HR Wallingford

ESTUARINE SEDIMENTS - NEAR BED PROCESSES
Field measurement of near bed cohesive sediment processes

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CONTRACT

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ABSTRACT

The ability to predict the movement of cohesive sediment within tidal waters has a significant economical and ecological importance in the development of new engineering works and the maintenance of existing installations. The processes of transport, deposition, consolidation and erosion of cohesive sediment are controlled by a complex array of physical and chemical factors which are only partly understood. Any attempt to predict the movement of cohesive sediment must first investigate the nature of the hydrodynamics of the water and then relate the movement of water to the movement of cohesive sediment.

A series of field deployments of a novel bed frame, with instruments for measuring near bed processes, were undertaken on intertidal mud flats at two sites. The first was at the West Usk lighthouse at the mouth of the River Usk on the Severn Estuary and the second at Eastham docks on the Mersey Estuary. Continuous measurements were made of hydrodynamics and sediment in the bottom 1m of the water column. These included: high frequency measurements of flow in x, y and z directions at 0.1 and 0.5m above the bed (using electromagnetic current meters); high frequency measurement of pressure fluctuations at 0.8m above the bed; suspended solids concentration at 0.1m, 0.5m and 1.0m above the bed; measurement of mean tidal flow (using propellor meters); measurements of bed level near the frame.

At the West Usk field study site 20 tides were monitored in 5 deployments between November 1989 and October 1990. The bed level changes measured on the May deployment showed significant change, 0.014m on the 24 May am tide and 0.012m on the 25 May am tide. The increase in bed level occurred mostly at the beginning of the tide simultaneous with a drop in suspended sediment concentration. Changes in bed level for the 4 October pm and 5 October pm tides were 0.001 and 0.002m respectively. The bed level change increased as well as decreased and the overall changes were much less than those measured in the May deployment. The change in bed level on these tides followed a broadly similar pattern to suspended solids concentration.

The calculation of shear stress, τ_e using spectral analysis gave excessively high results in many instances. This could be due to two possibilities, flexing of the EMCM mountings or disruption of the flow around the EMCMs caused by the frame.

Measurements of 3 spring tides and 2 neap tides at Eastham dock on the Mersey Estuary were carried out. Changes in bed level of 0.020m and 0.010m were measured on spring and neap tides respectively. Changes in concentration, bed level and shear stress tied in very well with each other. The concentration in the upper water column drops when the shear stress dropped. An increase in the concentration near the bed (0.1m) occurred as the concentration dropped above. After a short time (20 to 30 min) a change in bed level was detected indicating that deposition had taken place. The sediment lost from suspension, approximately 1.5kgm^{-2} (0.3kgm^{-3} in 5 metres water) on the spring tides and 0.68kgm^{-2} (0.15kgm^{-3} in 4.5m metres of water) on the neap tide could account for the increases in bed level measured.

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1 INTRODUCTION

The ability to predict the movement of cohesive sediment within tidal waters has a significant economical and ecological importance in the development of new engineering works and the maintenance of existing installations. Schemes such as the reclamation of intertidal flats, the construction of new berths, or the enlargement and extension of dredged channels require a sound engineering appraisal of the likely changes in the patterns of sediment movement which will result after the scheme is built. Moreover, prediction of the movement of cohesive sediment is crucial in the understanding of the distribution of certain pollutants, in particular heavy metals which are adsorbed on to clay and silt particles.

The processes of transport, deposition, consolidation and erosion of cohesive sediment are controlled by a complex array of physical and chemical factors which are only partly understood. Any attempt to predict the movement of cohesive sediment must first investigate the nature of the hydrodynamics of the water and then relate the movement of water to the movement of cohesive sediment. As yet, it is not possible to predict the behaviour of a cohesive sediment from its physical and chemical properties alone and the principal thrust of research has been to determine in the laboratory, for a given set of flow conditions, the behaviour of a cohesive sediment.

Laboratory tests for determining the erosional properties of cohesive sediments have been developed to a level where their application for determining critical shear stress and rate of erosion, in unidirectional (tidal) flows, has become routine. However the erosional properties found in the laboratory have not yet been verified by field observations. This series of field work aims in part to verify these laboratory results.

In addition to unidirectional flows the action of waves has a significant effect on cohesive sediment processes. Wave effects on the surface of mudflats are very difficult to replicate in the laboratory since the edge effects and end effects of any flume tend to overwhelm the surface processes being studied. Consequently wave effects (and combined wave and tide effects) need to be studied in the field. The aim of this work is to determine by field observations the critical conditions and rate of erosion and deposition under a range of combined wave and tide conditions and suspended sediment concentrations.

Since erosion and deposition, the governing processes for sediment transport, occur at the bed surface a field frame has been developed (Ref 1) and tested (Ref 2) which can measure parameters in the bottom 1m of the water column. To determine the combined wave and tide shear stress at the bed it is necessary to take high frequency measurements of water movements. High frequency measurements of pressure fluctuations are also taken, from which surface elevations can be calculated. Other measurements taken are bed level and suspended sediment concentration.

2 FIELD MEASUREMENTS

2.1 Field study locations

The field frame was deployed on intertidal mudflats on two different sites, the first was at the mouth of the River Usk on the Severn Estuary (Fig 1), the second at Eastham Dock on the River Mersey (Fig 2).

The River Usk field study site was located near the West Usk Lighthouse. The mud flats at this site are characterised by an ephemeral layer of soft mud on top of a non mobile muddy peat layer. The site had a tidal range of approximately 10m during spring tides. The frame was deployed on the mud flats at a height of approx 3m below the mean spring tide high water level enabling the equipment to be operated for about three hours over high water. This site was selected for the initial field trials (Ref 1) because of its convenient access and because it had a clearly identifiable layer of soft mud which varied in thickness. The mud flats were gently sloping with an expanse of many square kilometres exposed at low tide.

The field study site at Eastham Dock on the River Mersey was situated on the side of the Manchester ship canal approach channel on mud banks with an appreciable slope. The site has a tidal range of about 9m and the position of the frame was 6m below the mean high water mark. The mud flats were firm and had many small rocks on the surface. It appeared that this mud is permanent and would only be eroded in severe storms. The equipment was operated from a van situated on the adjacent dock.

2.2 Instrumentation and operation

The bed frame was designed to enable simultaneous measurements of tide and wave induced flow (Ref 1). It is triangular in shape with an open structure to offer as little resistance to flow as possible. Its three legs protrude into the bed to prevent movement (Plate 1).

The following instruments were mounted on the frame:

- 3 Braystoke current meters
- 4 electromagnetic current meters (EMCM)
- 3 Partech turbidity sensors
- 1 pressure sensor
- 3 ultrasonic probes

The Braystoke current meters were mounted at 0.1m, 0.5m and 1.0m above the bed and in such a way that they could swivel freely through 360 degrees to align themselves with the current. These were used to measure tidal flows and to give a field calibration of the EMCMs.

The EMCMs measured 2 components of velocities. These were mounted at 0.1m and 0.5m above the bed and set to measure in the x,y and x,z planes at each height. The output from these was logged at 5Hz to enable high frequency wave and turbulence fluctuations to be analysed.

The Partech turbidity sensors were mounted at 0.1m, 0.5m and 1.0m above the bed in positions that would not interfere with flow around the EMCMs.

The pressure sensor was mounted at 0.8m above the bed. The output was logged at 5Hz and enabled water depth and, if necessary, wave conditions to be found.

The ultrasonic probes were mounted at approximately 0.1m above the bed, either attached to a spur on each leg of the bedframe or about 3 metres away from the main bedframe. These enabled the bed level change during the tide to be monitored.

The output from each of the instruments was logged onto a computer over the monitoring period.

2.3 Data Analysis

The pressure sensor, Braystoke current meters and ultrasonic probes were pre-calibrated so no extra calibration was necessary for these instruments.

The calibrations of the EMCMs tend to drift slightly so a check is made by comparing a ten minute average of the modulus of the x and y velocities with the Braystoke current meters.

The Partech turbidity sensors were calibrated before and after deployment using formazin suspensions. The formazin to silt conversion factor was found using water samples.

The mean values of water levels, concentration and shear stress over ten minute intervals for each monitoring period were found.

From the tidal mean velocities at the three heights the shear stress at the bed could be calculated (see Appendix A) assuming a logarithmic vertical velocity profile.

From the pressure fluctuations the water surface elevation was calculated. From this, using wave theory and a bed roughness coefficient, the wave induced contribution to bed shear stress was calculated (Appendix A).

From the high frequency velocity fluctuations the combined wave and tidal flow induced shear stress at the bed was found using a spectral analysis technique (Appendix A). The two components were separated by splitting the spectra.

The Reynolds stress was found from the cross product of the high frequency fluctuations. The

Reynolds stress was used to estimate the combined wave and tide induced bed shear stress using a constant of proportionality (Appendix A).

3 RESULTS OF WEST USK DEPLOYMENTS

3.1 Details of deployments

A series of deployments of the bed frame at West Usk was undertaken between August 1989 and November 1990 (see summary Table 1). On the first two deployments, August 1989, and November 1989, high frequency velocity measurements were only taken in the x,y plane. Intermittent technical problems with some of the equipment were experienced, resulting in some incomplete data sets.

At the West Usk lighthouse field site the bed frame was deployed approximately 3m below the spring tide mean high water level. The orientation of the frame was set such that the principal tidal flow would be in the x direction of the EMCMs. The wave incidence was at approximately 90 degrees to the x axis. Cables connecting the sensors with the control units were run across the mud flats. The control units and data logging equipment were set up in a van stationed on the sea wall with power supplied from a portable generator. Each tide was monitored for between 3 and 4 hours, from approximately 4 hours after low water.

At this site 20 tides were monitored in 5 deployments between November 1989 and October 1990. Comprehensive data was obtained for 16 tides with some useful data from the other 4. Measurement of bed level throughout the tide was successful on 11 occasions with an actual change in bed level monitored on 9 tides.

3.2 Examples of recorded data

3.2.1 Short term variation

The data collected for each tide was processed in the form of ten minute bursts. The measured data collected using each instrument can be expressed graphically as measured value against time. The long term variation can be expressed in the form of ten minute average over the duration of the measurement period. For the parameters logged at high frequency, the short term variation, over a time period of around 1 minute can also be shown.

A plot of the short term variation of bottom velocities can show whether the flow fluctuations are tide dominated or wave dominated. Figure 3 shows two 40 second bursts of the current speed recorded, u (horizontal in the direction of the tidal flow), v (horizontal perpendicular to the tidal flow) and w (vertically). The upper figure shows the trace 70 minutes before high water when the water depth was about 2m and tidal flow about $1ms^{-1}$. The fluctuations are wave dominated with a period of about 2 seconds. The lower figure shows the trace at 30 minutes after high water when the water depth was 3m and the tidal flow was approximately $3ms^{-1}$. The wave influence in this data set is much less and the changes, particularly in u, are due to turbulent fluctuations in tidal flow.

Figure 4 shows the pressure over the same time periods as the flow shown in Figure 3. The upper trace shows a smooth fluctuation in pressure caused by waves once again with a period of around 2 seconds. The lower trace has a much less smooth appearance due to less influence of waves on the pressure variation and greater influence in turbulent fluctuations in tidal flow.

Figure 5 shows the short term variation of bed level and suspended sediment concentrations; as expected there is little fluctuation of the reading over this time period. The fluctuation monitored is most likely due to the measurement method rather than movement of the bed. The variation of concentration over a ten minute period, at 0.1, 0.5 and 1.0m above the bed, is shown on the lower figure. The values display some high frequency fluctuations around a short term mean due to turbulence. The turbulent fluctuations are interesting but of little analytical use in this instance as the Partech detector heads interfere too much with the flow around them.

Figure 6 shows a comparison of the pressure fluctuations and the velocity fluctuations in the direction of wave propagation. The measurements at 70mins before high water were a good match because the velocity fluctuations were due to waves. The measurements at 30mins after high water were turbulence dominated and therefore did not match so well.

The spectra of the flow fluctuations (in the direction of wave propagation) and pressure fluctuations are compared in Figure 7 (70 minutes before high water) and 8 (30 minutes after high water). The upper figure in each case shows the spectrum of the flow fluctuations. Shown on the figure is the fitted line used to split the contribution from waves (above the line) and contribution from tidal flow (beneath the line). The fitted line with gradient 5/3 was used to check that the turbulent energy decreases with frequency in a normal way (see Appendix A).

The middle figure shows the comparison of the wave induced portion of the flow spectrum (above the fitted line in the top figure) and the spectrum of the pressure variations. For both periods there is a close similarity between the wave induced part of the flow spectrum and pressure spectrum. This indicates that the spectral splitting technique (see Appendix A) is working satisfactorily. The surface elevation spectrum (the bottom figure) show that the peak frequency has changed from 0.35s (Fig 7) to 0.25s (Fig 8) in the 100mins between the data sets. The total energy of the spectrum has decreased indicating that the wave height has also decreased.

3.2.2 <u>Variation over tides</u>

The results of ten minute averaged data can be plotted against time for each instrument used. The results of successive tides from each deployment can be plotted together. In order to compare the tides the time is zeroed to each high water.

Figure 9 shows the variation of water depths over four tides during the May deployment and one tide during the October deployment. The maximum water depths vary between 3.5m and 3.0m above the bed. The tide curve is smooth and almost symmetrical in shape and there was little variation among the tides measured.

Variation in measured horizontal current speed on 3 tides in the May and October deployments are shown in Figures 10 and 11. The current speed generally had a maximum around the time of high water with a slight dip detected around high water on 25 May AM and 4 October AM. The tide on the 5 October AM had a period of low flow around high water. The tidal flow in the area of the survey is influenced significantly by eddy effects caused by a small headland seaward of the monitoring position; as a result the tidal flow is always in the same direction. Some of the flow measurements gave reasonable fit log profiles, particularly the 4 October PM and 5 October AM tides.

The concentration of suspended solids over the May and October tides is shown in Figures 12 and 13. The concentration is higher at 0.1m above the bed than at 1.0m above the bed during all tides. The May deployment had lower concentrations in suspension than the October deployment. The concentration is highest near the bed (0.1m above the bed) at the beginning of the measurement period. This decreased over the next 30mins on most tides. However on the 4 October PM and 5 October AM tides the decrease in concentration came 30 min before high water and 30mins after high water respectively.

The bed level over the tides is shown in Figure 14. The bed level increased on two tides in the May deployment (24 am and 25 am). These changes were approximately 16mm and 12mm respectively. The change occurred mainly at the beginning of the monitoring period. The bed level from 2 tides in the October deployment decreased as well as increased. The biggest increase was before high water on 4 October PM and after high water on 5 October PM. The maximum change was less than 3mm and could have been due to limitations in the measurement technique, for example changes in the water column affecting the instrument calibration or movement of the frame.

The wave characteristics changed over each tide; typical examples are shown in Figure 15. The zero crossing period (T_z) increased with increasing water depth from around 1.5s in 1m water depth to 2.5s in 3m of water. This effect is expected from wave physics.

The tide induced shear stresses for the May and October deployments are shown in Figure 16. These were calculated by determining the bed roughness where logarithmic velocity profiles were measured (Appendix A). Using this bed roughness the bed shear stress was calculated directly from the velocity readings.

3.3 Comparison of shear stress from different calculation methods

3.3.1 Shear stress induced by tidal flow

The shear stress induced by tidal flow was calculated using two different methods (Appendix A). The first was from the logarithmic profile for the mean velocity measurements (τ_p). The second method used spectral analysis of the high frequency turbulence fluctuations (τ_{ep}). The turbulent energy is proportional to shear stress.

The results of both calculations for the 24 April and 8 August are shown on Figure 17. For the 24 April tide the two methods agree well. On the 8 August tide the τ_{ep} values were however consistently higher than the τ_p values. The two methods both gave reasonable values for most tides, however a number of τ_{ep} values were excessively high. These high τ_{ep} values are most likely the result of measurement error caused by flexing of the equipment mountings or disturbance of flow around the current meters by the frame.

3.3.2 Wave induced shear stress

The wave induced shear stress was calculated from the spectral analysis of the high frequency velocity fluctuations (τ_{ew}) and from the pressure variations (τ_w) (see Appendix A). Unreasonably high values of τ_{ew} were obtained in a large proportion of the measurements. This is most likely due to measurement errors caused by either flexing of the instrument mountings or disturbance of the flow around the current meters.

Comparison of the results from the two methods are shown in Figure 18 for 25 May 1990 am and 5 October 1990 am tides where reasonable τ_{ew} were obtained. The values of shear stress decreased as the water depth increased at the start of the monitoring period and then increased as the water depth decreased towards the end of the monitoring period. The results of the two methods of calculating the wave induced shear stress agreed well.

3.3.3 Combined wave and tide shear stress

The combined wave and tide shear stress was calculated by two different methods. The first was by spectral analysis of the high frequency velocity fluctuations (τ_{et}) and the second is from the Reynolds stress calculated from the cross product of the data sets (τ_r). Both values are calculated from the high frequency velocity measurements and both gave spuriously high results. The error of both calculated values probably originates in errors in measurement resulting from flexing of the instrument mountings or interference in flow around the EMCMs caused by the frame.

A comparison of the two methods for the 5 October am tide where relatively reasonable results were obtained using both methods is shown in Figure 19. These also agree well and indicate that the shear stress when the water is shallow is far higher than at high tide when the water is deeper. This indicates that the effect of waves dominates the bed shear stress.

3.4 Discussion of results

Throughout the study a large number of instruments were deployed. A large amount of data from tides from four seasons was gathered. On some tides problems were encountered with the drifting calibrations of the current meters and turbidity meters, the data for some of the tides is therefore incomplete.

A summary of the results giving some maximum and minimum values of parameters is given in Table 2. The November, April and August deployments gave broadly similar results to the May and October deployments which have been described in detail. Some examples are given in the following discussion.

The tide curves had the same pattern from tide to tide, with the maximum depth at the measurement site being approximately 3 metres. The tidal current reached similar maxima for all the measured tides of around $0.3ms^{-1}$ at 0.5m above the bed (Figs 10, 11 and 17). The pattern of tidal flow in the study area was influence by an eddy caused by flow around a headland seaward of the study site. The current was always in a seaward direction. The time of highest flow speed was usually in the hour before high water but varied from tide to tide. This was particularly noticeable during the August deployment (Fig 20). A drop in the current speed at high water was recorded on some tides. The most pronounced drop in current speed was on the 5 October (Fig 11) when the speed dropped from $0.25ms^{-1}$ to $0.1ms^{-1}$. The measured tidal current speed is relatively low for the Severn Estuary where tidal flow can commonly reach speeds of $5ms^{-1}$.

