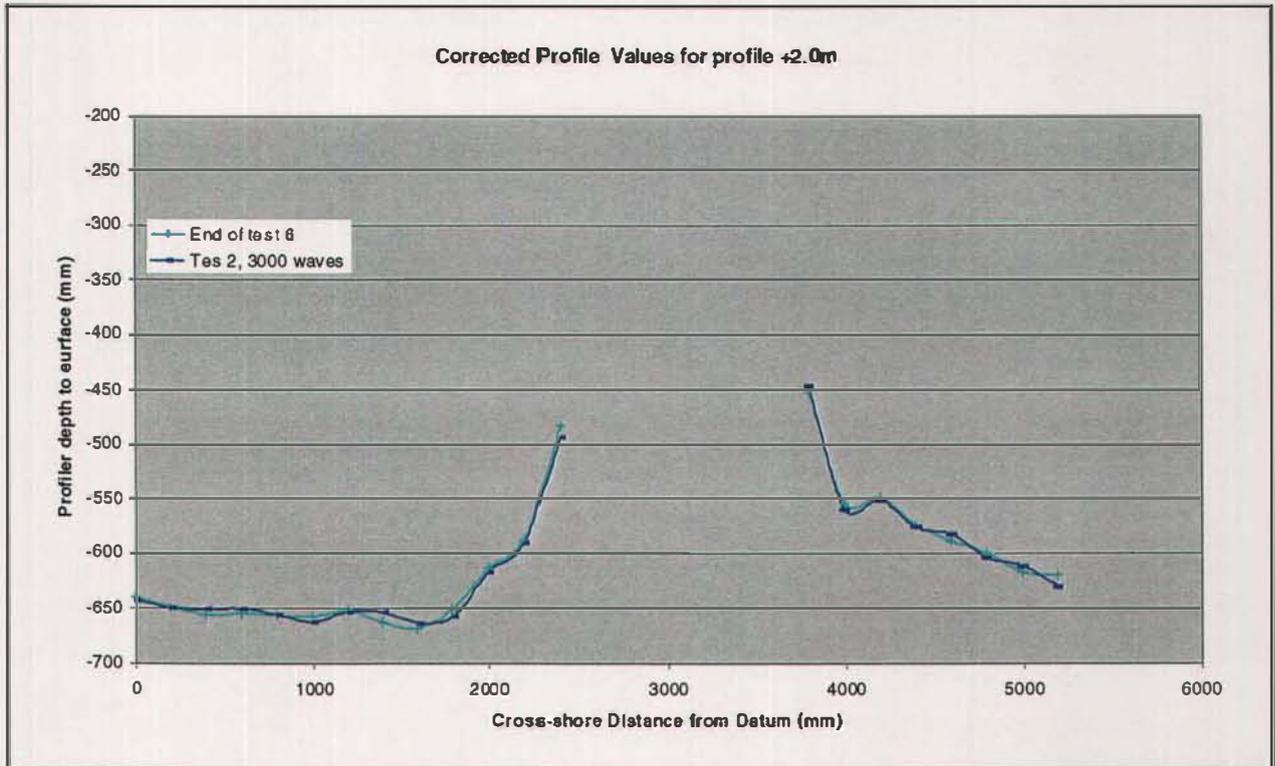


Figure 49 Test 2, time development of scour at $x_i = +2.00\text{m}$

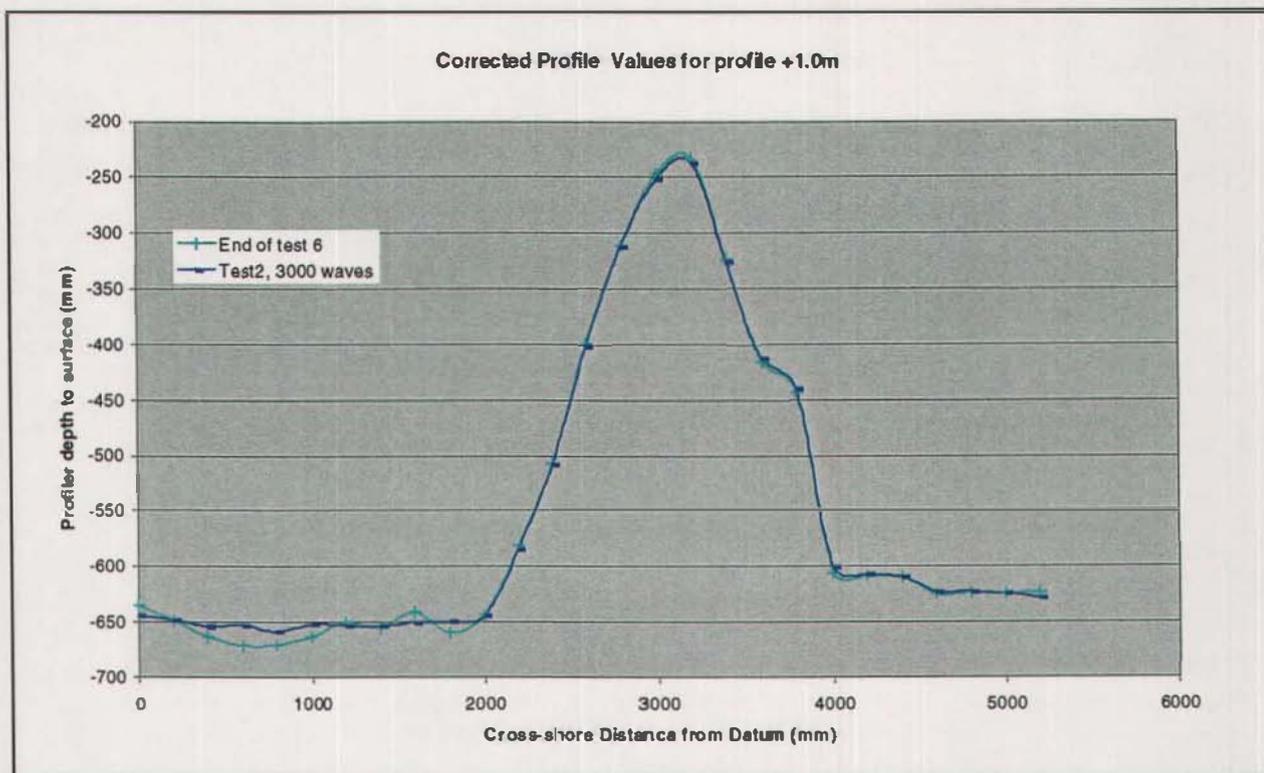


Figure 50 Test 2, time development of scour at $x_t = +1.00\text{m}$

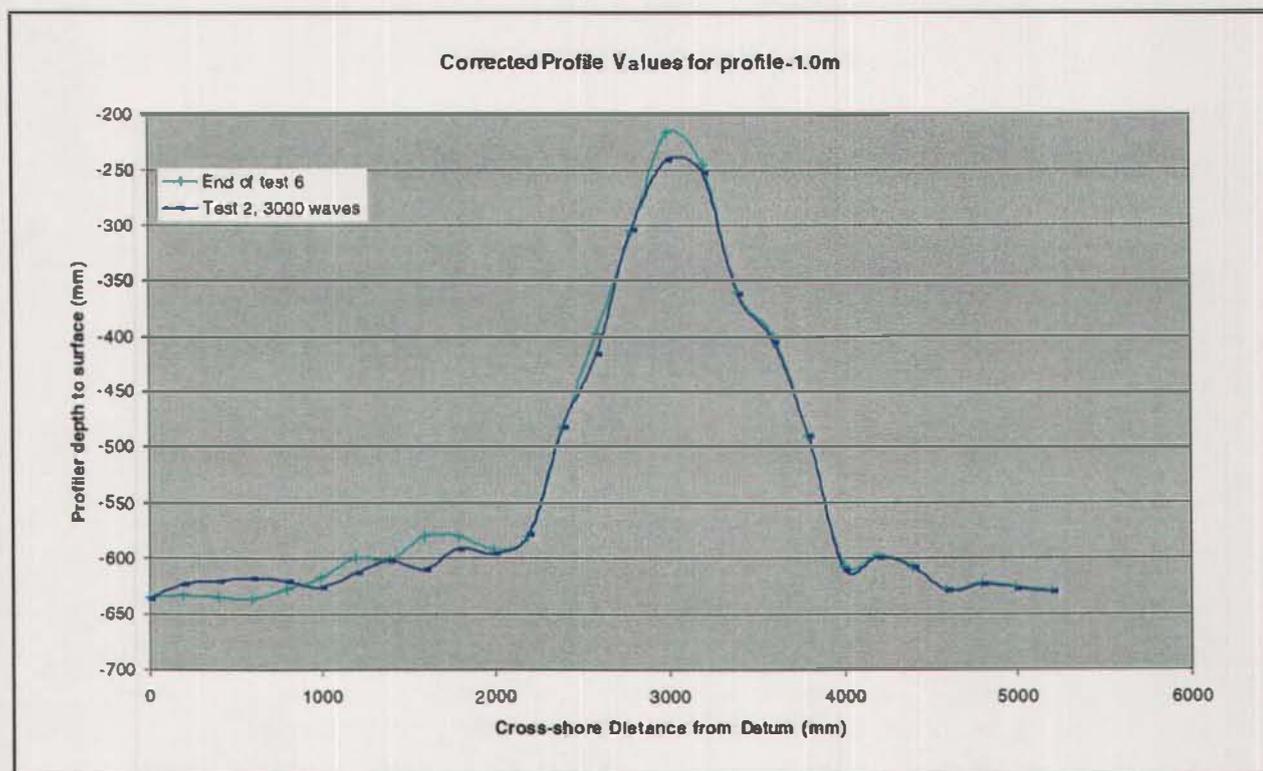


Figure 51 Test 2, time development of scour at $x_t = -1.00\text{m}$