The wave characteristics varied with water depth; as expected, as the water depth increased the wave period increased, particularly in the April deployment (Fig 21). Wave periods of 1.5s to 3.0s were measured.

On the 25 May the bed level was seen to increase by 0.012m. This change occurred at the same time as the concentration in suspension decreased (Fig 22). The bed level increased and concentrations increased during the period 100-50min before high water when the tide induced shear stress was low, however the bed level change did not appear to coincide very well with low shear stress period. The bed level changes on the 4 and 5 October (Fig 23) seemed to vary in a similar manner to the suspended sediment concentrations at 0.5m and 1.0m above the bed. The magnitude of the bed level change measured is very small and could be due to instrument error caused by slight movement of the bed frame or effects of changes in the water column on instrument calibration.

The analysis of the shear stresses, in particular the calculation of τ_{ew} gave excessively high results in many instances. This could be due to two possibilities, flexing of the EMCM mountings accentuating the velocity fluctuation, or disruption of the flow around the EMCMs caused by the frame. The spectra from which these high results originated, however, looked reasonable on inspection. Before future use of the equipment it would be useful to trace and eliminate the cause of these high results.

In instances where the spectral splitting technique gave reasonable values it was evident that the wave induced shear stress τ_{ew} (Fig 18) was greater than the tide induced shear stress (Figs 16 and 17), particularly for 5 October when the significant wave height was still only 0.35m. This was confirmed by the wave induced shear stress, τ_w, calculated from the wave parameters using wave theory. It can be reasonably assumed therefore that the factor governing erosion in most instances is the wave induced shear stress, particularly since wave heights far greater than that measured on the 25 May are common. Once the sediment is in suspension it will be transported principally by tidal flow. Waves will cause dispersion and mixing of the sediment and prevent it settling in shallow exposed areas.

4 RESULTS OF MERSEY DEPLOYMENTS

4.1 Details of deployments

At the Eastham Docks field site the bed frame was deployed approximately 5m below mean high water. The orientation of the frame was set once again such that the principal tidal flow would be in the x direction of the EMCMs. The wave incidence for both deployments was at about 45 degrees to the x-axis. The control units and data logging equipment were set up in a van stationed on the dock. Each tide was monitored for between 7 and 8 hours, from approximately 2 hours after low water. A summary of the deployments is given in Table 1.

Two deployments were undertaken, one involving monitoring of 3 spring tides, the other 2 neap tides (see Table 1). The weather was calm for both deployments and the wave heights were very small <0.01m (Ref 5).

4.3 Tidal Variation

The water depths over the spring and neap tides are shown in Figure 24. The tidal range of the spring and neap tides measured were 6.9m and 4.8m respectively. The tide curve was approximately symmetrical around high water.

The variation of bed level, suspended solids concentration and tide induced shear stress for each tide are shown in Figures 25 to 29. The concentrations in suspension decreased during periods of low shear stress indicating settling through the water column. This was supported by measurements of increasing concentration at 0.1m when the concentration at 1.0m and 0.5m decreased just after high water on 20 November and just before high water on the 26 November.

The shear stress on the spring tides (Fig 25 to 27) decreased to a minimum just after high water. There was then a short period of increased stress before then it decreased again to another minimum. Subsequently it increased again during ebb flow. The shear stress on the Neap tides (Fig 28 and 29) followed a slightly different pattern. The shear stress decreased to a minimum at about 30min before high water. A small peak of shear stress was observed at 1 hour after high water after which it decreased to another minimum before increasing during full ebb flow.

The bed level was observed to increase during periods of low shear stress (below $0.1Nm^{-2}$). There was a time delay between reduction in shear stress and increase in bed level. This is probably due to the time taken for the sediment to fall through the water column.

4.4 Discussion

The deposition of sediment at this study site during the monitored tides was dependent upon the tide induced shear stress, because there were no waves (in contrast with the West Usk site). The changes in concentration, bed level and shear stress tied in very well with each other. The concentration in the upper water column dropped when the shear stress dropped. An increase in the concentration near the bed (0.1m) occurred as the concentration dropped in the upper column (0.5m and 1.0m sensors). After a short time (20 to 30 min) a change in bed level was detected showing that deposition had taken place. A summary giving some maximum and minimum values of velocities, concentrations and shear stresses is given in Table 2.

The largest changes in bed level occurred on spring tides when there was the largest amount of material in suspension. This is accentuated because the settling velocity increased with concentration.

It can be assumed that the drop in suspended solids concentration just before and during deposition is a result of sediment depositing on the bed. From inspection of the data the decrease in the concentration of suspended sediment on the spring tides is approximately 0.3kgm^{-3} and on the neap tides is 0.15kgm^{-3}. The sediment lost from suspension is approximately 1.5kgm^{-2} (0.3kgm^{-3} in 5 metres water) on the spring tides and 0.68kgm^{-2} (0.15kgm^{-3} in 4.5m metres of water) on the neap tide. This will account for a 0.030m and 0.013m increase in bed level on the spring and neap tides respectively assuming a density of deposition of $50 kgm^{-3}$. This compared reasonably well with the 0.020m and 0.010m measured and indicates that the concentration changes measured would produce the bed level changes measured if the sediment deposited directly from suspension at the same position.

6 CONCLUSIONS

1. Two sets of field deployments of a specially designed bed frame, with instruments for measuring near bed processes, were undertaken on intertidal mud flats at two sites. The first was at the mouth of the River Usk on the Severn Estuary and the second at Eastham docks on the Mersey Estuary. Continuous measurements were made of the hydrodynamics and sediment in the bottom 1m of the water column. These included:
    - High frequency measurements of flow in x, y and z directions at 0.1 and 0.5m above the bed.
    - High frequency measurement of pressure fluctuations at 0.8m above the bed.
    - Suspended solids concentration at 0.1m, 0.5m and 1.0m above the bed.
    - Measurement of mean tidal flow.
    - Measurements of bed level near the frame.

2. At the West Usk field study site 20 tides were monitored in 5 deployments between November 1989 and October 1990. Comprehensive data was obtained for 16 tides with some useful data from the other 4. Measurement of wave conditions using the pressure sensor was successful on 8 tides and measurement of bed level throughout the tide was successful on 11 occasions with an actual change in bed level monitored on 9 tides.

3. Measurements of 3 spring tides and 2 neap tides at Eastham dock on the Mersey Estuary were carried out. Complete sets of information on bed level were obtained for two of the spring tides and one of the neap tides. The wave height at the site was below 0.01m throughout the monitoring period so analysis of the high frequency fluctuations to determine wave induced shear stress was not carried out.

4. The bed level changes measured on the May deployment at the West Usk site showed significant change; 0.016m on the 24 May am tide and 0.012m on the 25 May am tide. The increase in bed level occurred mostly at the beginning of the tide, simultaneous with a drop in suspended sediment concentration. Changes in bed level for the 4 October pm and 5 October pm tides were -0.001 and -0.002m respectively. The bed level change increased as well as decreased and the overall changes were much less than those measured in the May deployment. The changes may have been due to movement of the frame or changes in the water column affecting the instrument calibration. The change in bed level on these tides followed a broadly similar pattern to suspended solids concentration.

5. The shear stress induced by tidal flow was calculated from the logarithmic profile of the mean velocity measurements (τ_p) and using spectral analysis of the high frequency turbulence fluctuations (τ_{ep}). The wave induced shear stress was calculated from the spectral analysis of the high frequency velocity fluctuations (τ_{ew}) and from the pressure variations (τ_w). The combined wave

and tide shear stress was calculated using a spectral analysis of the high frequency velocity fluctuations (τ_{et}) and the second from the Reynolds stress calculated from the cross product of the data sets (τ_r). The calculation of shear stress from the high frequency fluctuations (τ_{ep}, τ_{ew}, τ_{et} and τ_r) gave excessively high results in many instances. This could be due to two possibilities, flexing of the EMCM mountings or disruption of the flow around the EMCMs caused by the frame. The spectra from which these high results originated, however, looked reasonable on inspection.

6. In the Eastham docks deployment changes in bed level of 0.02m and 0.01m were measured on spring and neap tides respectively. Changes in concentration, bed level and shear stress tied in very well with each other. The concentration in the upper water column dropped when the shear stress dropped. An increase in the concentration near the bed (at 0.1m) occurred as the concentration dropped above. After a short time (20 to 30 min) a change in bed level was detected indicating that deposition had taken place. The sediment lost from suspension, approximately 1.5kgm^{-2} (0.3kgm^{-3} in 5 metres water) on the spring tides and 0.68kgm^{-2} (0.15kgm^{-3} in 4.5m metres of water) on the neap tide could account for around 0.030m and 0.013m increases in bed level assuming a deposition density of around 50kgm^{-3}.

7 RECOMMENDATIONS

The bed frame system has been deployed with considerable success. Improvements to the system could be made by improving the reliability of the instruments. The EMCMs and turbidity meters used were prone to drifting of their calibrations. More recently designed EMCMs which do not drift would enable the frame to be deployed without the Braystoke current meters attached, thus reducing the number of instruments required and simplifying data processing. Likewise more reliable turbidity meters would increase the accuracy and confidence in the suspended solids measurements.

It is most important to locate the origin of the high values for shear stress (τ_e) found by the spectral analysis of the EMCM output. The determination of combined shear stress is vital in the study of near bed processes governing cohesive sediment transport.

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Tables

TABLE 1 Summary of instruments deployed

1 = Instrument deployed 0 = Not deployed

Date	Time of HW	Height of HW (m)	EMCM 0.1m xy	EMCM 0.1m xz	EMCM 0.5m xy	EMCM 0.5m xz	Braystoke current meters 0.1m	Braystoke current meters 0.5m	Braystoke current meters 1.0m	Partech turbidity meters 0.1m	Partech turbidity meters 0.5m	Partech turbidity meters 1.0m	Pressure Sensor	Ultrasonic bed level measurements
West Usk deployments														
29/11/89	1947	12.2	1	1	0	0	0	1	0	1	1	0	1	1
30/11/89	0804	12.2	1	1	0	0	0	1	0	1	1	0	1	1
30/11/89	2019	12.0	1	1	0	0	0	1	0	1	1	0	1	1
01/12/89	0837	12.0	1	1	0	0	0	1	0	1	1	0	1	1
24/04/91	1838	13.4	1	1	1	1	0	0	0	1	1	1	1	1
25/04/91	0700	13.7	1	1	1	1	0	0	0	1	1	1	1	1
25/04/91	1923	13.7	1	1	1	1	0	0	0	1	1	1	1	1
26/04/91	0747	13.9	1	1	1	1	0	0	0	1	1	1	1	1
27/04/91	0832	13.7	1	1	1	1	0	0	0	1	1	1	1	1
23/05/91	1812	13.0	1	1	1	1	1	1	1	1	1	1	1	1
24/05/91	0639	13.2	1	1	1	1	1	1	1	1	1	1	1	1
24/05/91	1903	13.3	1	1	1	1	1	1	1	1	1	1	1	1
25/05/91	0730	13.2	1	1	1	1	1	1	1	1	1	1	1	1
08/08/91	2030	13.1	1	1	1	1	1	1	1	1	1	1	0	1
09/08/91	0849	13.0	1	1	1	1	1	1	1	1	1	1	0	1
09/08/91	2107	13.3	1	1	1	1	1	1	1	1	1	1	0	1
10/08/91	0925	13.1	1	1	1	1	1	1	1	1	1	1	0	1
03/10/91	1818	13.0	1	1	1	1	1	1	1	1	1	1	1	1
04/10/91	0641	13.1	1	1	1	1	1	1	1	1	1	1	1	1
04/10/91	1900	13.6	1	1	1	1	1	1	1	1	1	1	1	1
05/10/91	0721	13.5	1	1	1	1	1	1	1	1	1	1	1	1
Eastham Dock deployments														
20/11/90	0018	8.7	1	1	1	1	1	1	1	1	1	1	1	1
21/11/90	1232	8.9	1	1	1	1	1	1	1	1	1	1	1	1
21/11/90	0050	8.5	1	1	1	1	1	1	1	1	1	1	1	1
26/11/90	1716	7.7	1	1	1	1	1	1	1	1	1	1	1	1
27/11/90	1824	7.9	1	1	1	1	1	1	1	1	1	1	1	1

TABLE 2 Summary of results

Date	Time of HW	Height of HW (m)	Velocity maxima 0.1m (m/s)	Velocity maxima 0.5m (m/s)	Water Depth max (m)	Suspended concentration (kgm^{-3}) 0.1m max	0.1m min	0.5m max	0.5m min	1.0m max	1.0m min	Shear stress maximum τ_p (N/m^2)	Bed level change (mm)	Wave characteristics Hs max (m)	Hs min (m)	Tz max (s)	Tz min (s)
West Usk deployments																	
29/11/89	1947	12.2	-	-	-	-	-	-	-			-	-	-	-	-	-
30/11/89	0804	12.2	0.21	0.25	2.31	0.500	0.200	0.300	0.100			-	0	-	-	-	-
30/11/89	2019	12.0	-	-	-	-	-	-	-			-	-	-	-	-	-
01/12/89	0837	12.0	-	-	-	-	-	-	-			-	-	-	-	-	-
24/04/91	1838	13.4	0.30	0.36	3.90	-	-	-	-	-	-	0.35	2.5	-	-	-	-
25/04/91	0700	13.7	0.28	0.36	3.91	-	-	-	-	-	-	0.36	1.5	0.053	0.026	3.100	1.600
25/04/91	1923	13.7	0.30	0.38	3.90	-	-	-	-	-	-	0.35	-	-	-	-	-
26/04/91	0747	13.9	0.29	0.38	3.90	0.800	0.500	0.500	0.100	-	-	0.30	-	0.170	0.080	2.900	2.100
27/04/91	0832	13.7	0.30	0.44	3.92	0.600	0.200	0.430	0.100	0.200	0.100	0.40	-	0.160	0.100	3.250	1.900
23/05/91	1812	13.0	0.30	0.21	2.90	0.500	0.380	0.200	0.150	0.100	0.500	0.21	-	0.080	0.050	2.700	1.500
24/05/91	0639	13.2	0.32	0.24	3.30	0.510	0.400	0.200	0.150	0.150	0.100	0.27	16	0.070	0.040	2.600	1.500
24/05/91	1903	13.3	0.31	0.24	3.40	0.700	0.500	0.50	0 150	0.100	0.500	0.26	-2	0.150	0.100	2.700	1.500
25/05/91	0730	13.2	0.29	0.22	3.50	1.100	0.600	0.110	0.020	0.100	0.150	0.23	12	0.100	0.050	2.700	1.500
08/08/91	2030	13.1	0.32	0.39	-	0.700	0.400	0.200	0.100	0.150	0.500	0.65	-5	-	-	-	-
09/08/91	0849	13.0	0.28	0.35	-	0.800	0.600	-	-	0.200	0.100	0.16	0	-	-	-	-
09/08/91	2107	13.3	0.26	0.35	-	0.800	0.600	0.200	0.100	0.100	0.050	0.36	-	-	-	-	-
10/08/91	0925	13.1	0.26	0.36	-	0.800	0.600	0.200	0.100	0.200	0.100	0.17	0.15	-	-	-	-
03/10/91	1818	13.0	0.25	0.16	-	1.100	0.500	0.500	0.300	0.300	0.150	0.23	-	-	-	-	-
04/10/91	0641	13.1	0.27	0.17	-	1.450	0.700	0.600	0.350	0.350	0.100	0.25	-	-	-	-	-
04/10/91	1900	13.6	0.30	0.22	-	1.750	0.500	1.550	0.400	0.500	0.100	0.28	-1	-	-	-	-
05/10/91	0721	13.5	0.31	0.21	3.30	1.800	0.300	1.850	0.450	1.750	0.050	0.23	-2	0.380	0.270	2.300	3.300
Eastham Docks deployments																	
20/11/90	0018	8.7	0.35	0.42	5.50	0.830	0.200	0.870	0.180	0.560	0.090	0.90	-	-	-	-	-
20/11/90	1232	8.9	0.42	0.45	5.50	0.950	0.200	0.870	0.180	0.560	0.150	0.90	23	-	-	-	-
21/11/90	0050	8.5	0.44	0.45	5.20	0.820	0.200	0.810	0.180	0.540	0.070	0.85	25	-	-	-	-
26/11/90	1716	7.7	0.38	0.44	3.80	0.250	0.070	0.200	0.065	0.160	0.045	0.6	11	-	-	-	-
27/11/90	1824	7.9	0.36	0.40	4.00	0.275	0.080	0.080	0.075	0.160	0.050	0.5	-	-	-	-	-