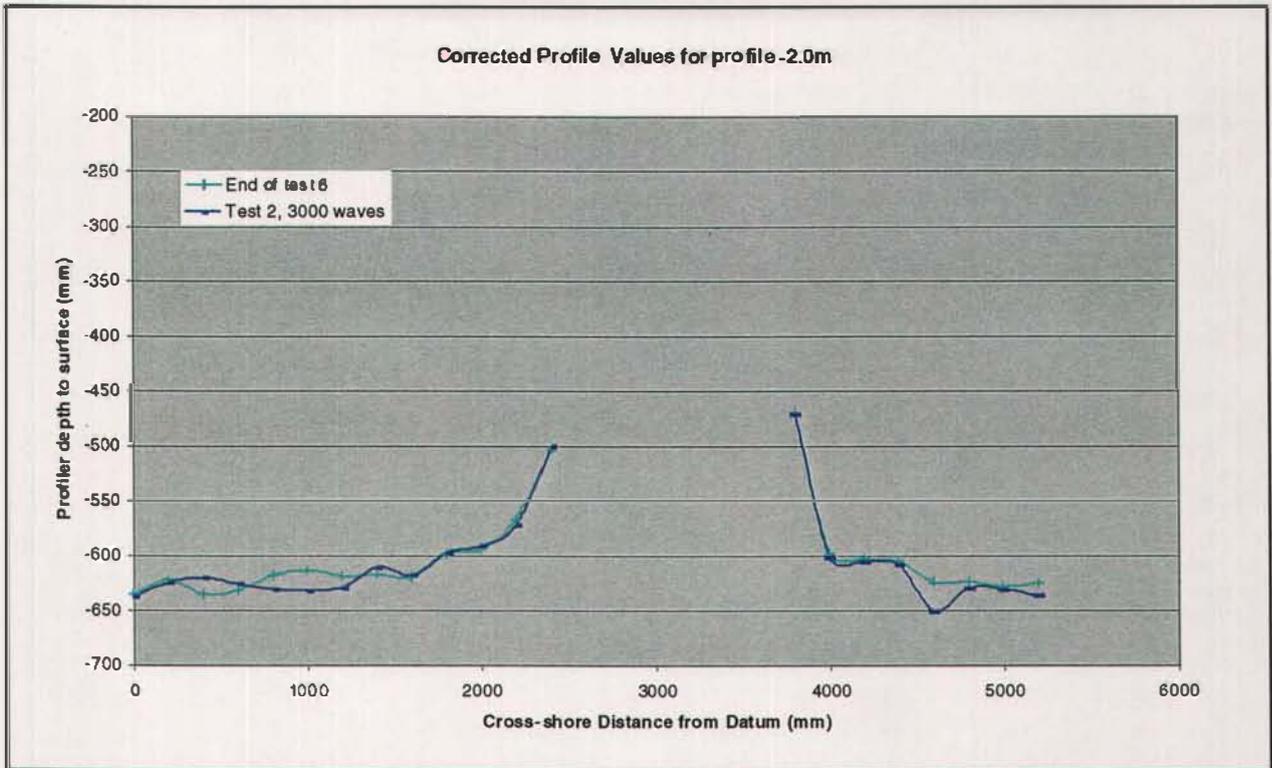


Figure 52 Test 2, time development of scour at $x_i = -2.00\text{m}$

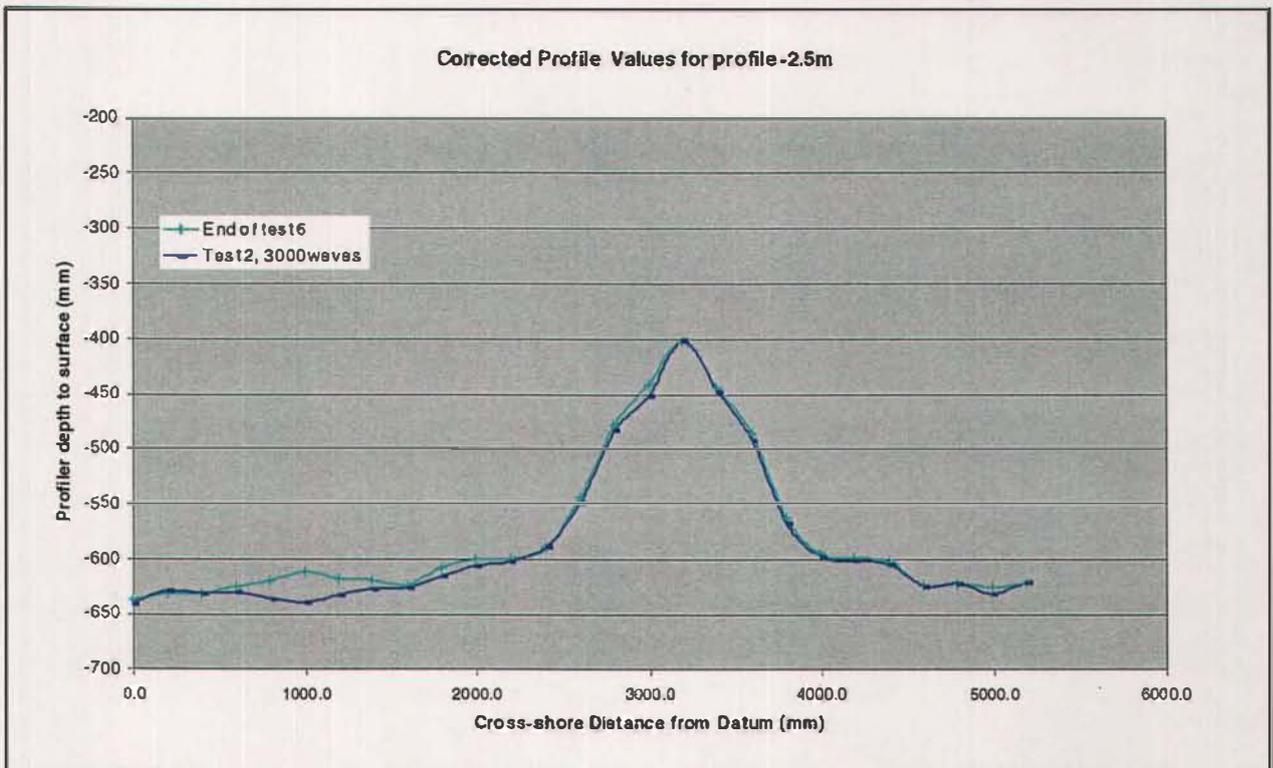


Figure 53 Test 2, time development of scour at $x_i = -2.50\text{m}$

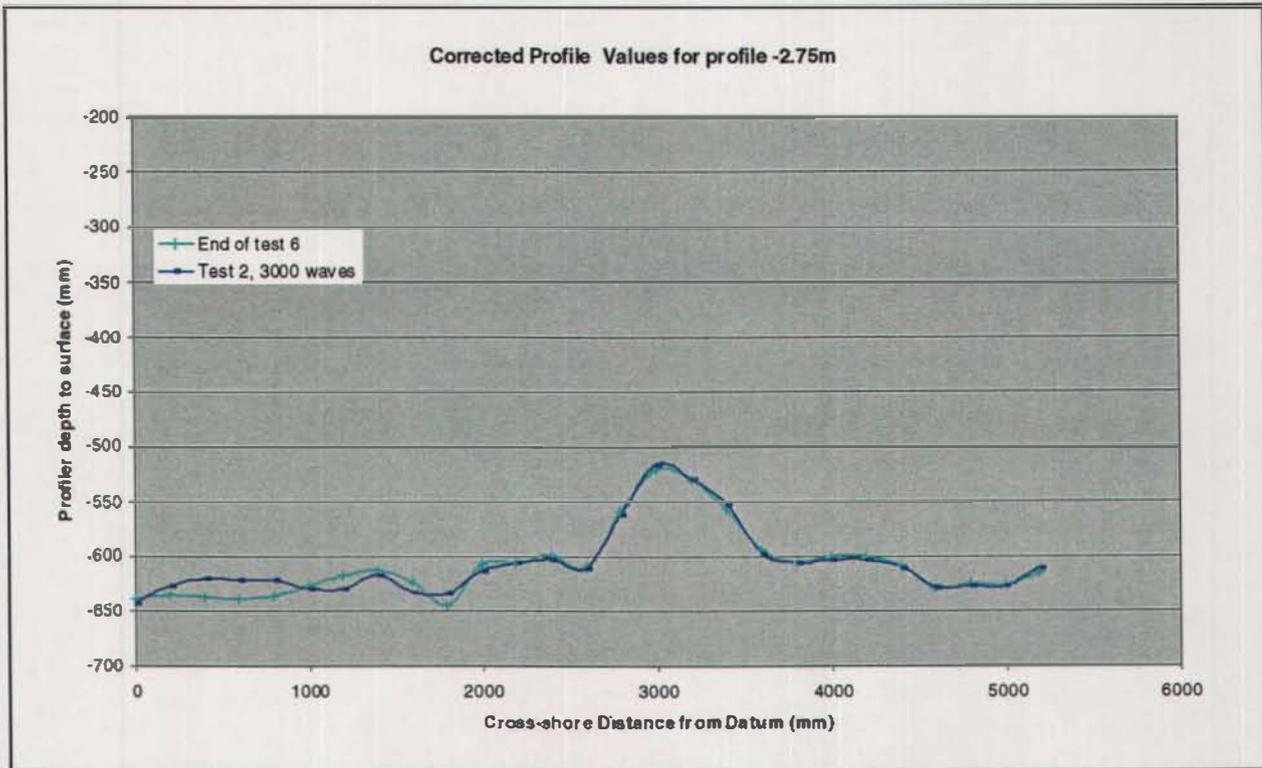