Figures

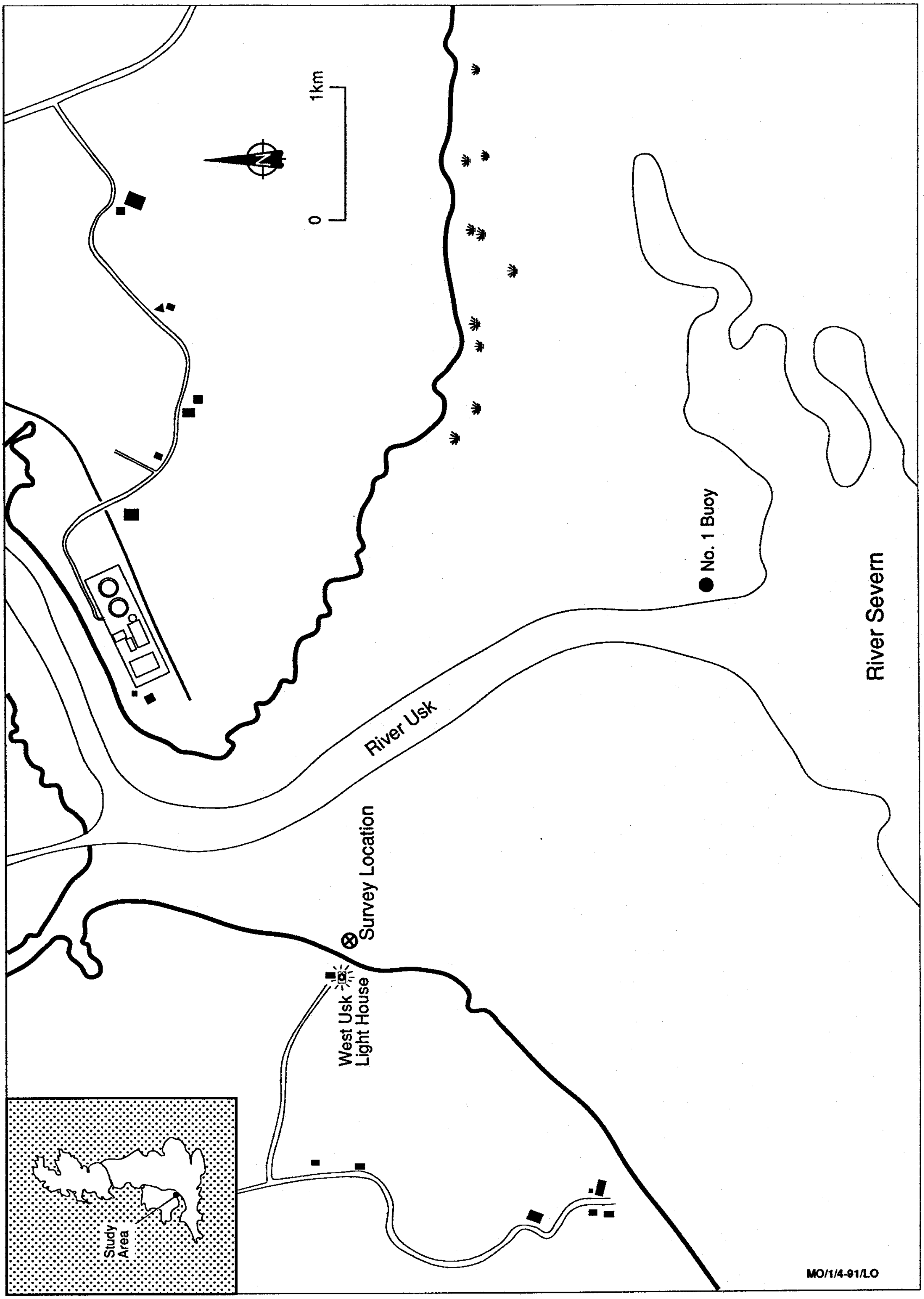

Fig 1 West Usk field study site

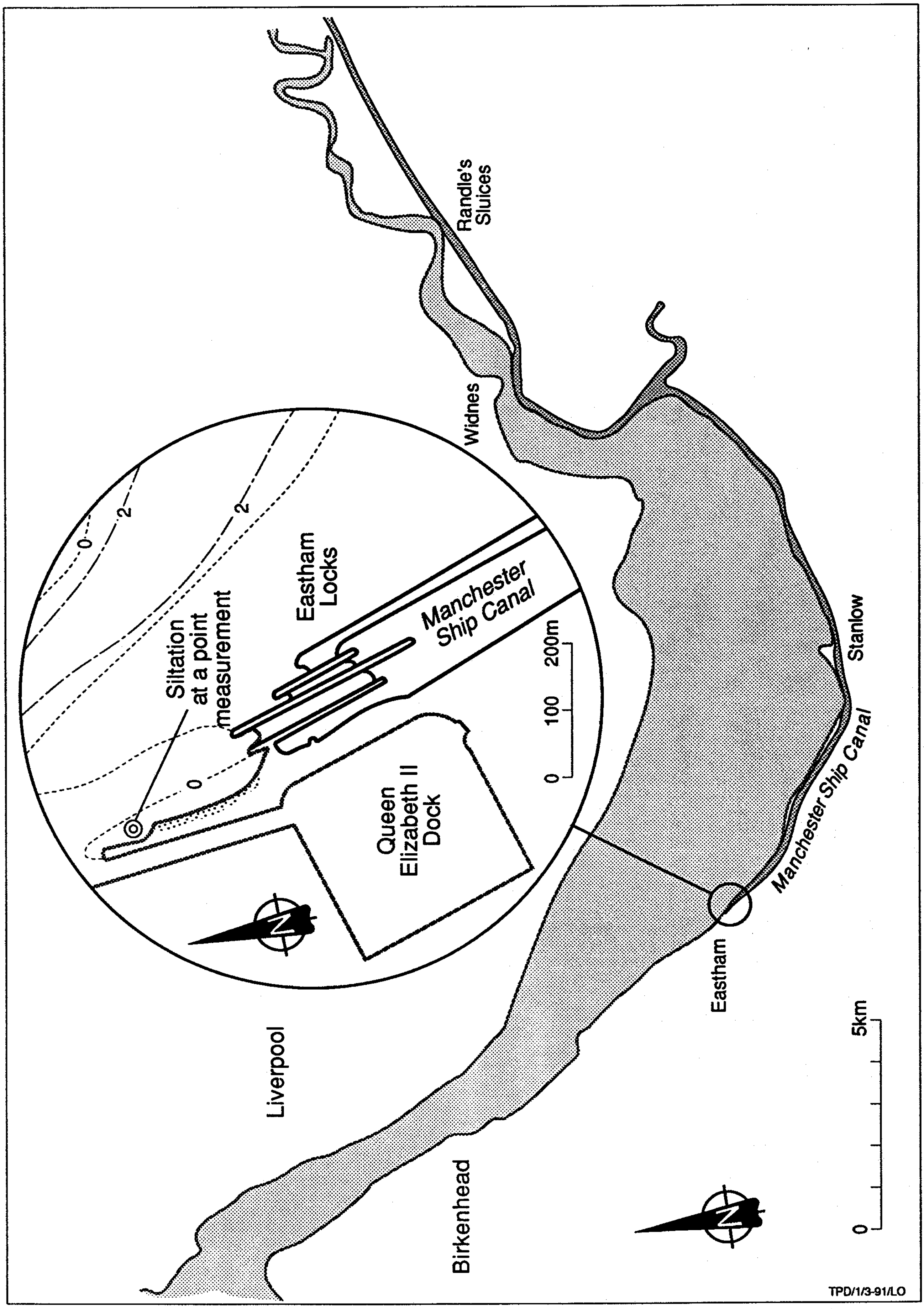

Fig 2 Eastham Dock Field Study Site

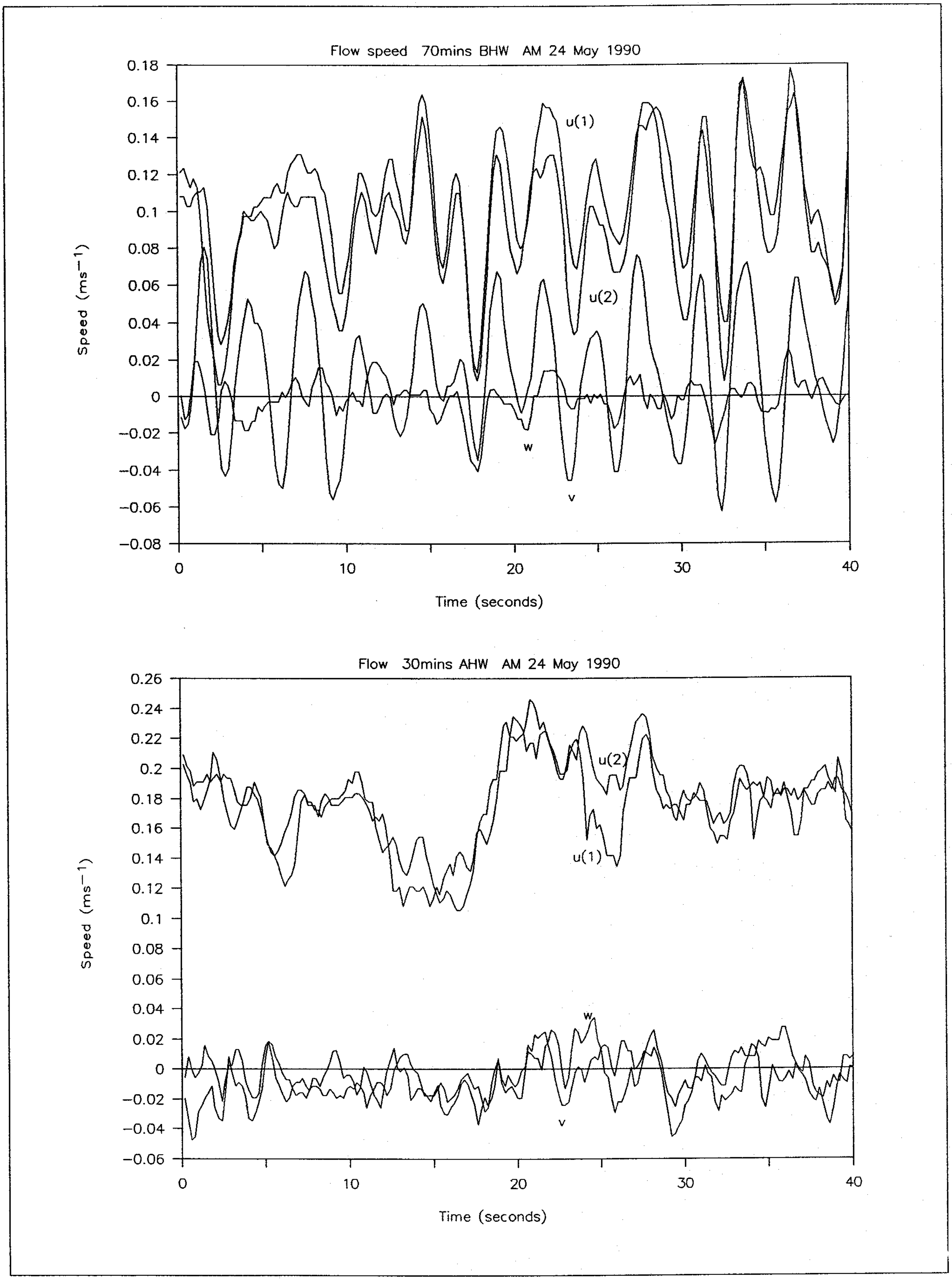

Fig 3 Short term flow variation (u, v and w)

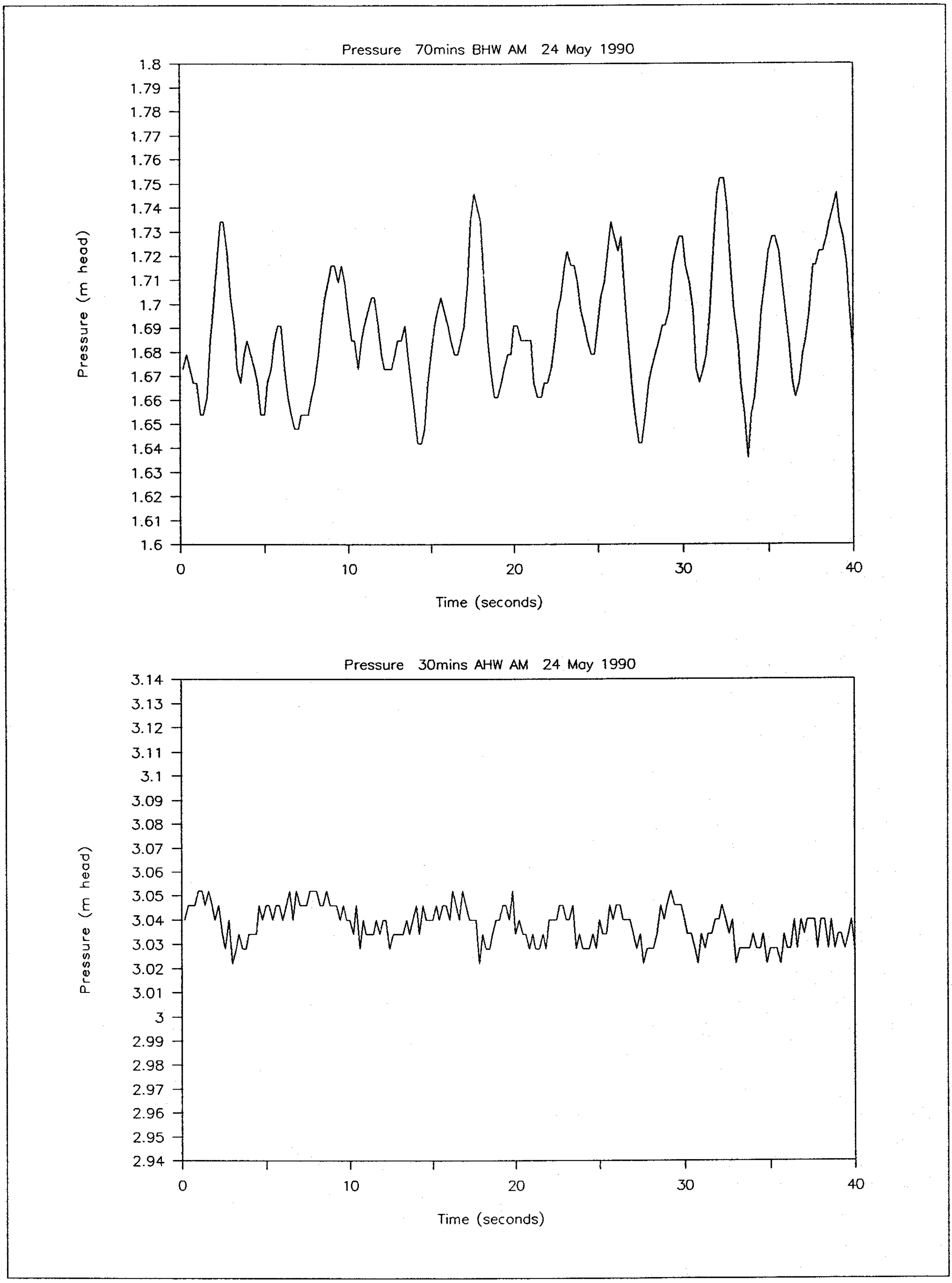

Fig 4 Short term pressure variation

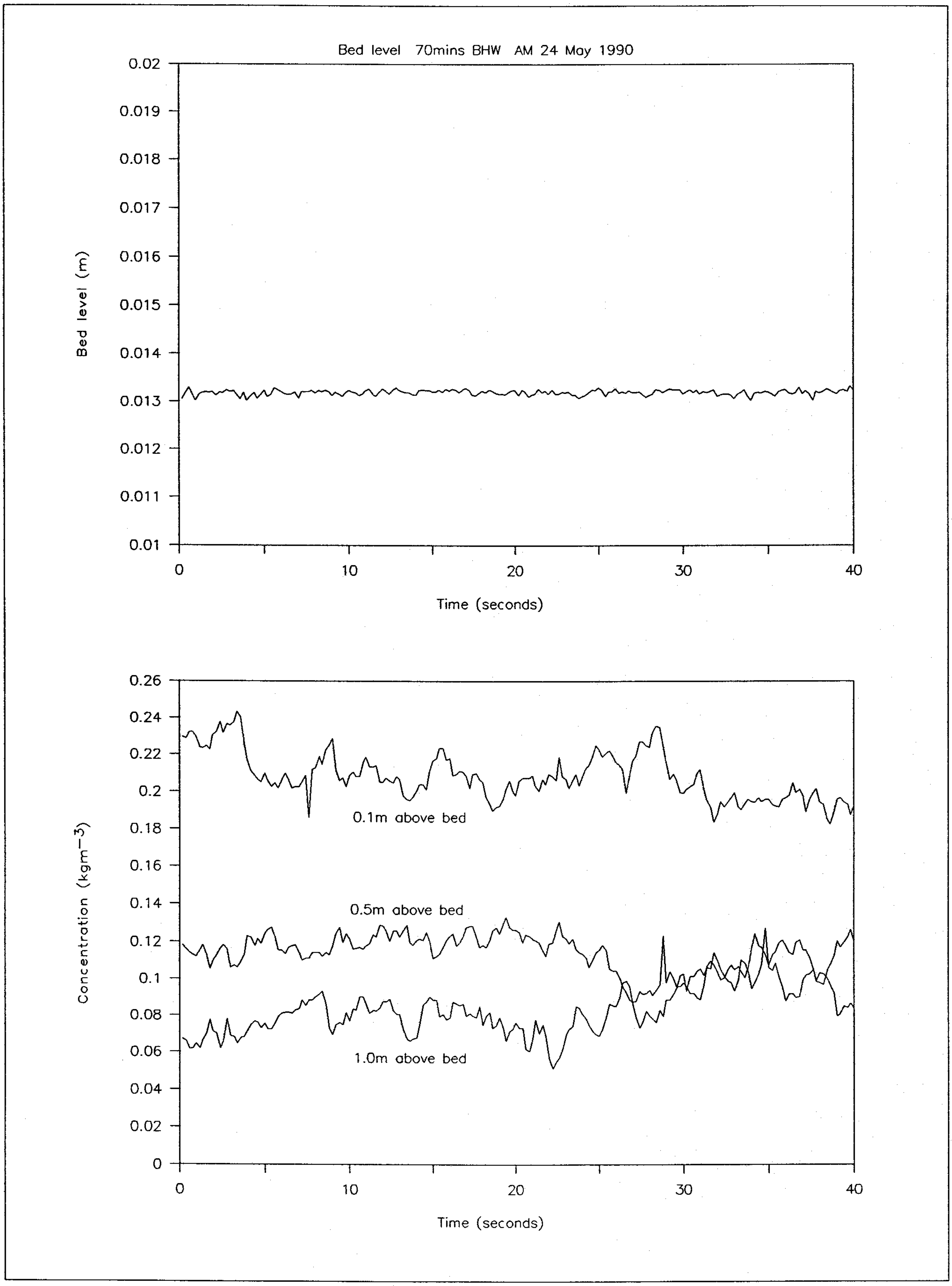

Fig 5 Short term variation in bed level and concentration

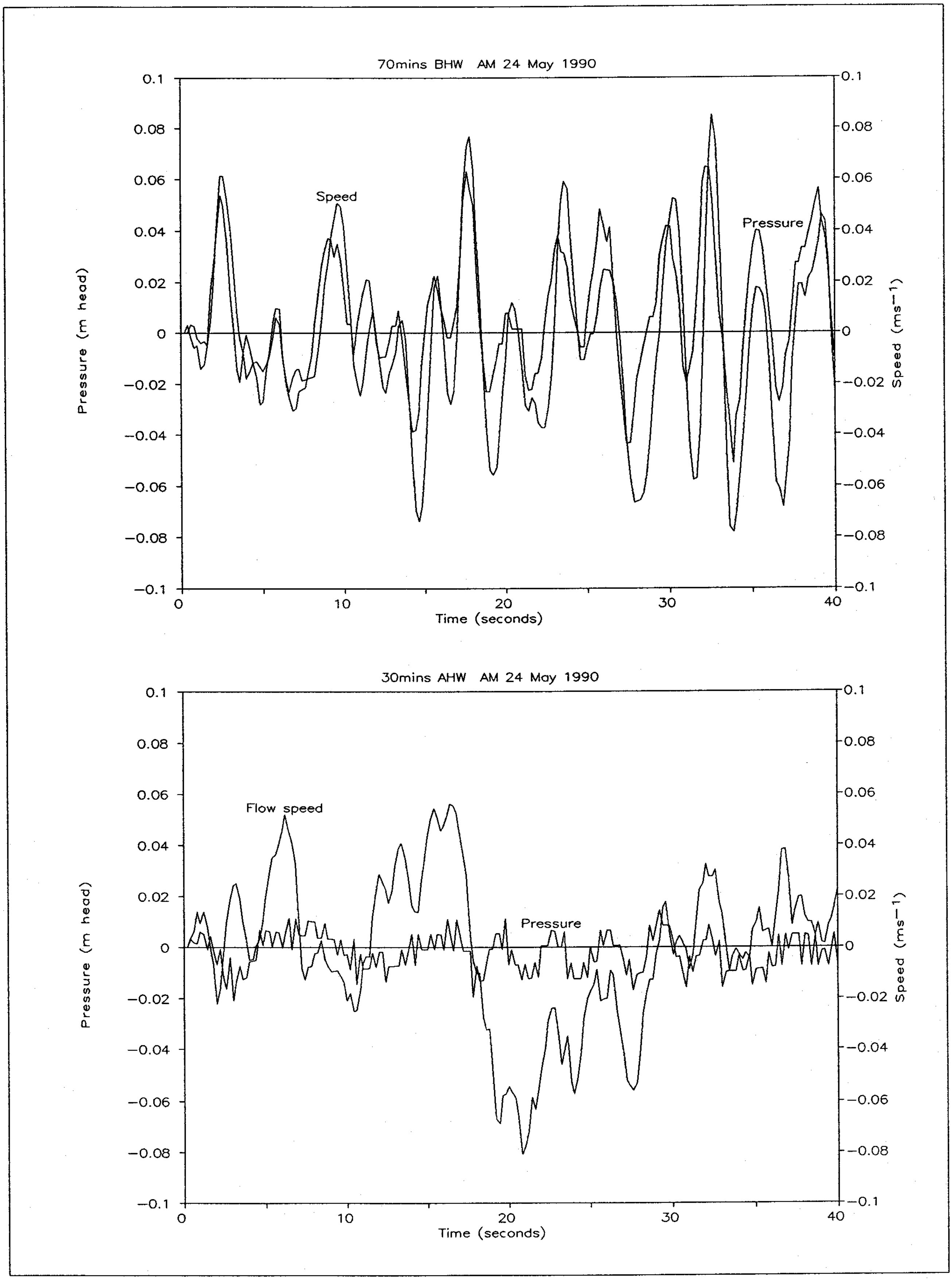

Fig 6 Comparison of short term fluctuation in flow (v) and pressure

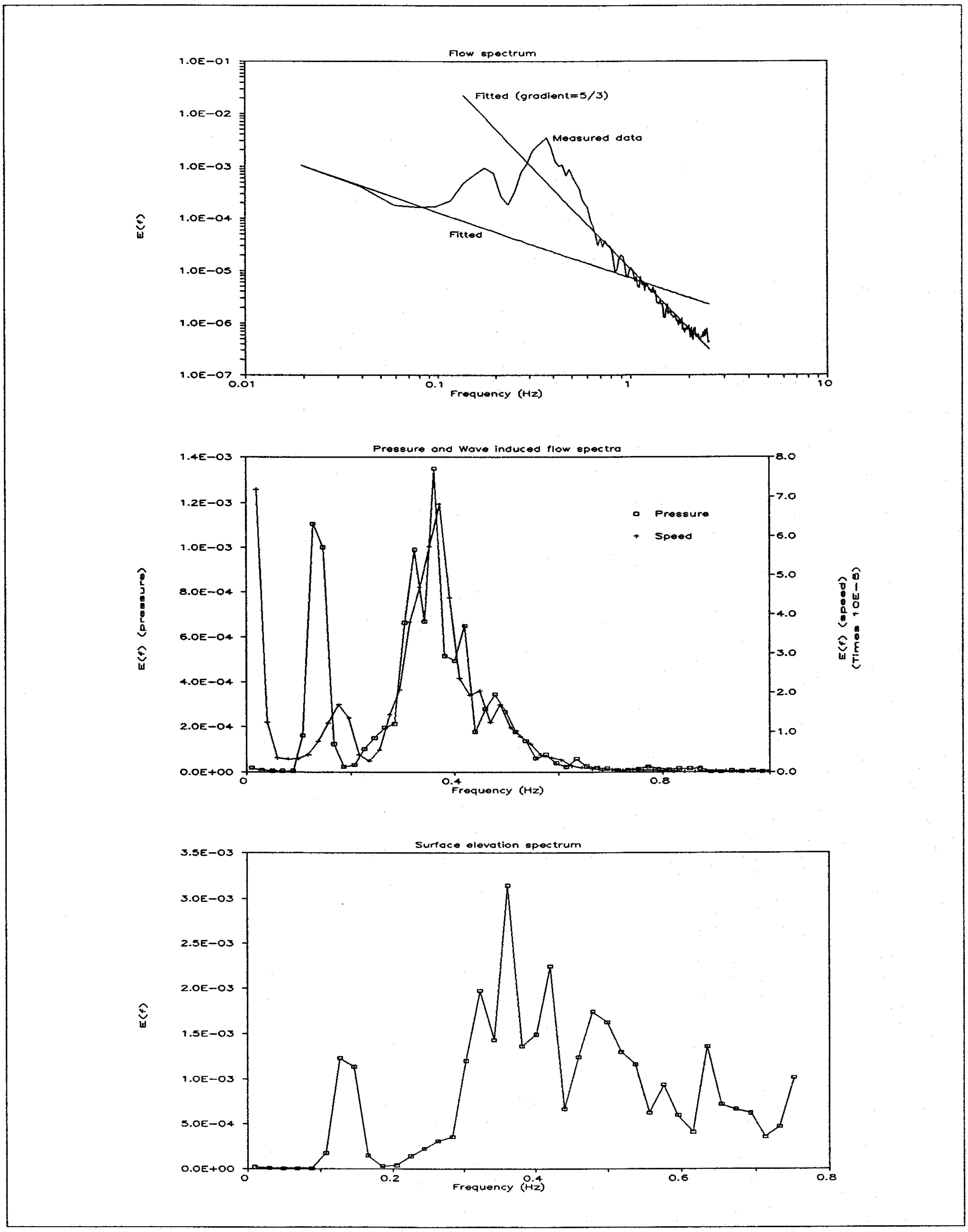

Fig 7 Comparison of spectrum of flow (v) pressure and surface fluctuations 70 mins BHW 24 May 1990 pm

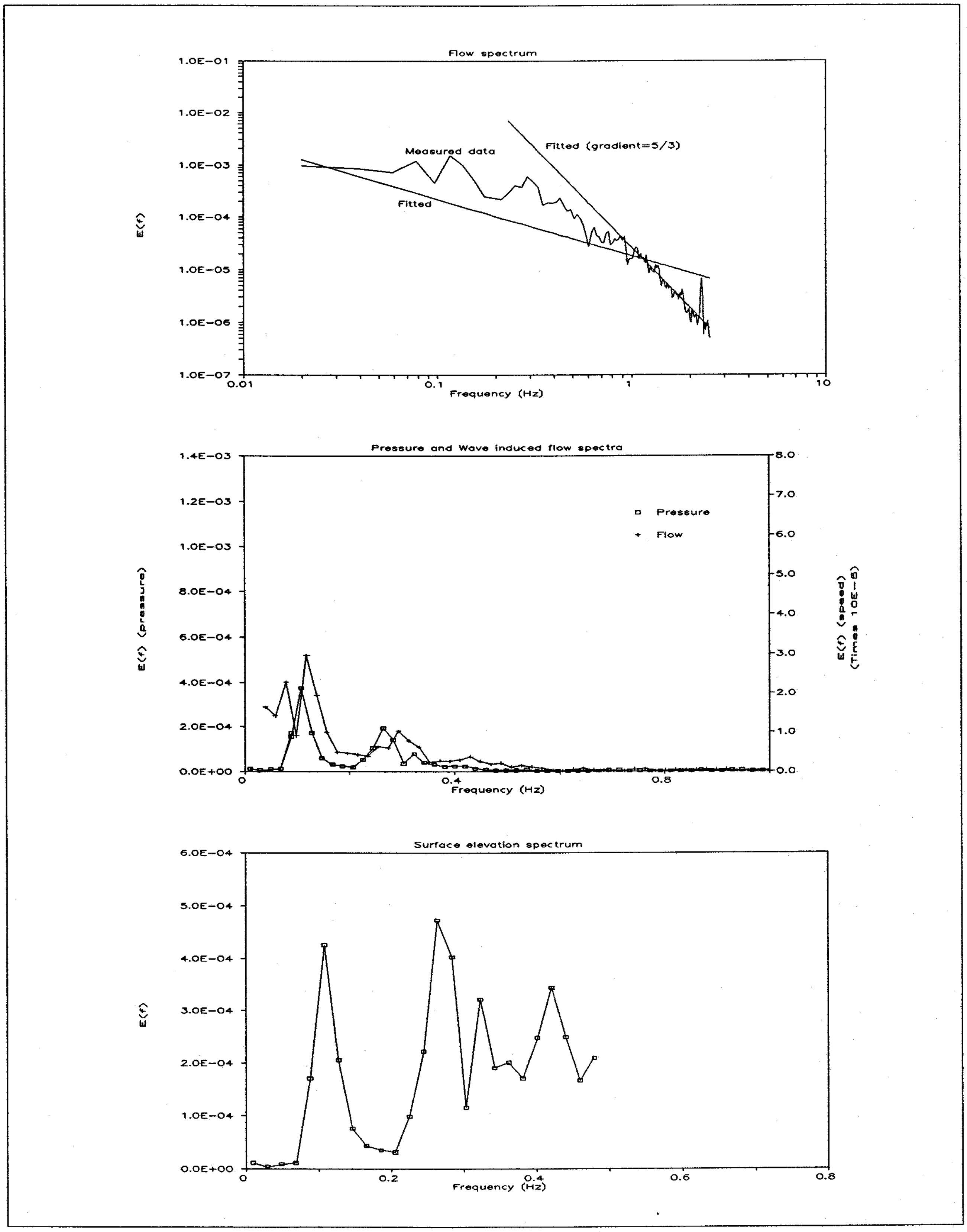

Fig 8 Comparison of spectrum of flow (v) pressure and surface fluctuations 30 mins AHW 24 May 1990 pm