Figure 54 Test 2, time development of scour at $x_i = -2.75\text{m}$

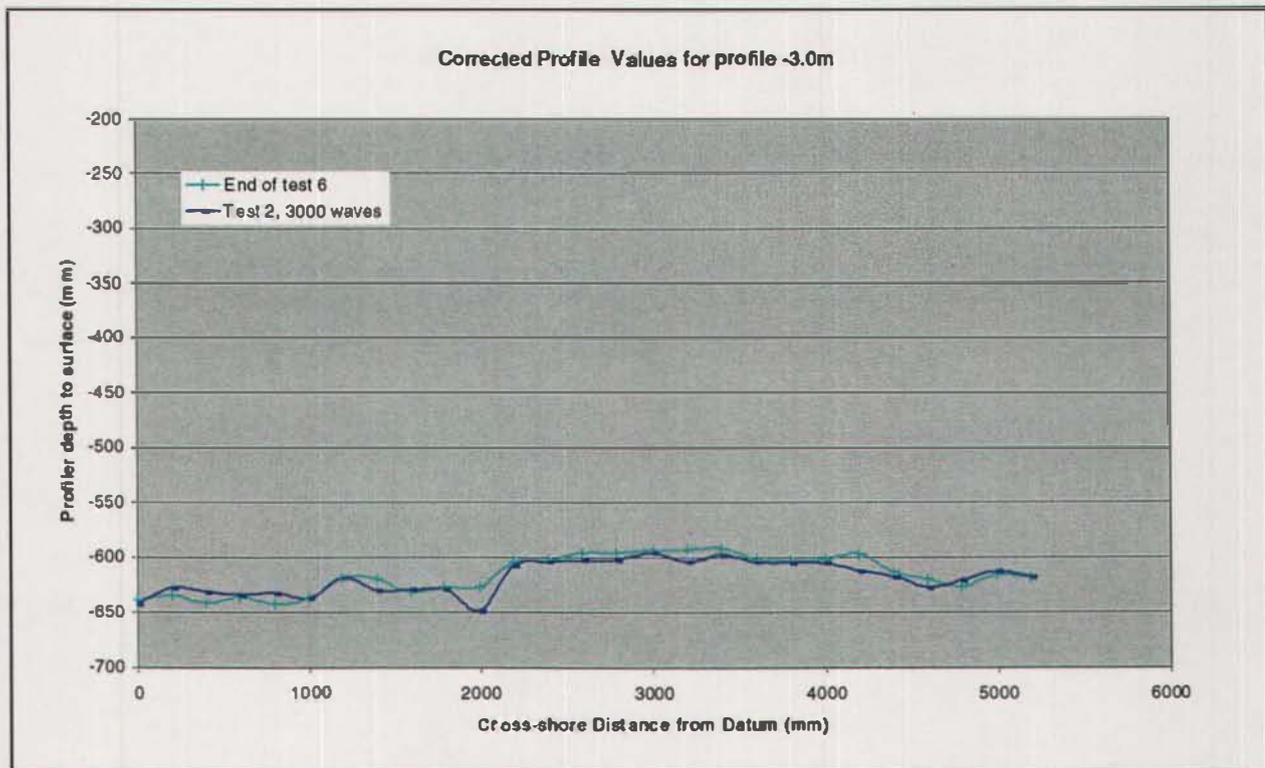


Figure 55 Test 2, time development of scour at $x_i = -3.00\text{m}$

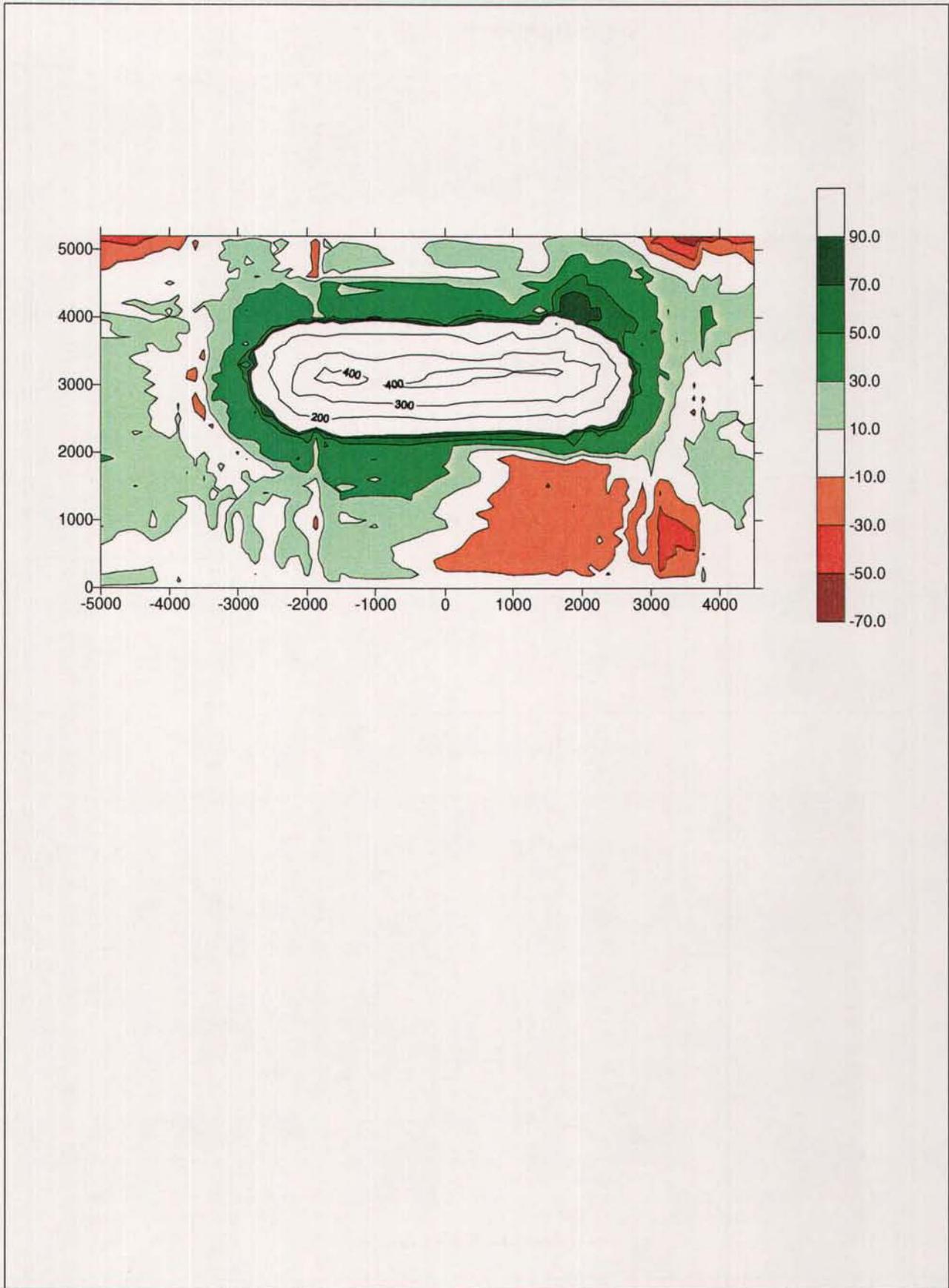


Figure 56 Test 2 final bathymetry - contour bands in millimetres