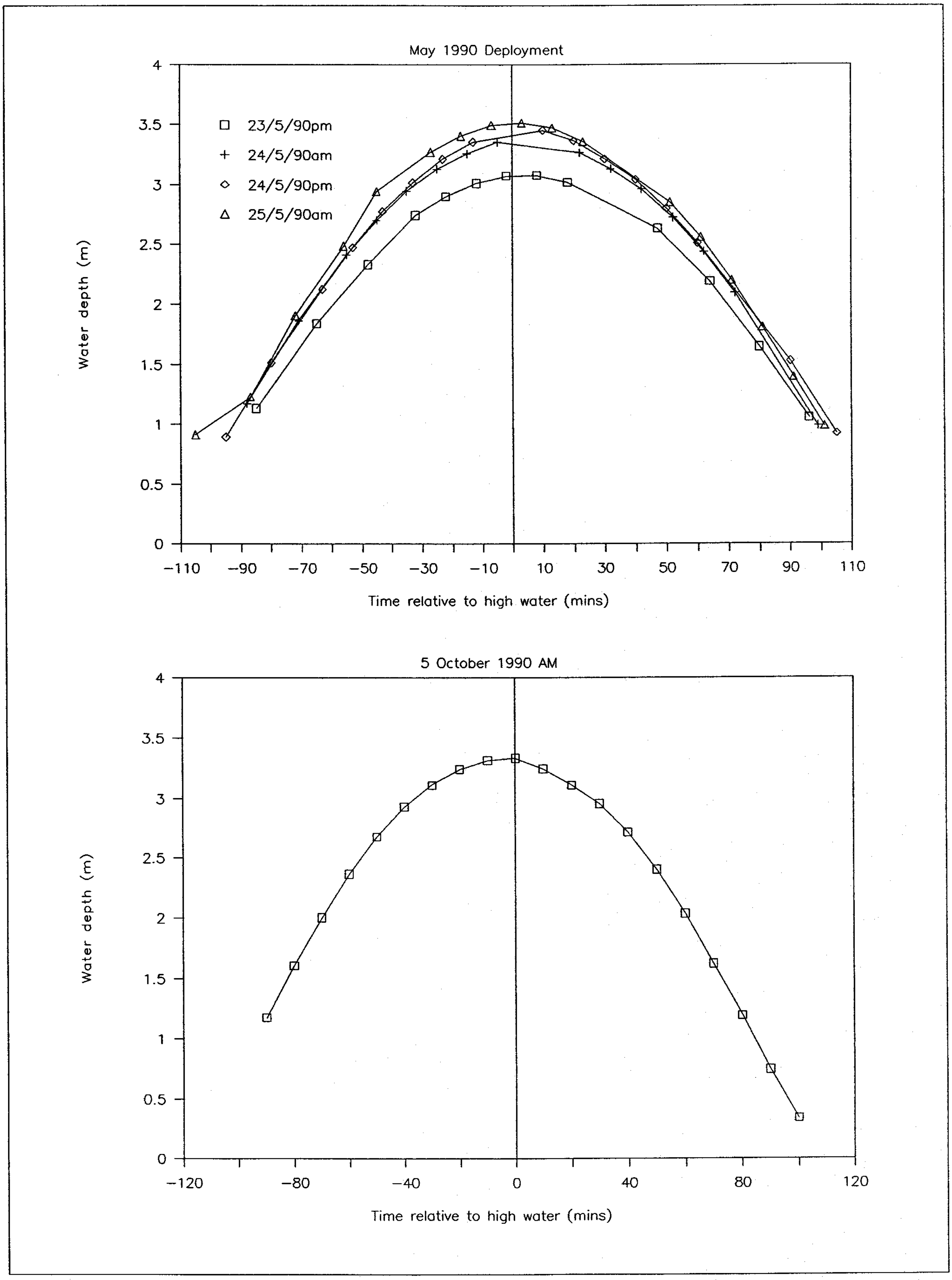

Fig 9 Water level over tides May and October 1990 deployments

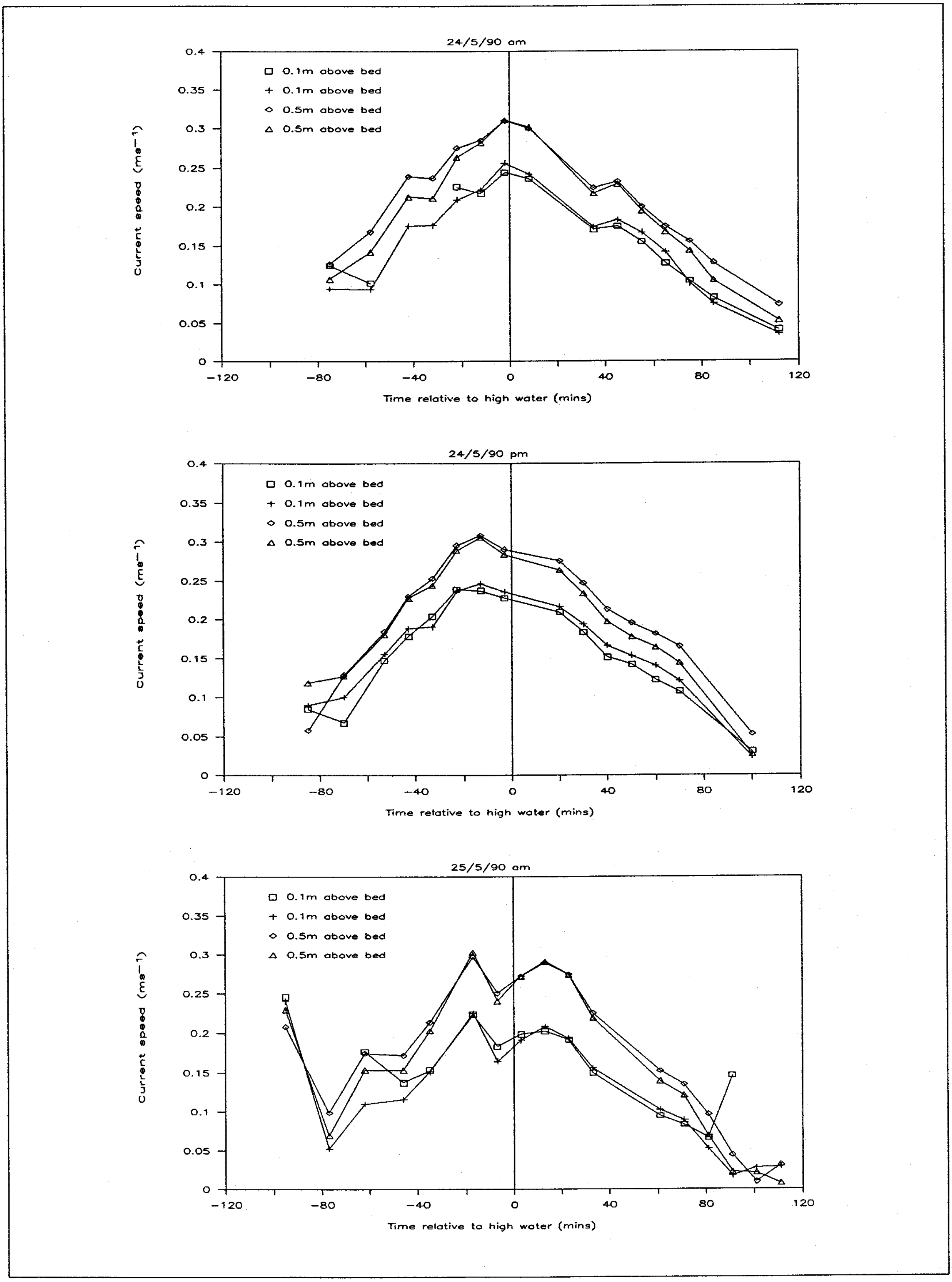

Fig 10 Current speed variation over tides
May 1990 deployment

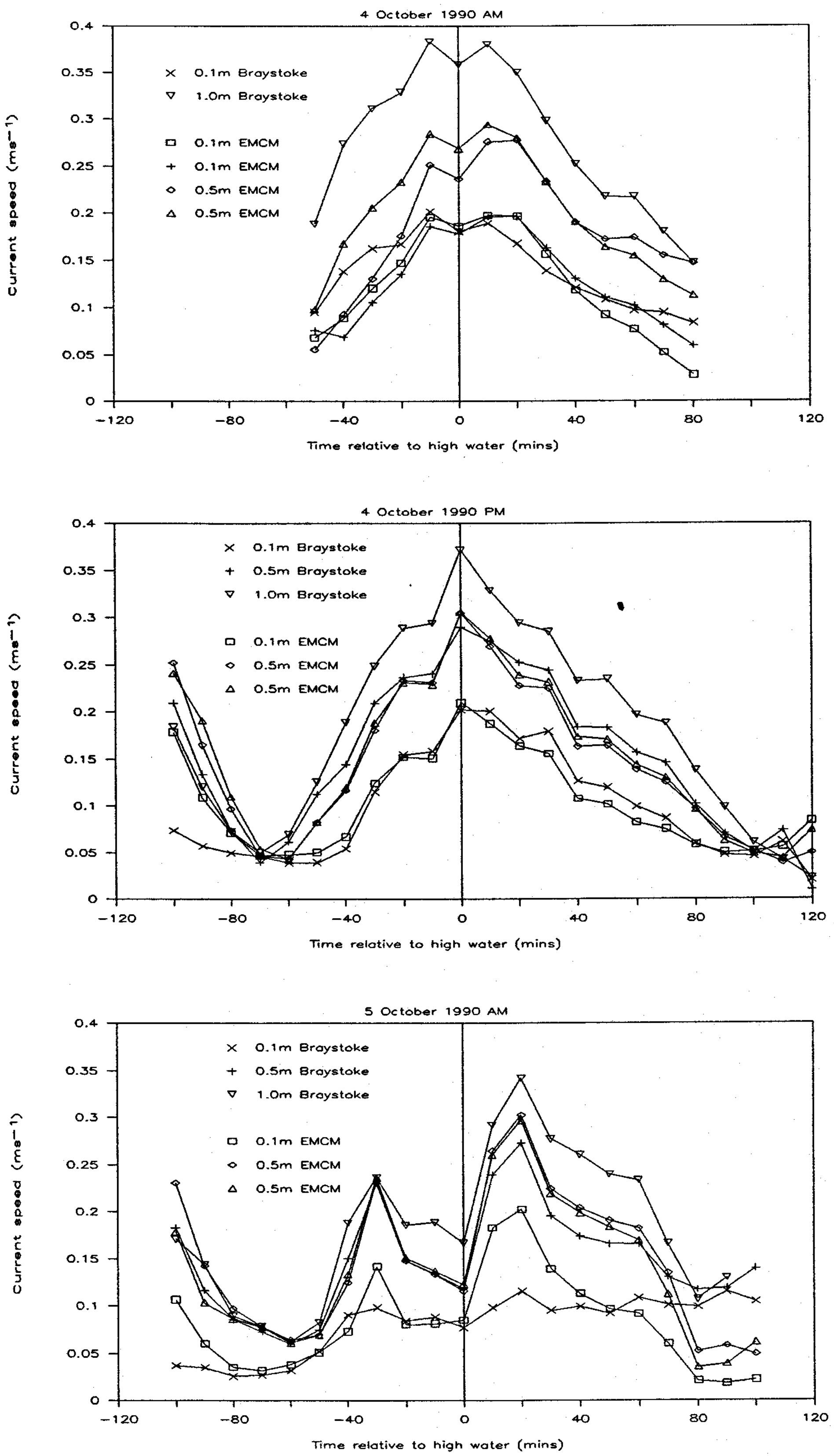

Fig 11 Current speed variation over tides
October 1990 deployment

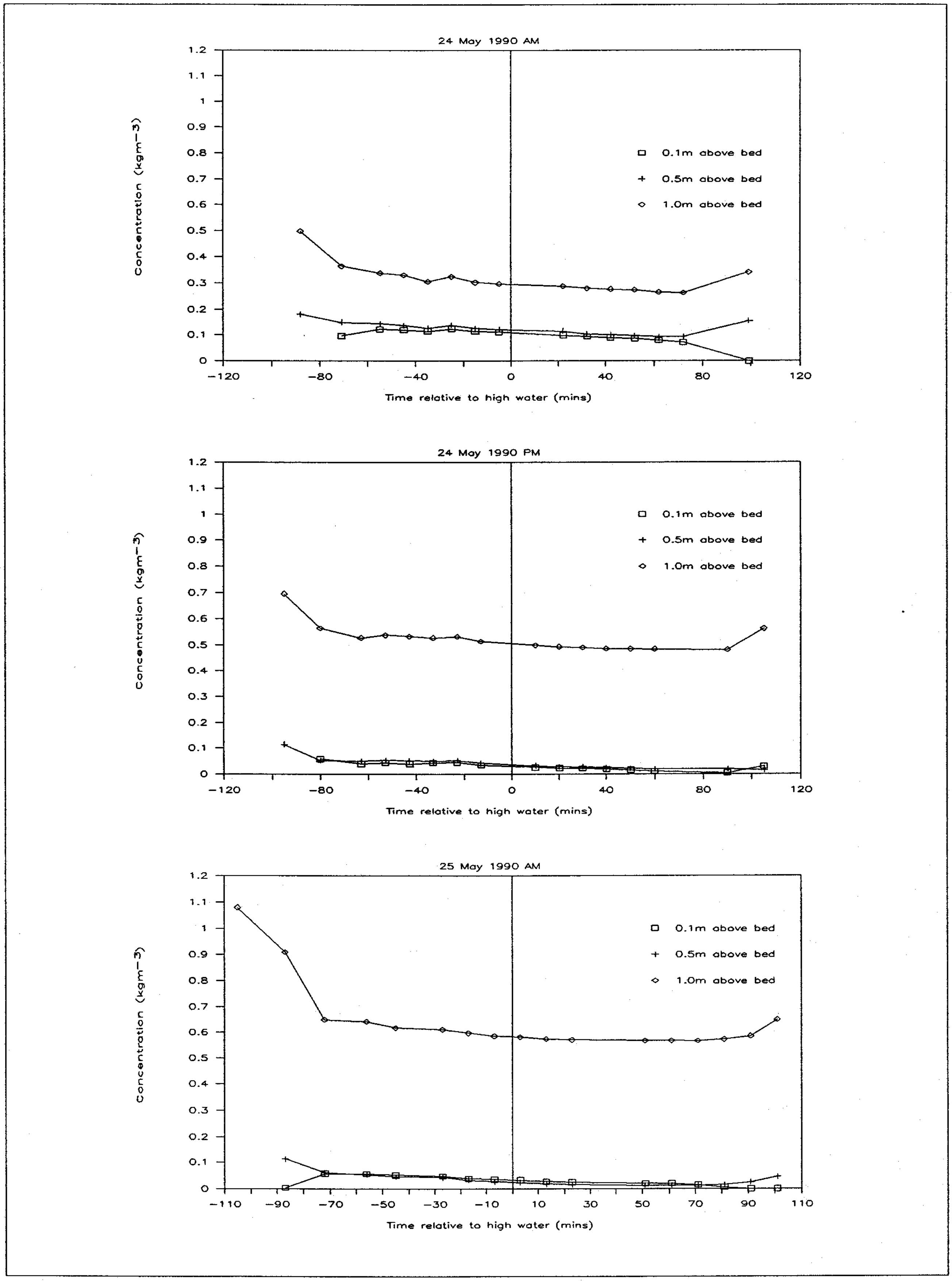

Fig 12 Concentration of suspended solids
May 1990 deployment

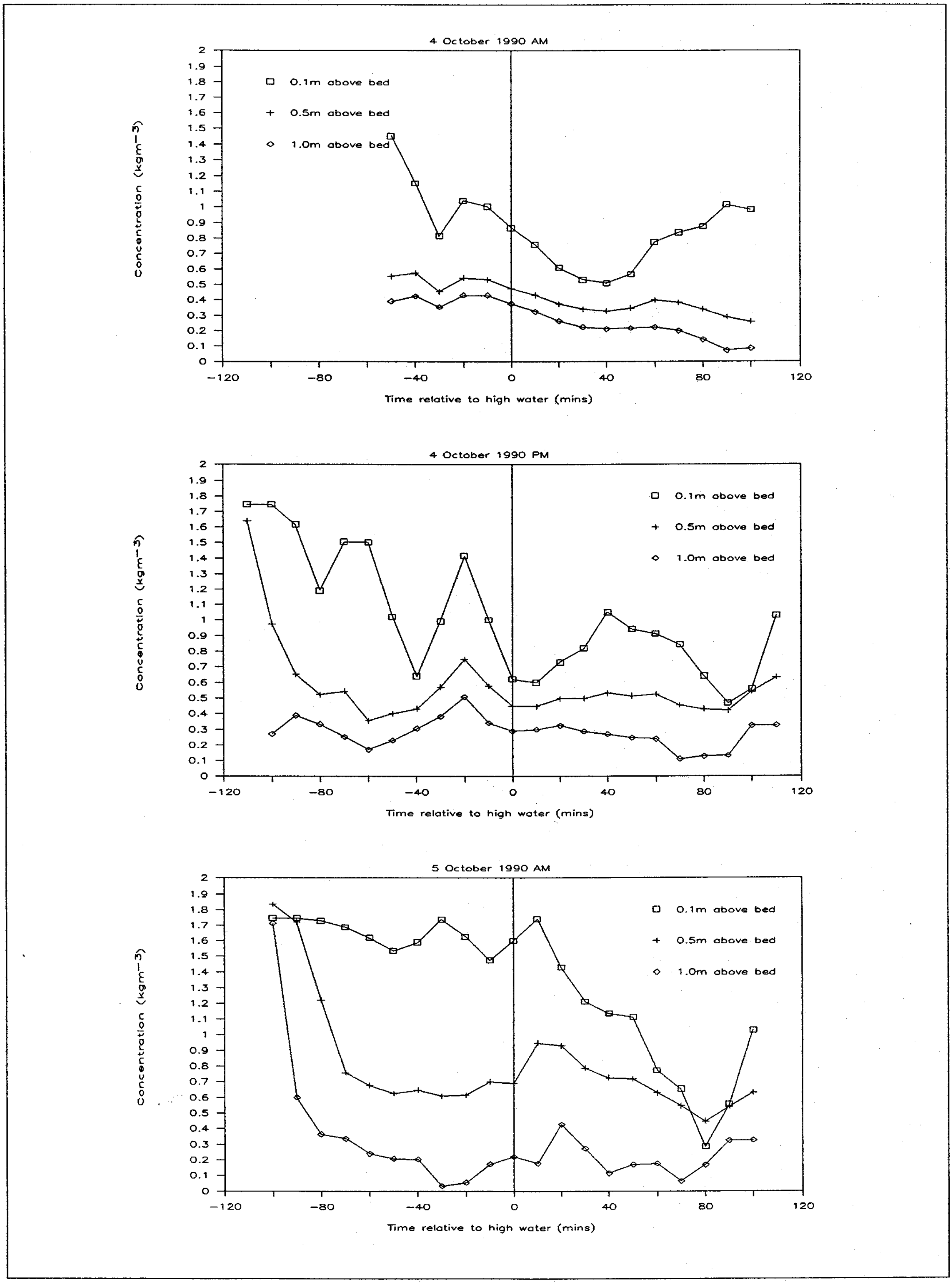

Fig 13 Concentration of suspended solids
October 1990 deployment

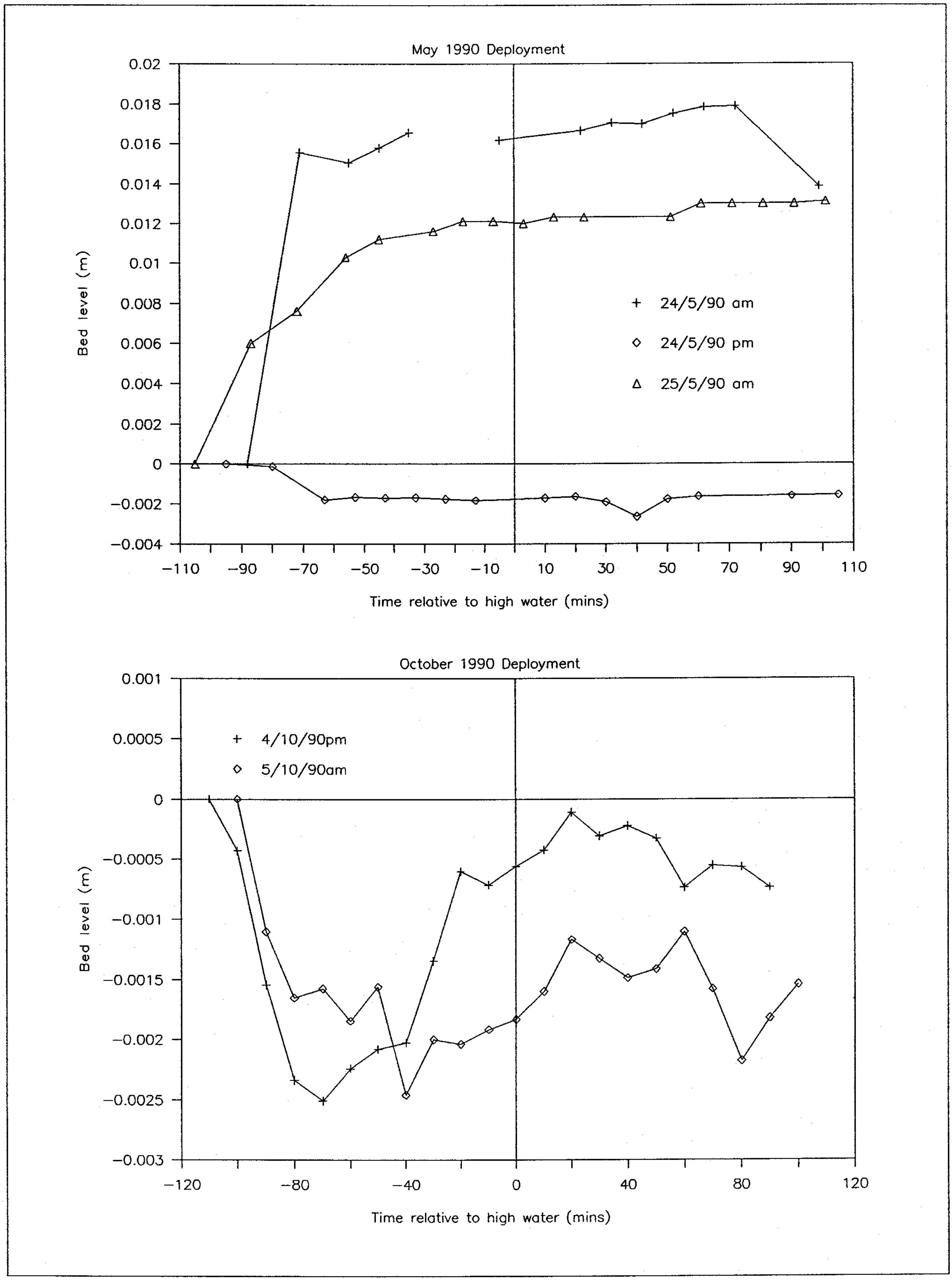

Fig 14 Bed level over tides May and October 1990 deployments

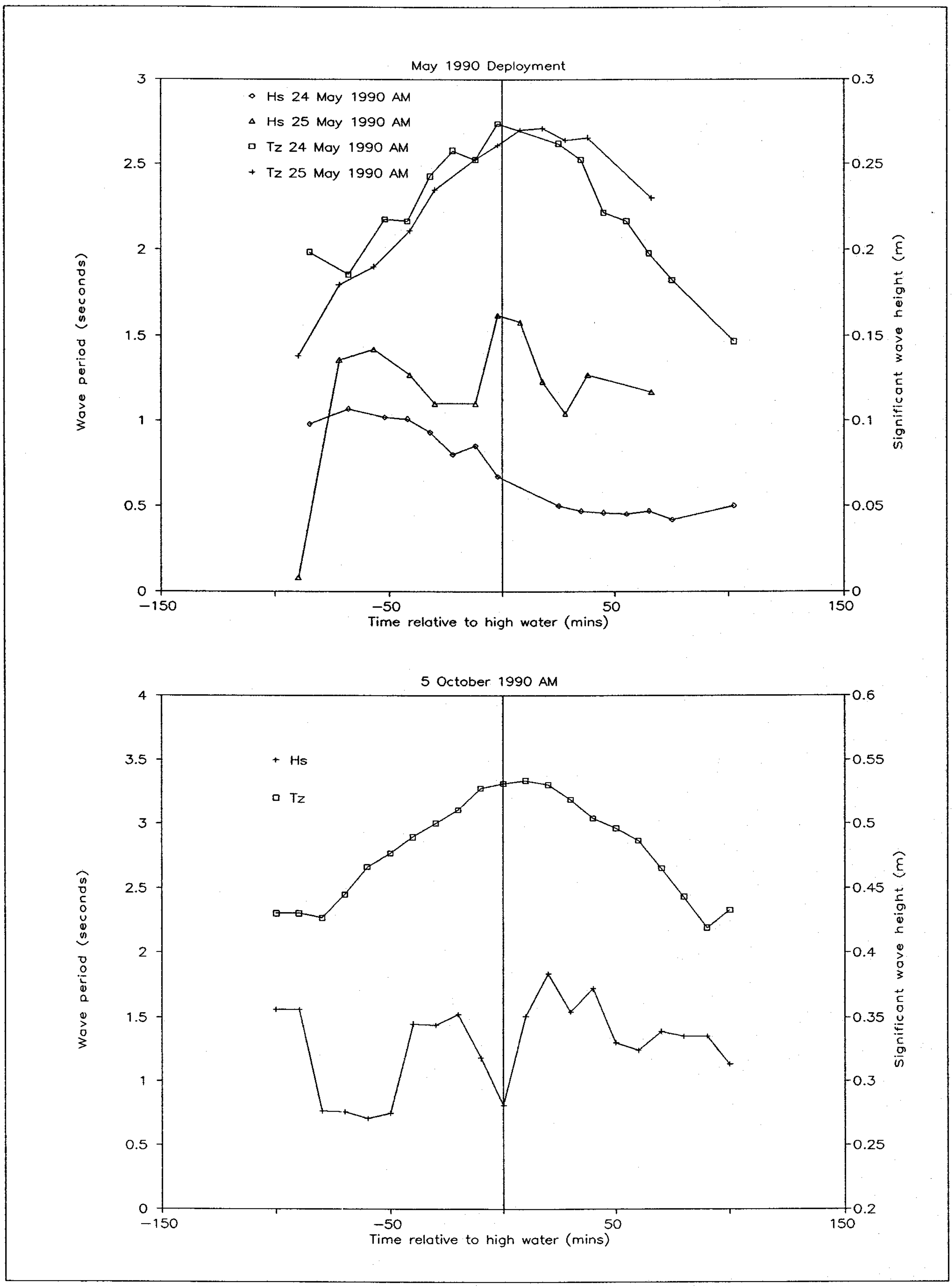

Fig 15 Wave characteristics over tides May and October 1990 deployments

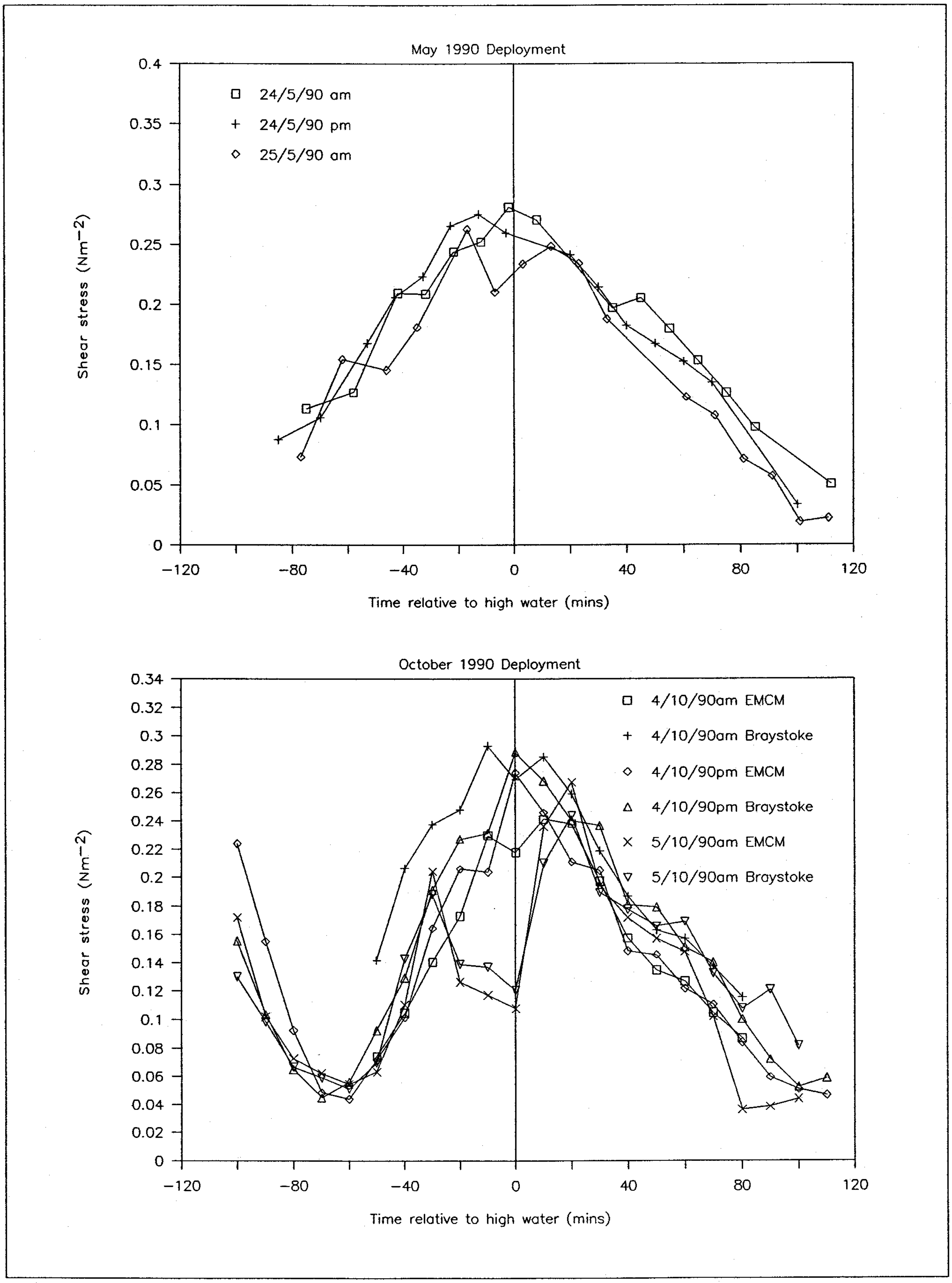

Fig 16 Tide induced shear stress over tides
May and October 1990 deployments

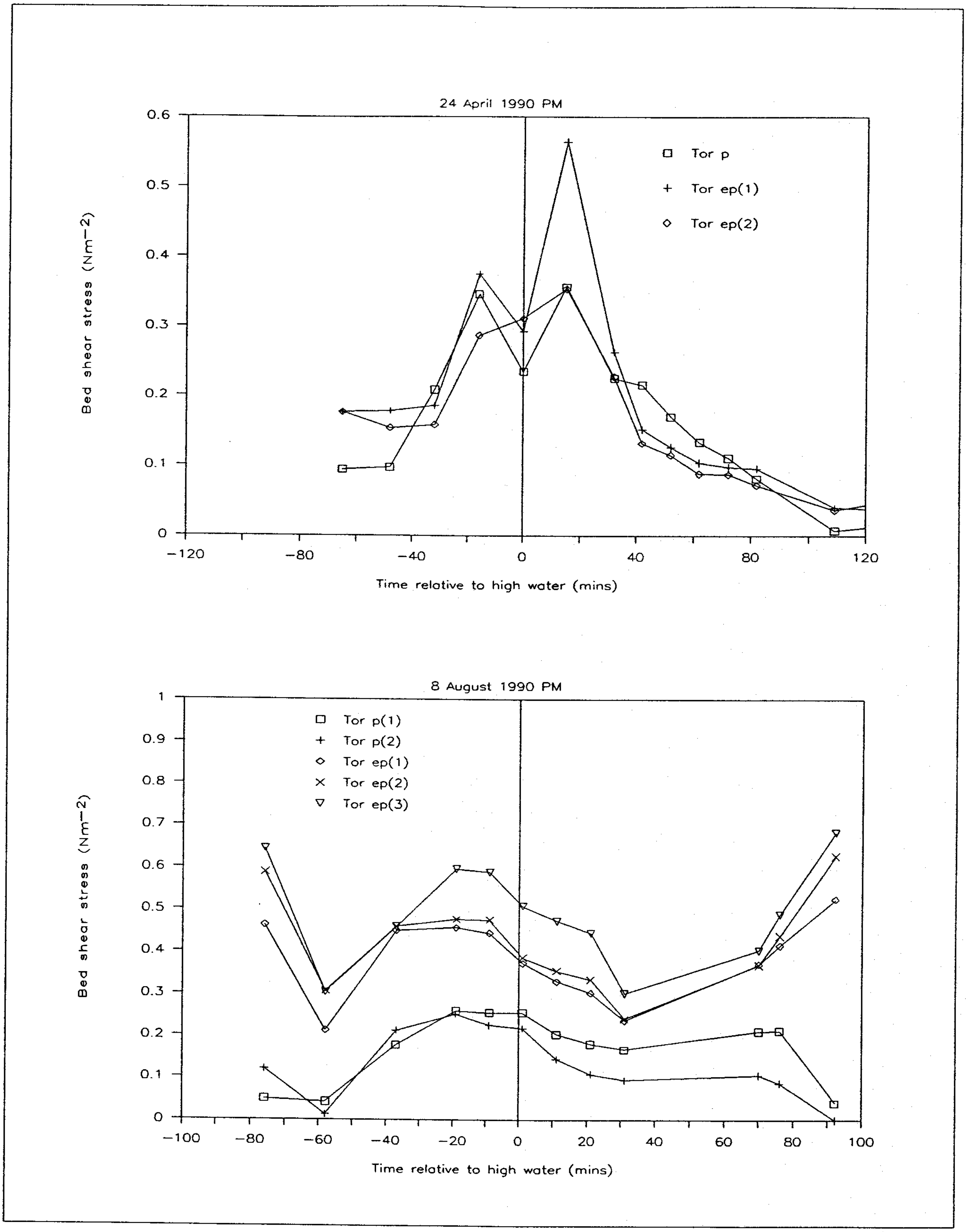

Fig 17 Comparison of tide induced shear stresses Tor p and Tor ep 24 April and 8 August 1990

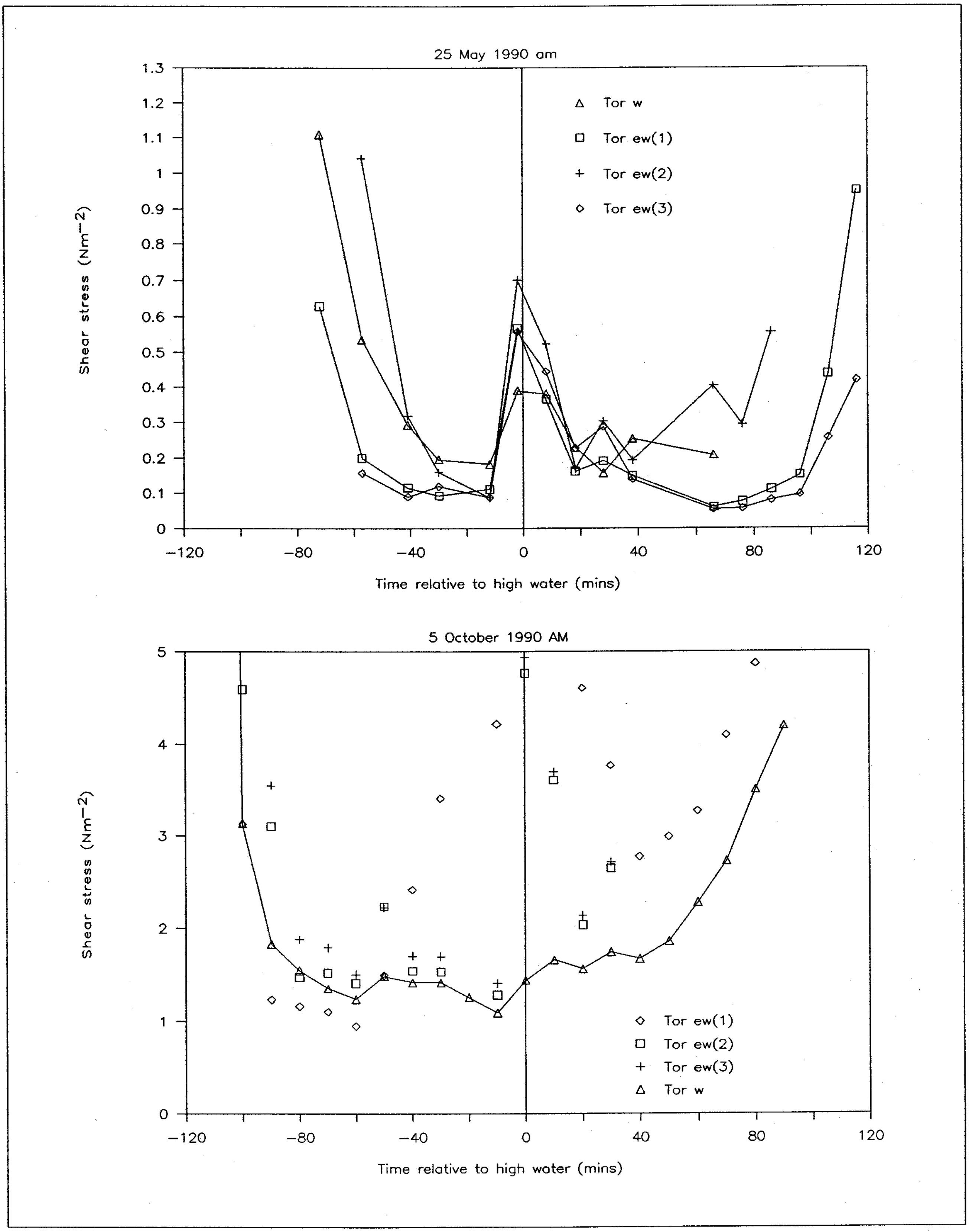

Fig 18 Comparison of wave induced shear stresses Tor ew and Tor w 25 May and 5 October 1990

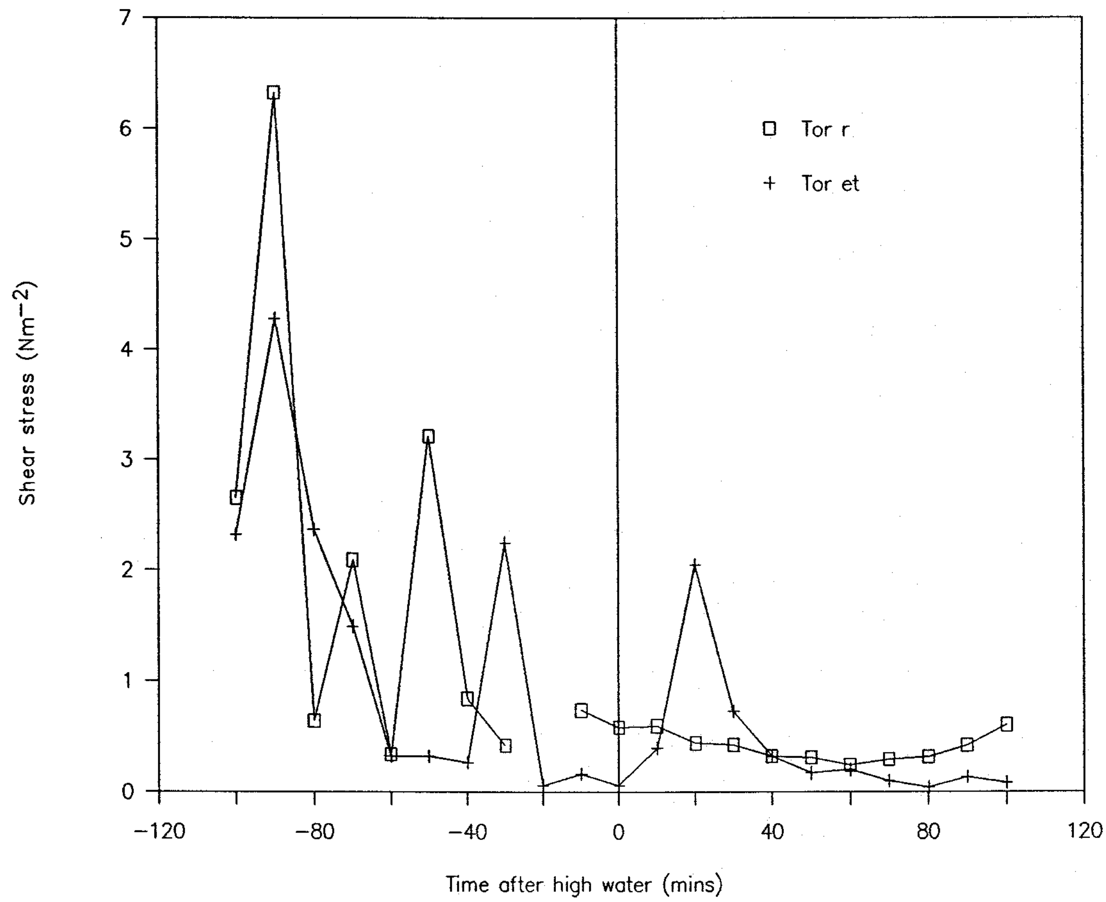

Fig 19 Comparison of combined wave and tide shear stresses Tor et and Tor r 5 October 1990