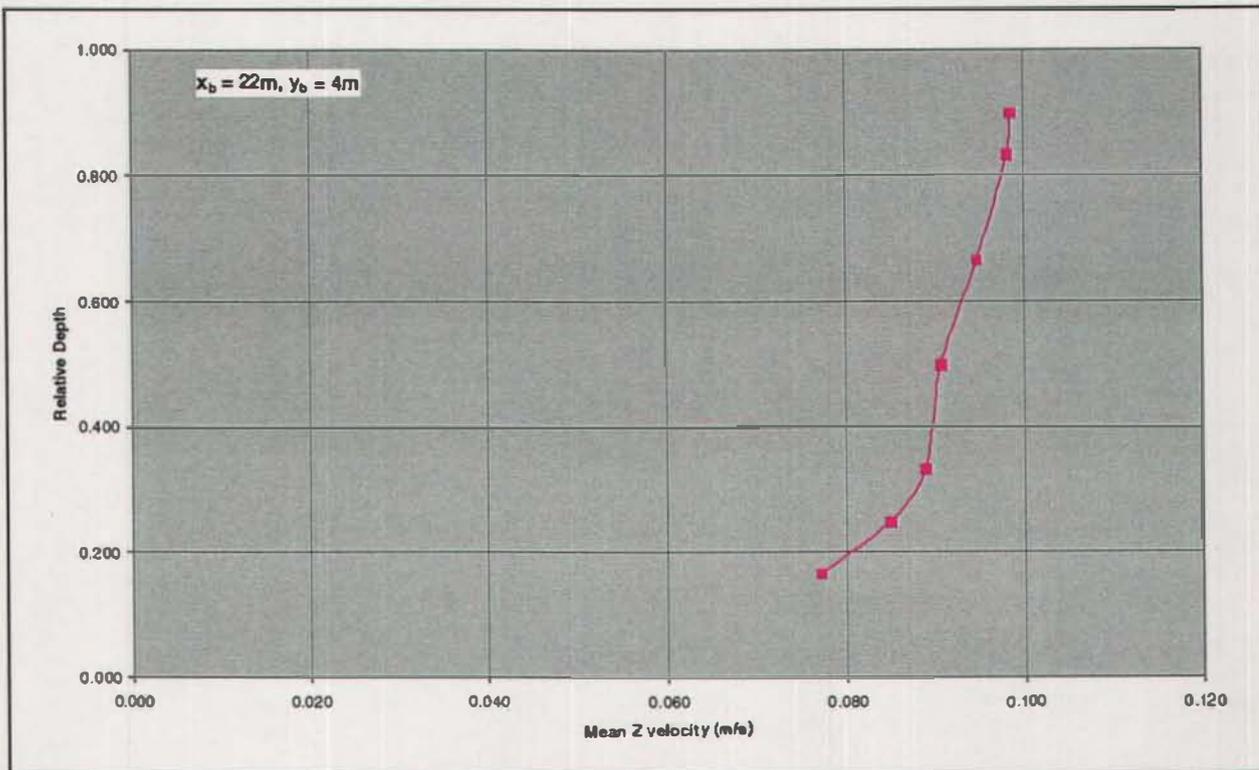


Figure 57 Vertical current profile at location $x_b = 22.0$, $y_b = 4.0$

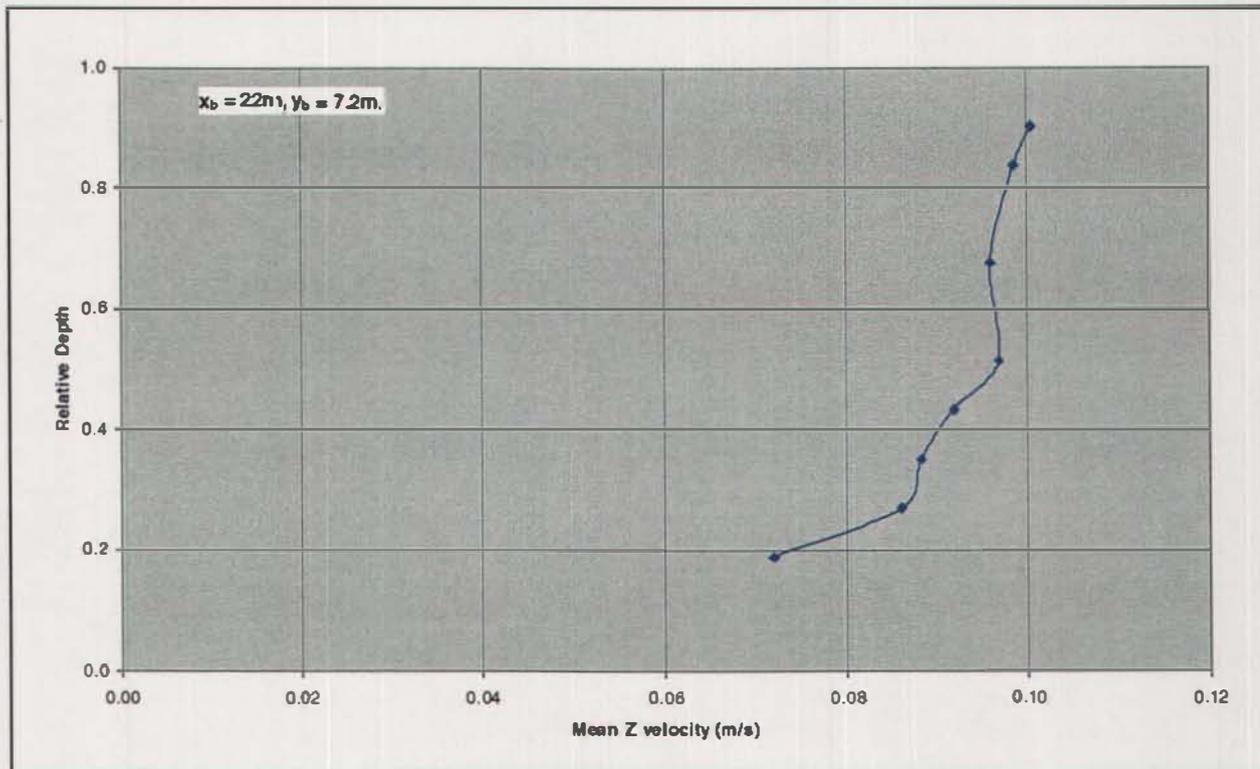


Figure 58 Vertical current profile at location $x_b = 22.0$, $y_b = 7.2$

Plates



Plate 1 Experimental setup for SCARCOST tests in UKCRF



Plate 2 Breakwater and profiler rails