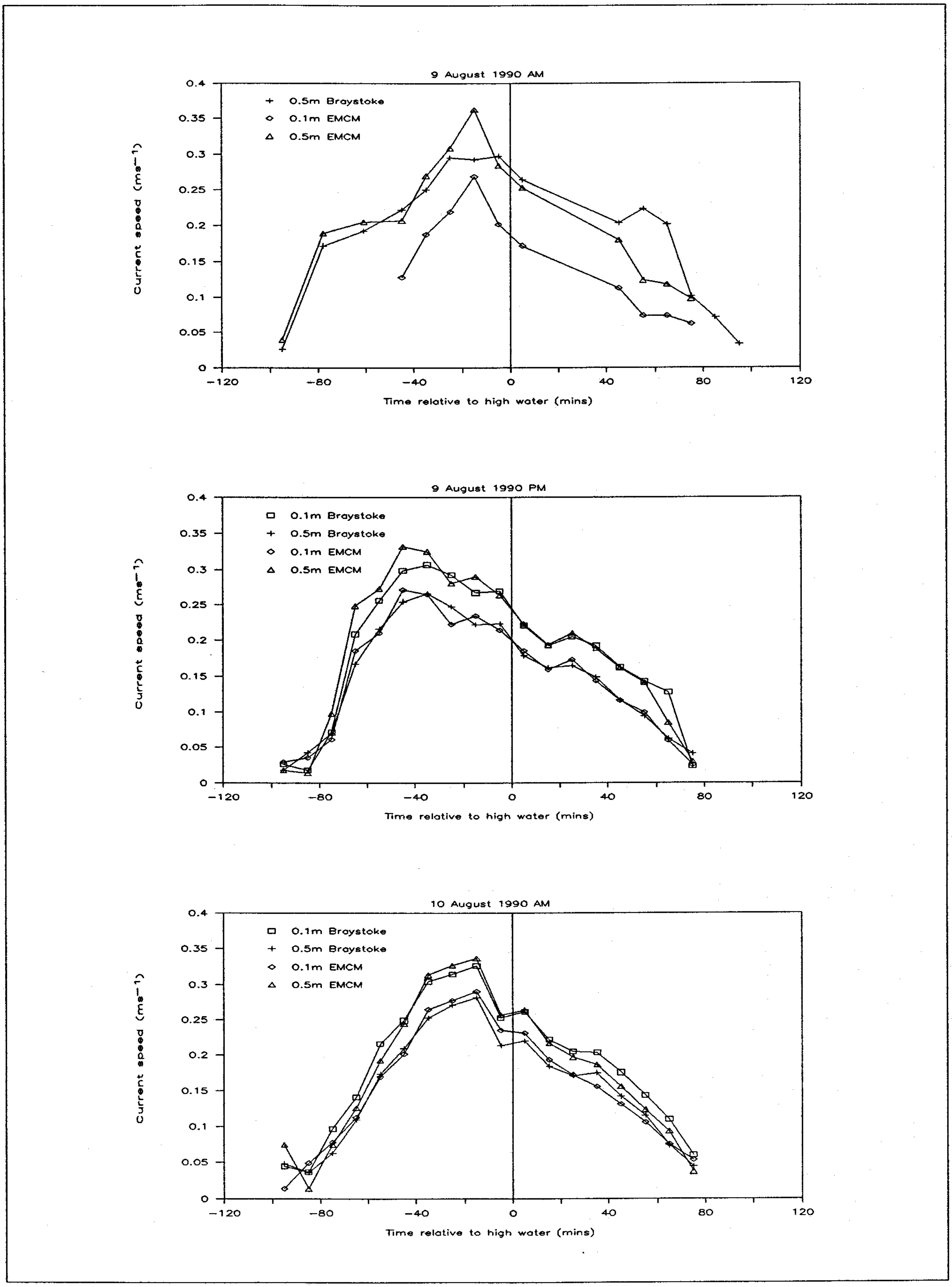

Fig 20 Current speed over tides
August 1990 deployment

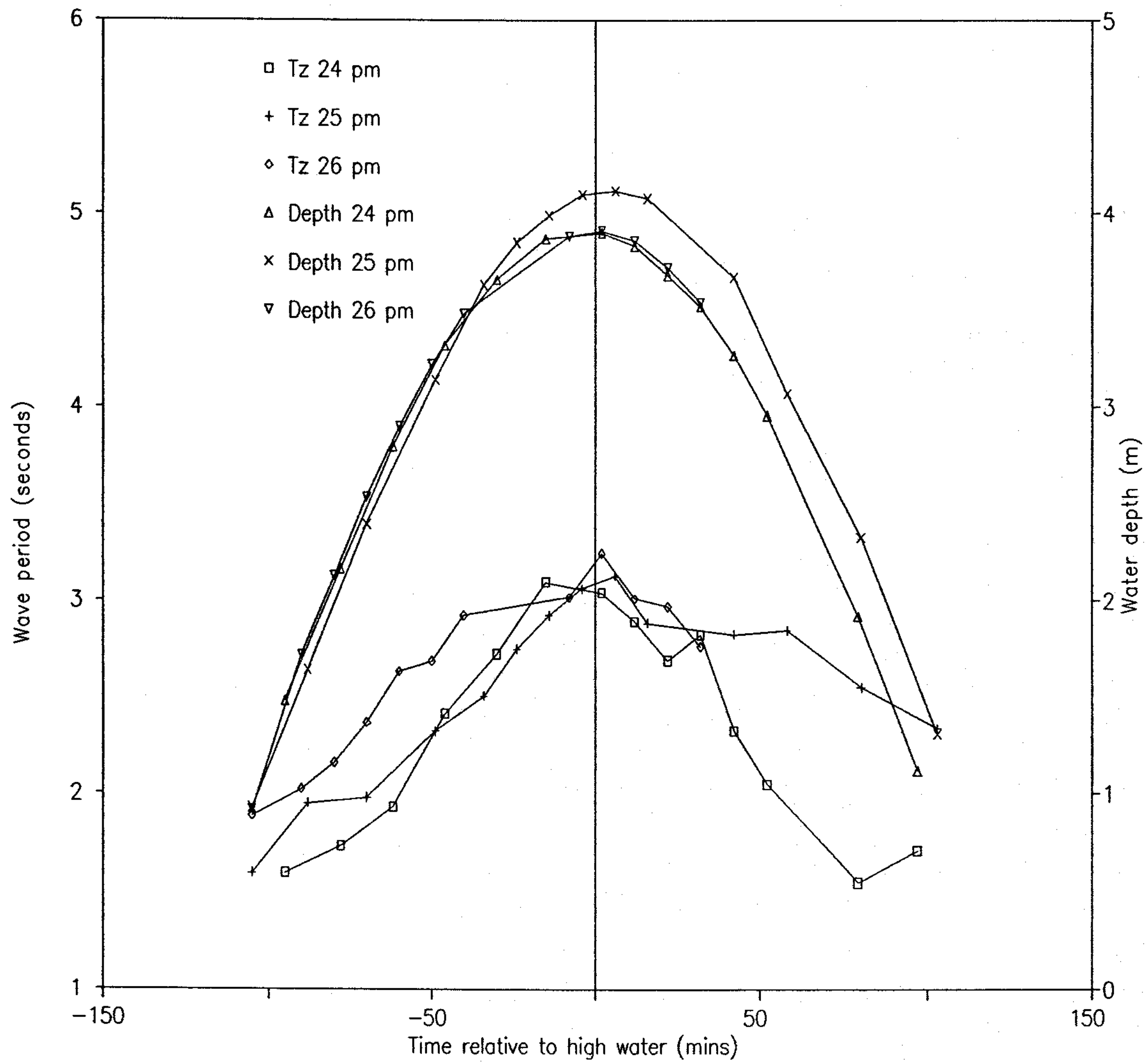

Fig 21 Comparison of wave characteristics with water depth April 1990 deployment

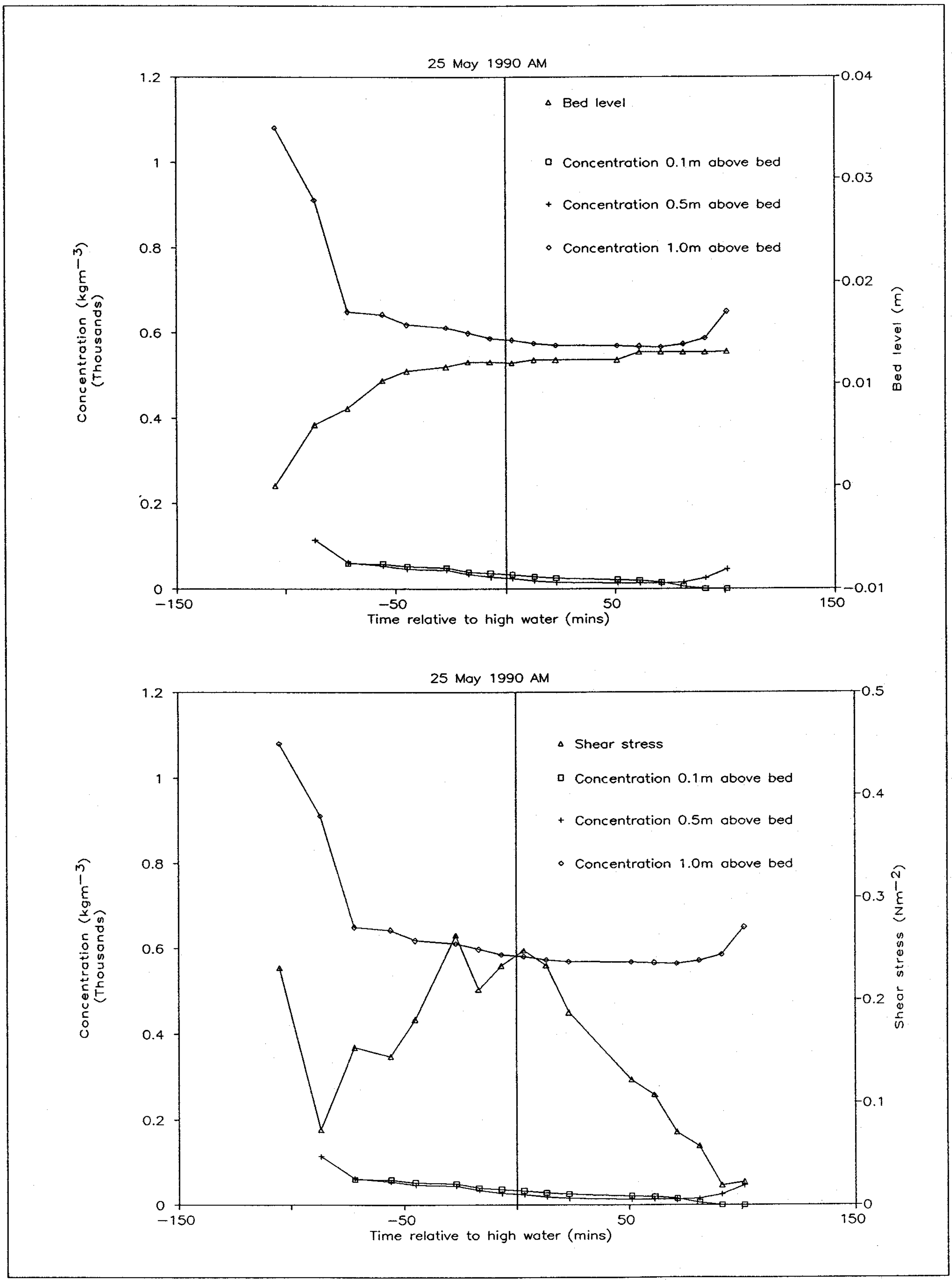

Fig 22 Comparison of bed level, concentration and shear stress variation 25 May 1990

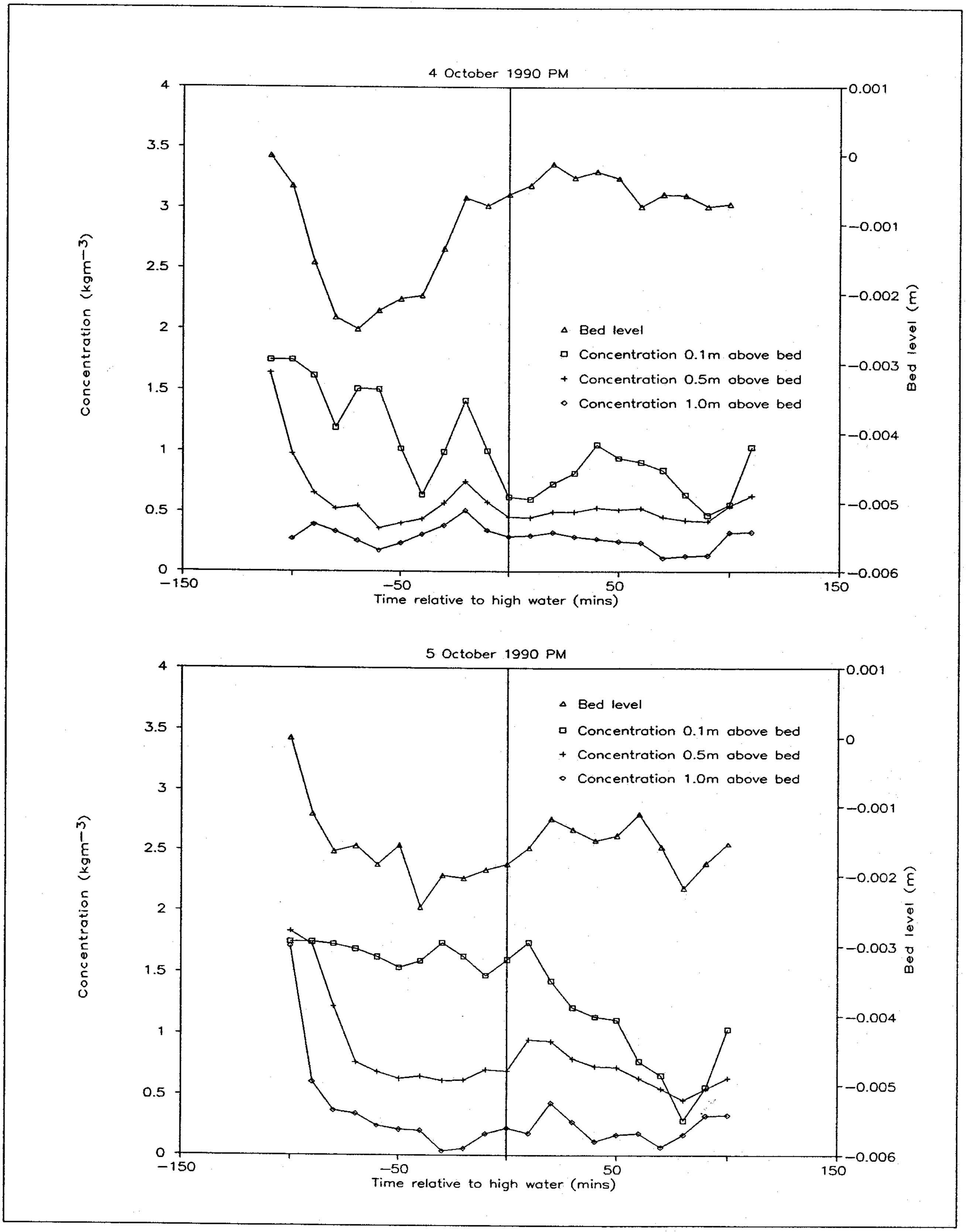

Fig 23 Comparison of bed level and concentration variations 4(pm) and 5(am) October 1990