Plate 3 Test 1 final bathymetry seen from Southeast. Length of ruler is 1m

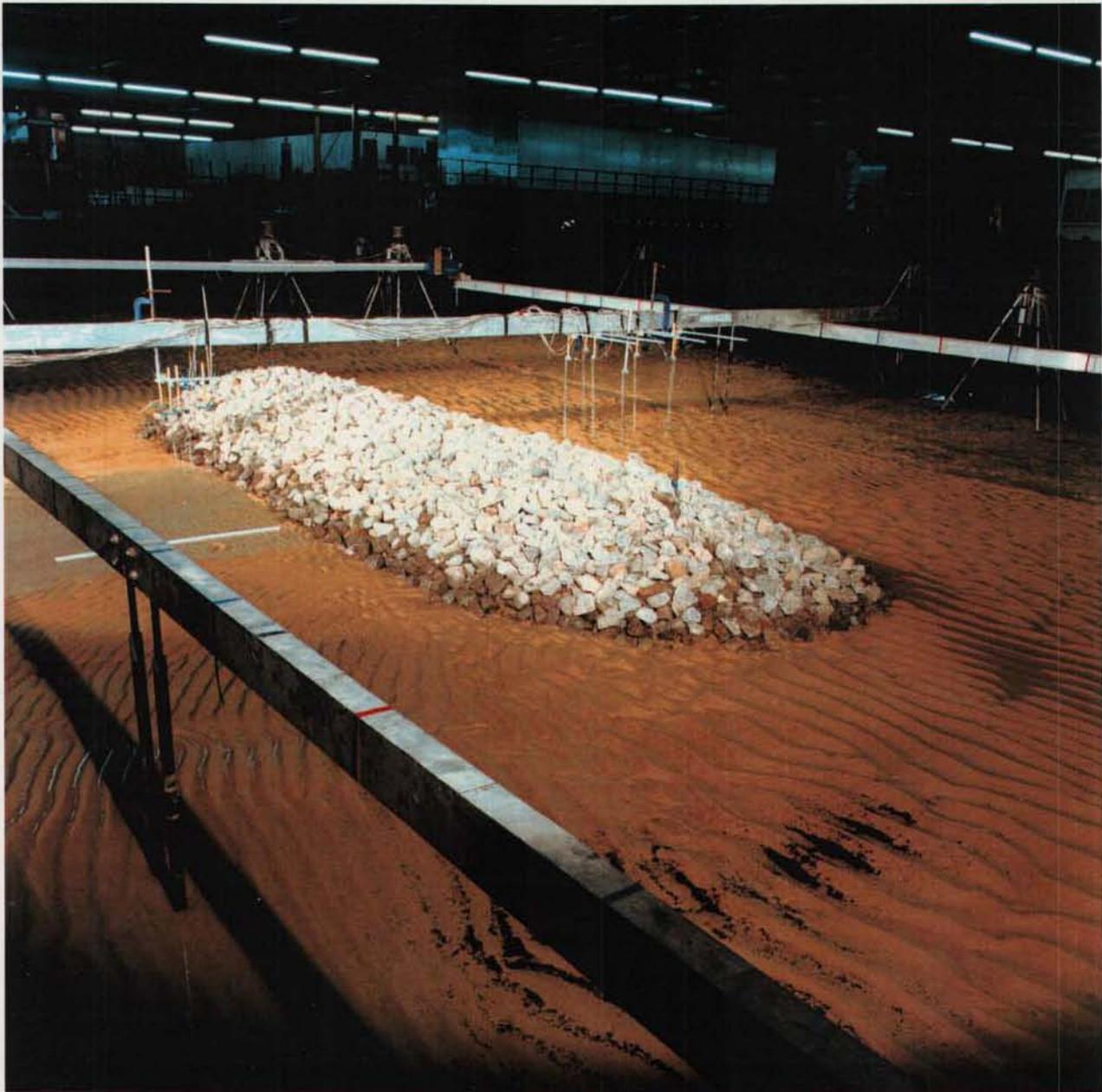


Plate 4 Test 1 final bathymetry: South roundhead from rear. Length of ruler is 1m



Plate 5 Test 1 final bathymetry: North roundhead from front. Length of ruler is 1m



Plate 6 Test 1 final bathymetry: North roundhead from rear

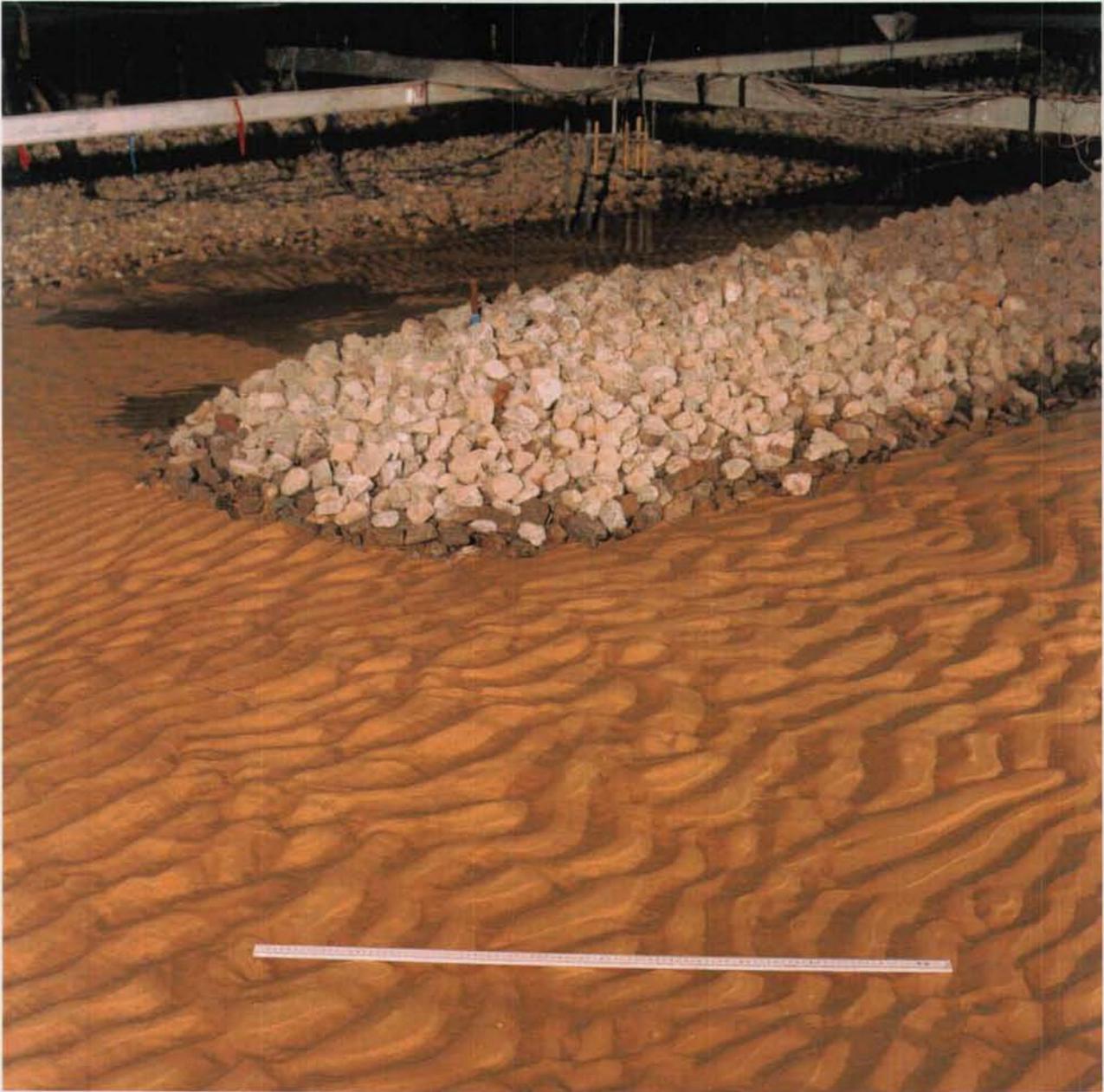


Plate 7 Test 5 final bathymetry: South roundhead from front. Length of ruler is 1m



Plate 8 Test 5 final bathymetry: South roundhead from rear. Length of ruler is 1m



Plate 9 Test 5 final bathymetry: North roundhead from front. Length of ruler is 1m



Plate 10 Test 5 final bathymetry: North roundhead from rear. Length of ruler is 1m

Appendices

Appendix 1

Description of CD containing summary statistics

Appendix 1 Description of CD containing summary statistics

The summary data CD is assumed to be in drive E:. File names are given in *italics*. The CD contains the following 10 directories:

1. Admin
2. Analysis files
3. Drawings
4. Longshore calibration
5. Photographs
6. Recirculation tests
7. Surfer final bathymetry
8. Time development
9. Velocity data
10. Wave data

E:\Admin Directory Contents

This directory is used to store important details relating to the collected raw data files and the physical model experimental set-up. It contains the files:

- E:\Admin\ADV *positions.xls*
- E:\Admin\bed *measurements.xls*
- E:\Admin\bed *evaluation.doc*
- E:\Admin\file *database.xls*
- E:\Admin\probe *details finalised.xls*
- E:\Admin\probe *details.xls*
- E:\Admin\run *length time calc tests.xls*
- E:\Admin\scarcost *survey.xls*
- E:\Admin\sizes.xls
- E:\Admin\water *depth & temp summary.xls*

E:\Admin\ADV *positions.xls* is an Excel spreadsheet giving information on the position of the ADVs. The information has been copied as Table 3. The position names are given in E:\Admin\file *database.xls*.

E:\Admin\bed *measurements.xls* (Excel) provides bed change measurements, which were taken after completion of each test run. After completion of each run, measurements were taken of the water depth at each wave gauge on the array beam, the distance that sand had moved offshore at locations +4.5 and 0.0m (breakwater reference system), extent of diffracted ripple location behind the structure and representative ripple dimensions (length and height).

E:\Admin\bed *evaluation.doc* is a Word '97 file containing notes on the behaviour of the sand bed during the calibration of the waves.

E:\Admin\file *Database.xls* (Excel) provides details in chronological order of the files collected during the physical model study. Each sheet represents one week, which is then split into individual days. Relevant details of all files are included, such as:

- ADV positions (see E:\Admin\ADV *positions.xls* to convert position name to breakwater co-ordinates)
- Directional array longshore positions, file descriptions etc. and any files collected, which had a problem associated with it (profiler malfunction for example).

E:\Admin\Probe *Details finalised.xls* (Excel) provides important details of the probes (ADV and waves) and channels.

E:\Admin\Run *Length Time Calc tests.xls* (Excel) is the working spreadsheet, which was used to calculate run lengths based on average period. This contains important information. Each test has its own table and

includes details of the test characteristics, along with the time for each run calculated on the required number of waves and the average wave period. In addition, to these calculations, the table provides details of whether the run was done in two parts and if so the duration of the first part is provided. Details are also given of the ADV beam positions measured during each run.

E:\Admin\Survey\Scarcost Survey.xls (Excel) contains complete details of the Scarcost surveys. Two surveys were conducted to obtain the important features within the basin. Six worksheets are contained within this file.

1. "Measurement 120599" contains measurements from the survey carried out on 12/05/99. This includes CRF boundaries, slope, hydrocyclones, remote gauges and sand bed extents. The pogo slipped and so the height measurements can not be relied upon
2. "Measurement 180599" contains measurements carried out on the 18/05/99. This includes the spending beach and the breakwater
3. "Survey Layout" is a plot of the main features in the CRF.
4. "Breakwater Co-ordinates" are the xyz co-ordinates for the breakwater toe, crest and marking pegs.
5. "Breakwater" is a plot of the above breakwater features.
6. "Wave" gauge isolates the co-ordinates for the measured wave gauge positions. Important: gauge 30 refers to wave gauge 21.

E:\Admin\Sizes.xls (Excel) contains a size analysis of the armour layer, sand bed and spending beach, plus Figure 6.

E:\Admin\Water Depth & Temp Summary.xls (Word) provides summaries of the temp and depth of water at the concrete lip, for each day in which waves and currents were measured.

E:\Analysis files directory contents

E:\Analysis files contains 39 Matlab m-files used in the calibration and analysis of the recorded data. The files belong to the University of Plymouth. Permission for their use must be obtained from the University.

E:\Drawings directory contents

E:\Drawings contains the drawings used in Figure 1.

E:\Longshore Calibration

This directory and sub-directories contain files collected during the longshore current calibration procedure. The target imposed longshore current was 0.1m/s, which was required to travel uniformly South. During this task pump and gate settings were adjusted to create the required conditions. The directory contents are:

- *Currentmap.ppt* – a powerpoint picture of the time-averaged current vectors around the breakwater, measured in a current only (no waves).
- *Depth summary.xls* – Excel spreadsheet containing time-averaged currents over 2 depth profiles away from the structure. Contains figures 57 and 58.
- *Longvect.sif* – is the original Surfer plot of current vectors
- *Map summary.xls* - presents a summary of ADV positions and the statistics derived for each measurement location. Included in this is a diagram of ADV orientation. The velocity statistics are in terms of ADV orientation and have not been changed to basin or SCARCOST co-ordinates.
- *mapvect.txt* is an ascii file containing x,y co-ordinates of the measurement positions and ADV u,v velocity vectors.

E:\Photographs directory contents

This directory contains 18 *.jpg images (each a scanned photograph taken during the SCARCOST tests) and a file *SCARCOST PHOTOGRAPHS.doc* that identifies each image.

E:\Recirculation tests directory contents

E:\Recirculation tests contains a number of files containing comments on the performance of the sediment recirculation system and the sediment transport during the tests.

E:\Surfer Final Bathymetry directory contents

E:\Surfer Final Bathymetry contains Surfer files from the full survey of each test. The file types are explained below:

1. *.dat – ascii file of interpolated surface elevation, corrected for beam sag is format (x_i, y_p, z_i) with all values in millimetres
2. *.grd – Surfer file of data after gridding, interpolation and contouring

There is also a file *all-plots.doc* containing pictures of the final bed profiles.

E:\Time development directory contents

E:\Time development contains 10 Excel spreadsheets, 2 from each test. Both contain the same data – the only difference is in the presentation of the results. The 2 summary files have names *Testx Time Dev Summary.xls* and *Test x time.xls*, with $x = 1, 2, 3, 5$ or 6 . They are Excel files that summarise, correct for sag and plot all the profile data for that test. These profiles were chosen to monitor the development of scour and deposition at $x_t = \pm 1.0\text{m}, \pm 2.0\text{m}, \pm 2.5\text{m}, \pm 2.75\text{m}$ and $\pm 3.0\text{m}$. Each of these positions is represented by three worksheets. E.g. -1.0m data summarises the raw data from the profile files. This is then plotted on the worksheet -1.0m raw data. In -1.0m data the sag correction equations are used to compensate for sagging in the raw values. This is shown in the second table to the right of the worksheet. These corrected values are then plotted in the third worksheet called corrected values -1.0m. The unlabelled columns are the profiler cross-shore position (all values in mm). The corrected profiles in files *test n time.xls* are used as figures in this report.

E:\Velocity data directory contents

E:\Velocity data contains 4 subdirectories:

1. E:\Velocity data\Test 1
2. E:\Velocity data\Test 2
3. E:\Velocity data\Test 3
4. E:\Velocity data\Test 5

Each directory contains a single file of compressed ADV time series and 4 types of ascii file:

1. *Atrddmm?.sts*
2. *Dtrddmm?.ad0*
3. *Dtrddmm?.ad1*
4. *Dtrddmm?.ad2*

Where *A*.sts* and *D*.ad?* denote the type of analysis done, t is the test number (so all files in sub-directory Test 1 have $t = 1$ etc) r is the run, *dd* denotes the day of the month that the tests were done in, *mm* is the month and ? is a wildcard standing for a single letter. The first test during a run was given the letter *a*, subsequent tests on the same day during the same run were given the letters *b, c*, etc. To find out the positions that the velocity measurements were made use *E:\Admin\file database.xls* to identify the ADV position name and use *E:\Admin\ADV positions.xls* or Table 3 to locate the co-ordinates of that position. All the wave data comes from the *.dac files collected by the Prosig Dats for windows system.

The compressed time series are in a file *Tn-ADV-ts-zip* where n is the test number. Compression is by Win-Zip (see www.winzip.com). Individual file names have the same format as *A*.sts* files but with extension *.adv Each file consists of 9 columns of velocity data (ms^{-1}) sampled at 100Hz. There is no time information in the file. Each column refers to a separate ADV position and flow direction as shown in Table 12.

Each row in an *A*.sts* files, also refers to a separate ADV position and flow direction, as shown in Table 12, which gives the row, ADV number, relative positions and the UKCRF axis. Row *n* of an *A*.sts* file gives the statistics of the velocities in column *n* of the corresponding *A*.adv* time series.

Table 12 Location and orientation of ADVs in the rows of each *A*.sts* file of statistics and each Column of *A*.adv* time series

Column/Row No.	ADV number/description and original ADV Axis	UKCRF axis
1	0/west & x	X
2	0/west & -y	Y
3	0/west & z	Z
4	1/east & x	X
5	1/east & -y	Y
6	1/east & z	Z
7	2/centre & -z	X
8	2/centre & y	Y
9	2/centre & -x	Z

The *A*.sts* files provide 9 statistics on each of the ADV time-series – each statistic is in a different column. An example of the format of an *A*.sts* file is presented in Table 13.

Table 13 Typical *A*.sts* file but with headings included to show meaning of values

Row No.	Mean	Standard Deviation	Co-variance	max velocity	Min velocity	Rms Velocity	Skewness	Kurtosis
1.000	-0.0198	0.0678	0.0046	0.7344	-0.4629	0.0707	0.2499	4.7580
2.000	-0.0194	0.1496	0.0224	1.0049	-0.6016	0.1509	-0.2016	2.7156
3.000	-0.0084	0.0408	0.0017	0.1709	-0.2392	0.0417	-0.1975	3.1710
4.000	-0.0181	0.0616	0.0038	0.2637	-0.5371	0.0642	0.0636	3.1927
5.000	-0.0231	0.1486	0.0221	0.4883	-0.4971	0.1504	-0.1366	2.4844
6.000	-0.0042	0.0389	0.0015	0.1280	-0.3467	0.0392	-0.0120	3.6674
7.000	-0.0065	0.0570	0.0032	0.2285	-0.2705	0.0573	0.0778	3.1227
8.000	-0.0252	0.1396	0.0195	0.3584	-0.6670	0.1419	-0.3200	2.8568
9.000	-0.0014	0.0412	0.0017	0.1963	-0.2871	0.0412	0.0492	3.5592

The formats of the *D*.ad0*, *D*.ad1* and *D*.ad2* files are the same. These provide the period averaged velocities in the xyz CRF orientation. They have been obtained using *periodav.m*. This file determines the location of the zero-upcrossing positions and then averages the velocities between these points. In this case the cross-shore time-series is used to define a wave and then these positions are used to average all three velocities. In addition, the absolute value between the highest velocity and the lowest velocity is calculated. The file extension *ad0*, *ad1* and *ad2* relate to the ADV 0, 1 and 2 respectively. Each of the three file types consist of four columns and a number of rows relating to the measured waves (defined by the zero-upcrossing method). Each value represents the period averaged velocity of a defined wave in the x, y or z direction (CRF orientation) with the last column being the velocity amplitude. These files can be used to produce feather plots.

E:\Wave data directory contents

E:\Wave data contains 3 subdirectories:

1. E:\Wave data\Matlab
2. E:\Wave data\spectral
3. E:\Wave data\warp time series

Each directory contains data from a different form of wave analysis. E:\Wave data\Matlab contains time-domain and spectral analysis of the *.dac files collected using the Prosig Dats for Windows system (so these results were collected at the same time as the ADV velocities). The directory E:\Wave data\spectral contains the spectral analysis files derived from binary files collected using HRWaves, so the channels are identified by their "grey cable number" in Table 2. The directory E:\Wave data\warp time series contains the results from the time series analysis of the *.raw files collected at 20Hz by HRWaves.

Each directory has the following 5 subdirectories:

1. E:\Wave data*\Test 1
2. E:\Wave data*\Test 2
3. E:\Wave data*\Test 3
4. E:\Wave data*\Test 5
5. E:\Wave data*\Test 6

E:\Wave data\spectral\Test n\Ttrddmm?.spc directory contents

The 5 directories E:\Wave data\spectral\Test n, with n = 1, 2, 3, 5 or 6 contain files with names *Ttrddmm?.spc* that use the same naming convention for test, run, day, month and file as previously. The files have a header section giving calibration information then spectra for each of the sampled channels (identified by their "grey cable number" in Table 2). Frequency, spectral density, significant wave height, zero-crossing period and spectral width are given for each frequency component. Figures quoted in Tables 6, 7, 9, 10 and 11 are taken from the bottom line of the spectra (except for peak frequency, which is picked out in each case).

E:\Wave data\warp time series\Test n\Ttrddmm?.wrp contents

The 5 directories E:\Wave data\warp time series\Test n, with n = 1, 2, 3, 5 or 6 contain files with names *Ttrddmm?.wrp* that use the same naming convention for test, run, day, month and file as previously. The files have a header section giving calibration information then statistics for each batch of the sampled channels (identified by their "grey cable number" in Table 2). The columns given are:

- Channel – grey cable channel number
- Batch – waves are analysed in batches
- Bad – number of bad records in a batch
- Waves = number of waves in the batch
- Hmax – maximum wave height in the batch (m)
- H3 – average of the highest 1/3rd of wave heights (m)
- Hbar – average of all the wave heights (m)
- Mean – mean water level (m)
- Batch mean – mean water level within a batch (m)
- Tbar – average wave period in the batch (s)

E:\Wave data\Matlab\Test n\Mtrddmm?.??? Contents

The 5 E:\Wave data\Matlab\Test n directories each contain 9 types of file. The first part of the file names (*Mtrddmm?* or *Strddmm?* or *Wtrddmm?*) follows the standard naming convention of test, run, day, month, test. Each file has 22 columns, one for each of the wave probes sampled. Columns 1 to 11 correspond to Grey cable numbers 0 to 10 respectively and columns 12-22 correspond to grey cable numbers 17-27 respectively. Use Table 2 to determine the position of the wave gauges in the UKCRF and note that the channels have been re-ordered to the same order as for the sampling and analysis by HRWaves. The 9 file types are:

1. *M*.hgt* This file holds the values are every wave height measured between zero-upcrossing points. This file can be used to derive various wave height statistics as well as for showing histograms of wave height distribution. The array is padded to a uniform size with zeros.

2. *M*.pos* This file records the positions of all zero-crossing points found for each time-series. The values are position of the zero-crossing in the time series, not time itself. The sampling rate is 100Hz.
3. *M*.thm* This file consists of a row of 22 numbers with each one giving the maximum wave height derived from time-domain analysis of a channel.
4. *M*.ths* This file consists of a row of 22 numbers with each one giving the significant wave height derived from time-domain analysis of a channel.
5. *M*.tmn* This file consists of a row of 22 numbers with each one giving the mean wave height derived from time-domain analysis of a channel.
6. *M*.tsd* This file consists of a row of 22 numbers with each one giving the standard deviation of wave height derived from time-domain analysis of a channel.
7. *S*.gph* This file has 23 columns, the first column being the frequency bins used in the spectral analysis and the other 22 are the spectral densities similarly derived for each wave probe. These files can be used produce spectral plots for each channel. In this case column 1 is frequency, column 2 is the spectral density for channel 0, column 3 is the spectral density for channel 1 and so on.
8. *S*.spc* These files hold all the properties derived from the spectral analysis. There are 22 rows, one for every channel. There are 20 columns and the column contents are given in Table 14.
9. *W*.sts* These files hold the statistical analysis properties derived purely from the wave gauge time-series. They therefore represent properties of surface variation. The statistics derived are the same as for the ADV A*.sts files, (channel number, mean, standard deviation, co-variance, max elevation, min elevation, rms elevation, skewness and kurtosis). Here there are 22 rows (for 22 wave gauges) instead of 9 rows (for 9 ADV channels).

Table 14 Definition of values in each column of s*.spc files

Column No:	Characteristic	Description
1	m_0	0 th order moment of spectrum
2	m_1	1 st order moment of spectrum
3	m_2	2 nd order moment of spectrum
4	m_3	3 rd order moment of spectrum
5	m_4	4 th order moment of spectrum
6	H_{m0}	Statistical approximation of H_s
7	$T_{0,1}$	m_0/m_1 average zero upcrossing period
8	$T_{0,2}$	$\text{Sqrt}(m_0/m_2)$ average zero upcrossing period
9	$T_{2,4}$	$\text{Sqrt}(m_2/m_4)$ Average crest to crest period
10	E4	Epsilon4, Broadness parameter (see IAHR list)
11	E2	Epsilon2, narrowness parameter (see IAHR list)
12	Qp	Peakedness factor (see IAHR List)
13	STP1	Steepness of waves
14	Fp	Spectral peak frequency
15	Mwdl	Mean water depth
16	Dp1	Still water depth
17	Var	Variance of energy in time domain
18	Tides_st	Not used
19	Tides_end	Not used
20	Suml	Summation of spectral energy

Some directories also contain a file *Tn-wave-ts.zip* where *n* is the test number. This is a WinZip file contained compressed ascii surface elevation time series. Individual file names have the same format as *W*.sts* files but with extensions **.clb*. Each file consists of 22 columns of surface elevations (m) sampled at 25Hz. There is no time information in the file. The column order is the same as for the summary statistics files.

Reflection analysis

The directories Test 3, Test 5 and Test 6 contain sub-directories \reflection analysis\ containing the results of the spectral analysis of the directional wave gauge array in front of the breakwater. These directories contain 2 types of file: *Ltrddmm?.spc* and *Rtrddmm?.spc* that follow the standard convention for test, run, day, month and test. These files are analysed from the corresponding *Ttrddmm?.dac* files so the position of the directional array in front of the breakwater can be determined by locating the *T*.dac* file in *E:\Admin\file database.xls*.

Ltrddmm?.spc holds all the properties derived from the directional spectral analysis in one row of data, with 85 entries. The properties in each entry are given in Table 15.

Table 15 Definition of values in each column of *L*.spc* files

Column Number	Characteristic	Description
1-4	Dp1	Mean water depth
5-8	Var	Variance of energy in time domain
9-12	Tides_st	Not used
13-16	Tides_end	Not used
17-20	m_0	0 order moment of spectrum
21-24	m_1	1 st order moment of spectrum
25-28	m_2	2 nd order moment of spectrum
29-32	m_3	3 rd order moment of spectrum
33-36	m_4	4 th order moment of spectrum
37-40	H_{m0}	Statistical approximation of H_s
41-44	$T_{0,1}$	m_0/m_1 average zero upcrossing period
45-48	$T_{0,2}$	$\text{Sqrt}(m_0/m_2)$ average zero upcrossing period
49-52	$T_{2,4}$	$\text{Sqrt}(m_2/m_4)$ Average crest to crest period
53-56	E4	Epsilon4, Broadness parameter
57-60	E2	Epsilon2, narrowness parameter
61-64	Qp	Peakedness factor
65-68	STPI	Steepness of waves
69-72	Fp	Spectral peak frequency
73-76	Sum1	Summation of spectral energy
77	fpm	Mean spectral peak
78	Theta_d	Peak direction
79	Var_i	Summation of spectral energy m_0 over incident direction
80	Var_r	Summation of spectral energy m_0 over reflected direction
81	H_{m0_i}	H_s over incident direction
82	H_{m0_r}	H_s over reflected direction
83	Theta_s	Peak direction summated over frequencies
84	Am1	?
85	Am2	Not used

Rtrddmm?.spc is the more useful table as it only contains the statistics shown in Table 16 in a single row of 12 entries. Statistics quoted for incident spectral significant wave height and average reflection coefficient in the body of the report are taken from columns 1 and 6.

Table 16 Definition of values in each column of *R*.spc* files

Column Number	Characteristic	Description
1	H_third	Hs, incident spectral significant wave height
2	Fp	Peak frequency
3	Lx	Spectral Peak Wave length
4	Ur	Ursel Number
5	Ir	Iribarren Number
6	Kr_av	Average reflection coefficient
7	Kr_p	Peak reflection coefficient
8	Kr_ts	Reflection transfer function
9	Kr_fdrf	Frequency dependant reflection function
10	Mrlld	Mean reflection line distance
11	Rx	Peak reflection line dist
12	depth	Mean depth between the three wave gauges