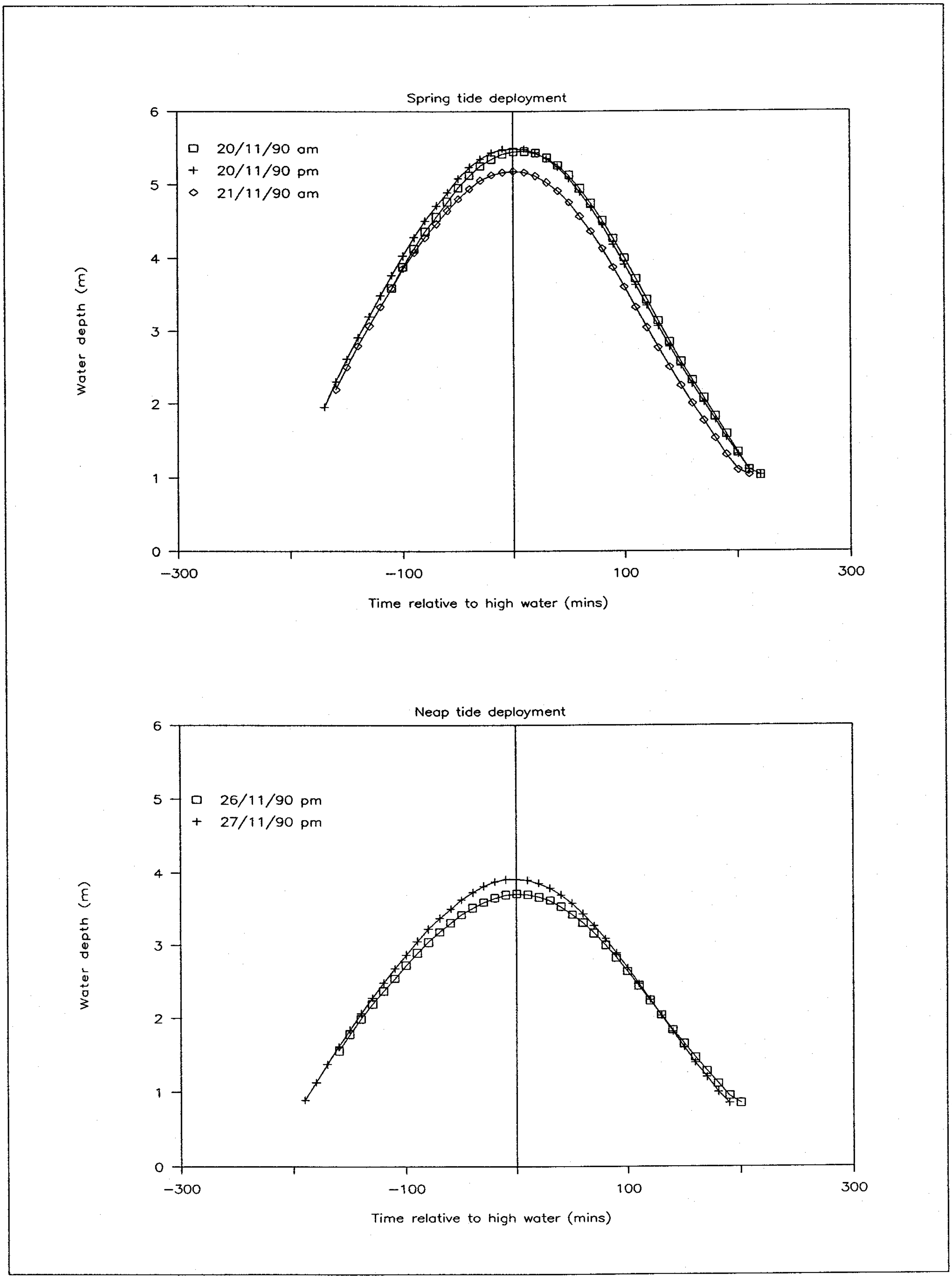

Fig 24 Water levels Spring and Neap tides

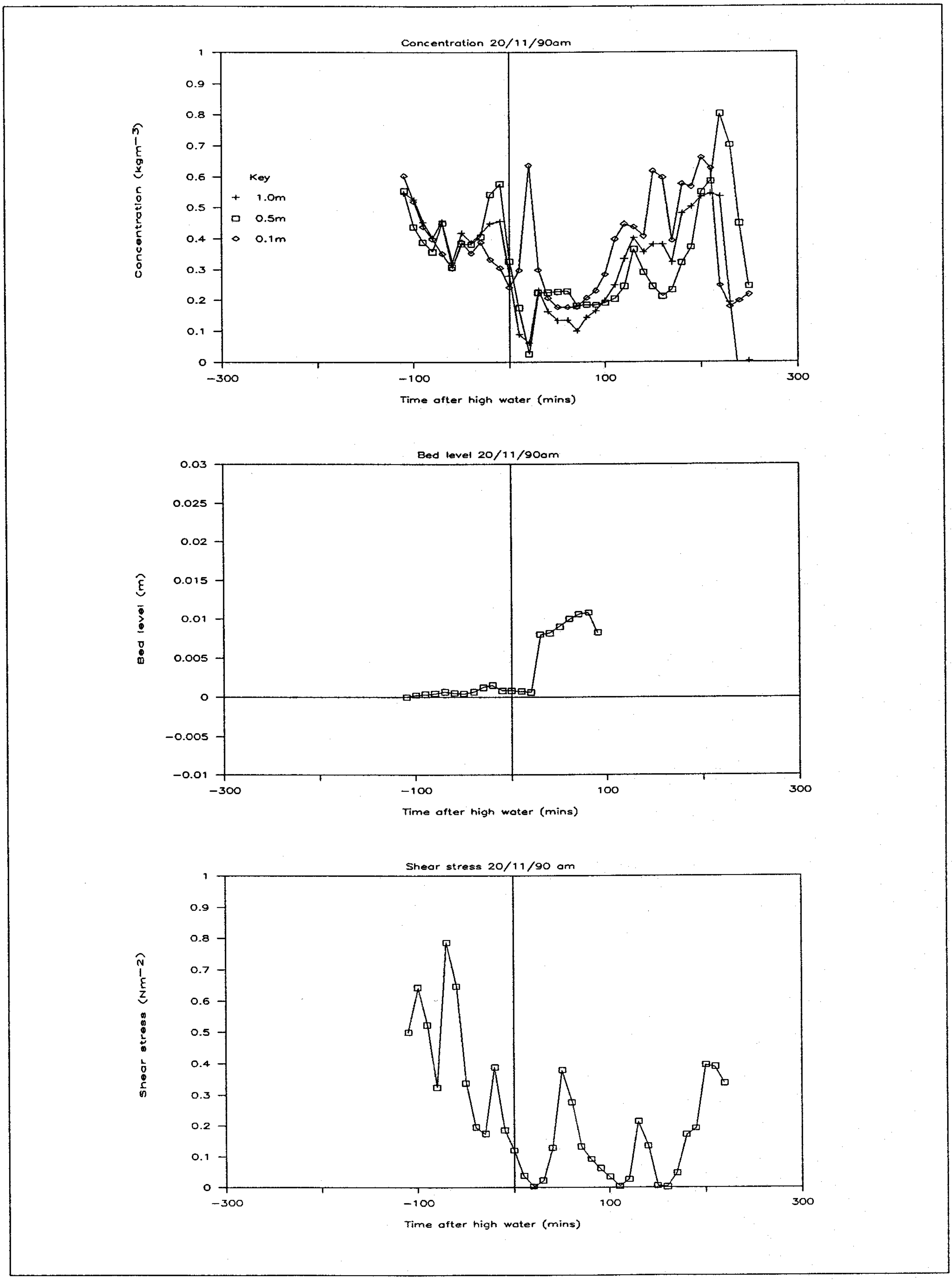

Fig 25 Concentration, bed level and shear stress
20 November 1990 am

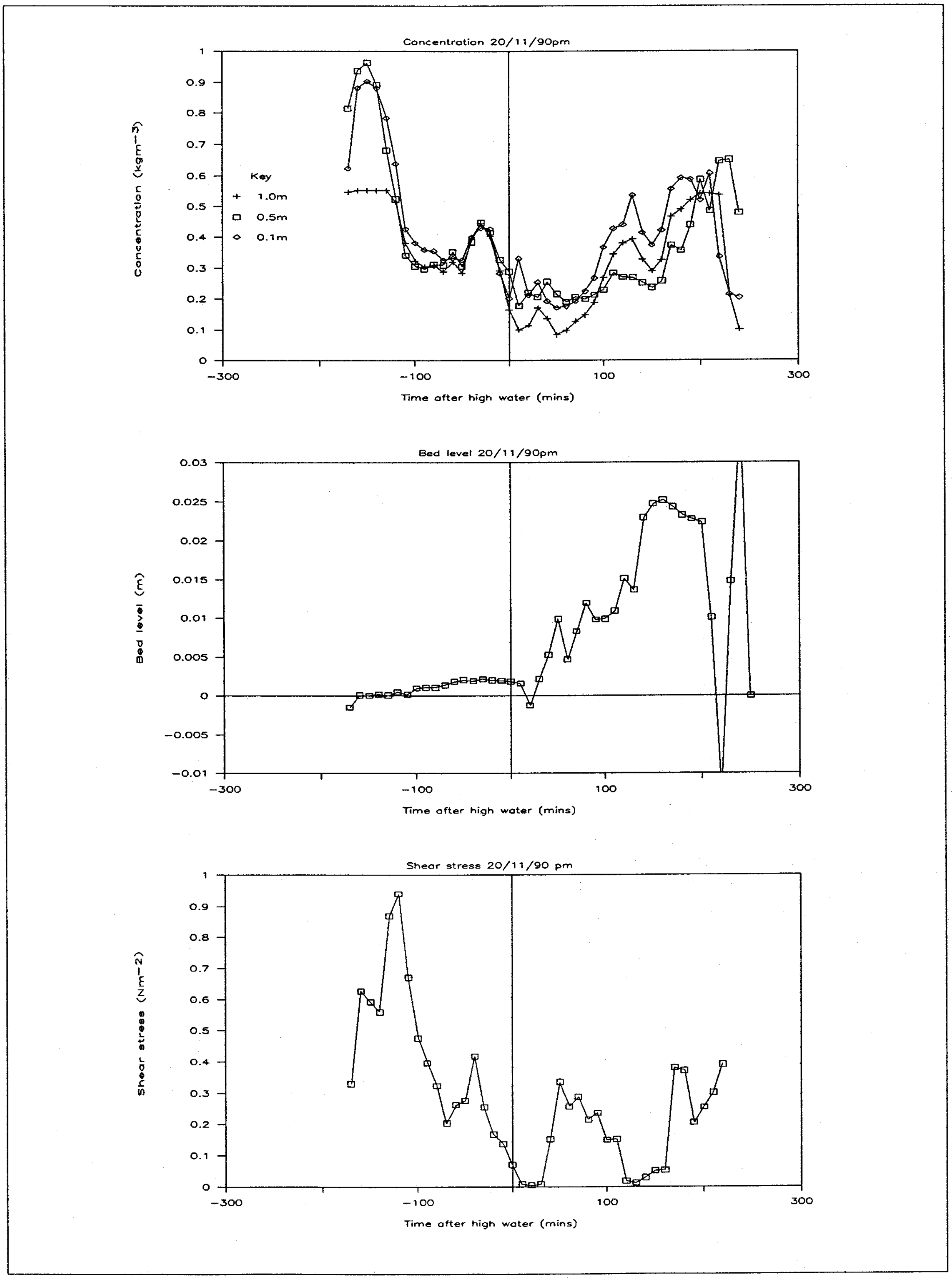

Fig 26 Concentration, bed level and shear stress 20 November 1990 pm

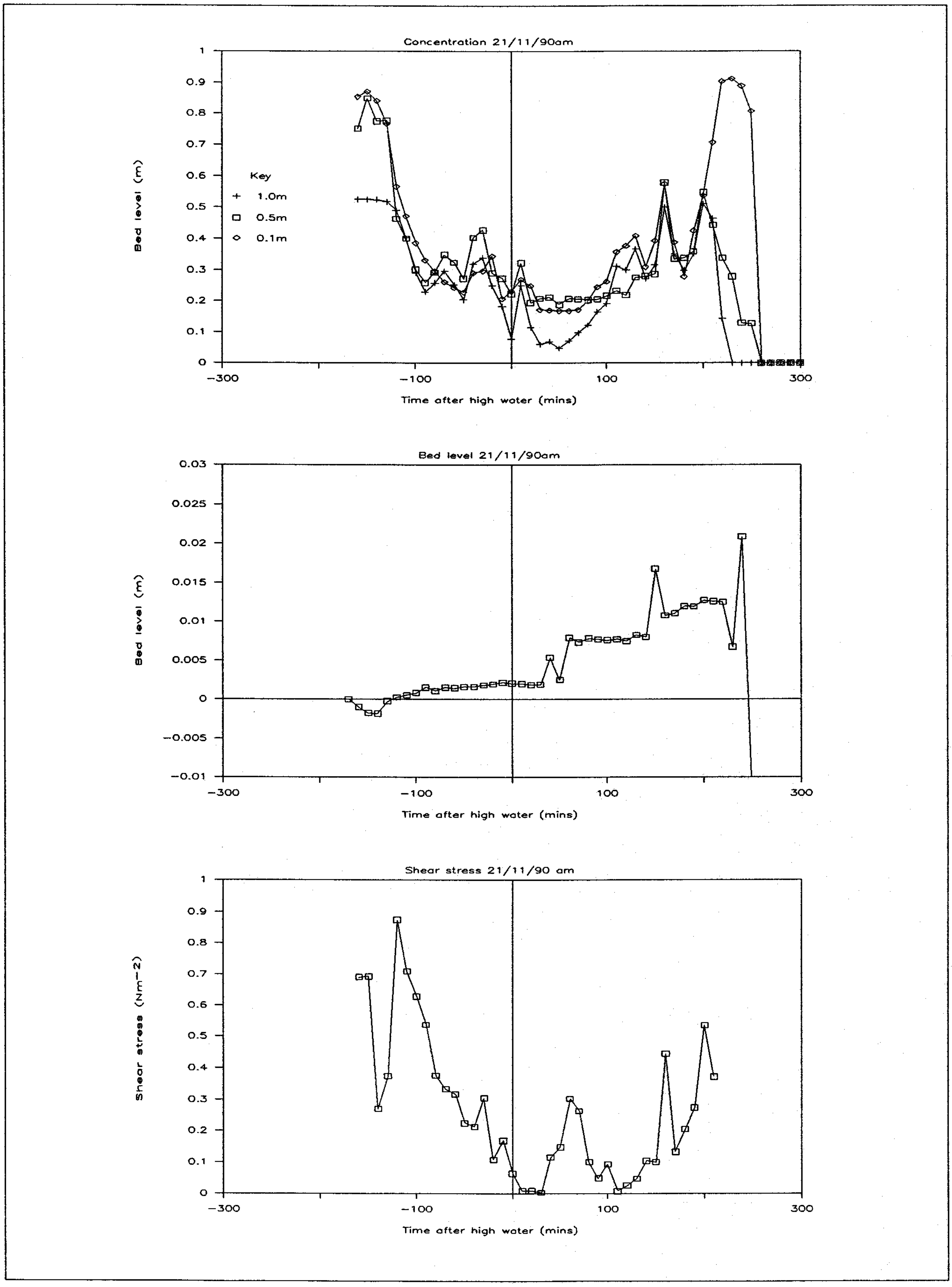

Fig 27 Concentration, bed level and shear stress
21 November 1990 am

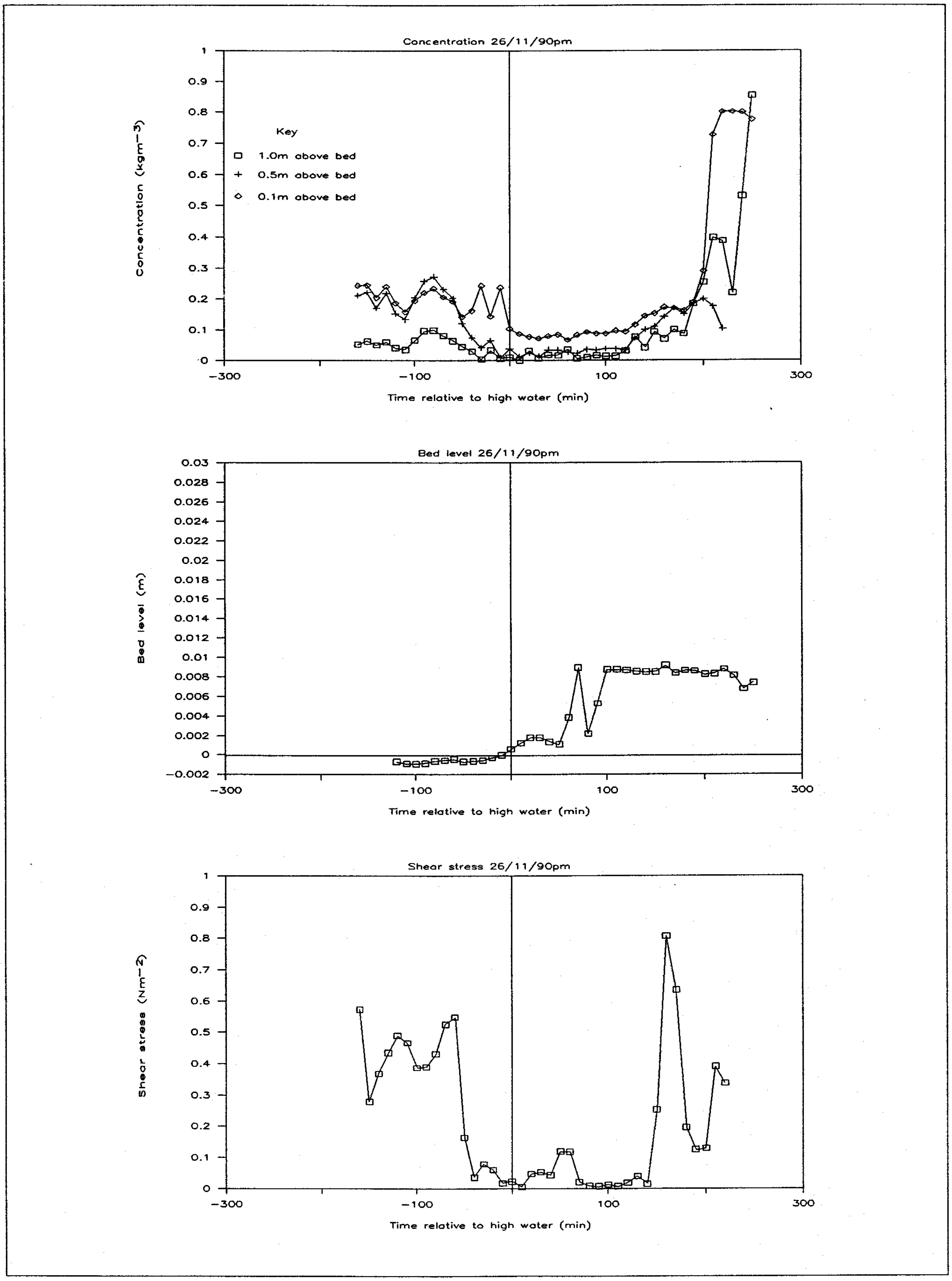

Fig 28 Concentration, bed level and shear stress
26 November 1990 pm

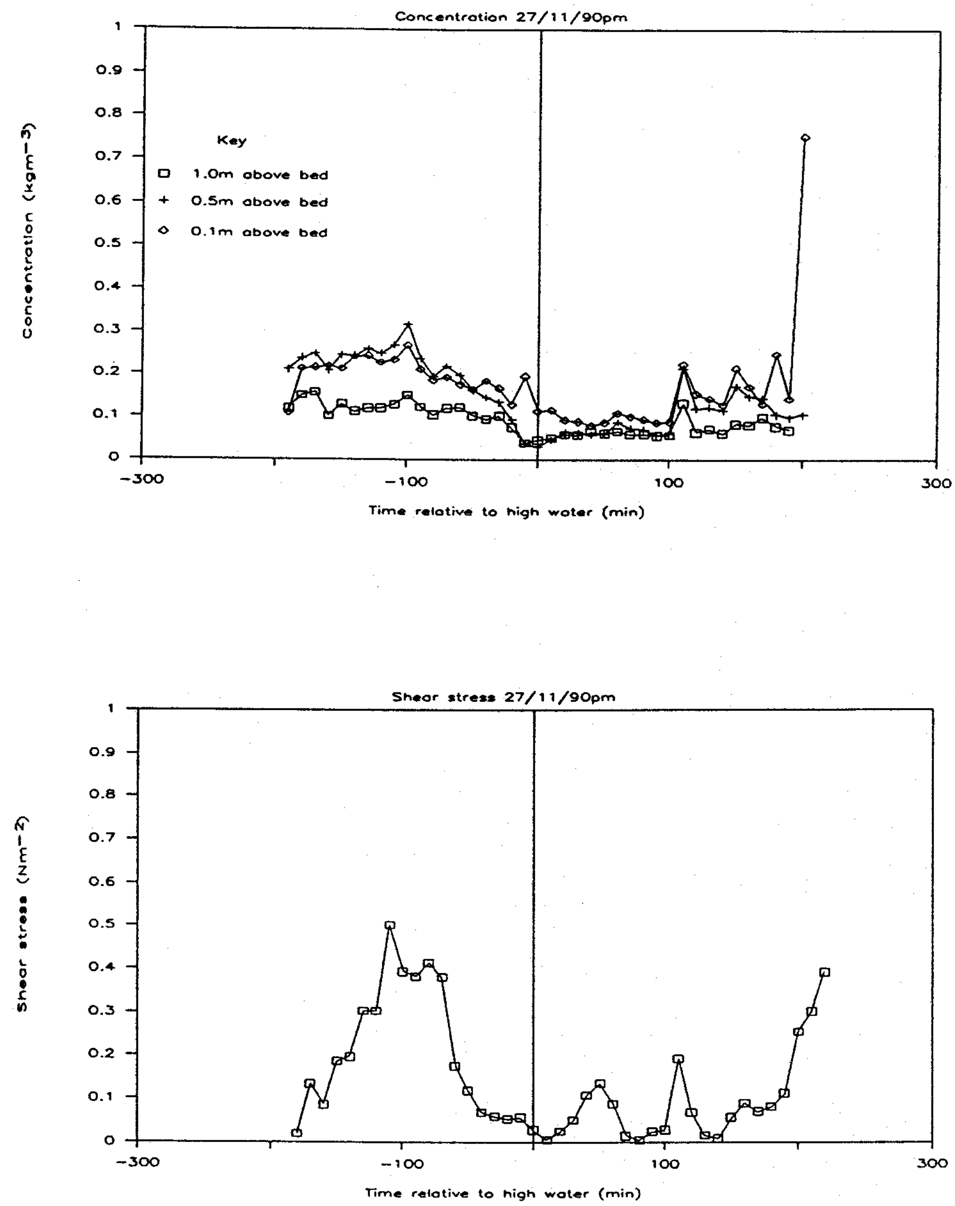

Fig 29 Concentration and shear stress
27 November 1990 pm

Plate

Plate 1 Bed frame

Appendix

APPENDIX A

Data analysis

1. Analysis of water pressure data

Analysis of the water pressure data to give significant wave height (H_s), zero crossing period (T_z) and mean water depth involved several stages. First, each ten minute record was filtered to remove the change in baseline water pressure caused by tidal level change. The average of each successive block of 256 values was calculated and a simple linear fit applied to the variation of mean water level from block 1 to block 2, from block 2 to block 3 etc. Each value was then set to the difference between the original value and the 'mean' depth at that instant. Error checking was limited to an automatic alert if the difference between successive pressure values exceeded a given value.

The pressure fluctuations could not be used directly to calculate wave heights because of differences in pressure attenuation between low and high frequencies. A standard correction factor dependent upon the water depth and frequency had to be applied the data.

At the high frequency end of the spectrum there tended to be a small proportion of spurious energy. Because of this correction factor, this tail part of the spectrum assumed much greater proportion when converted to a surface elevation spectrum. Accordingly, an upper frequency cut off was set at 0.75Hz to exclude this energy from the spectrum.

The significant wave height (H_s) and mean wave period (T_z) could then be calculated for each ten minute record using the following equations:

$$H_s = 4\ m_o^{0.5} \quad \text{(A1)}$$

$$T_z = (m_o/m_2)^{0.5} \quad \text{(A2)}$$

where

$$m_n = \int_{f_l}^{f_u} E(f)\ f^n df$$

E(f)= wave spectrum

f_u and f_l = upper and lower frequency limits

2 Analysis of EMCM velocity data

Each velocity record consisted of a tide induced component and a wave induced component. The mean tide induced component was considered to vary slowly. Hence, the running average over a 2-3 minute period will give the mean tidal velocity. This tidal velocity can be subtracted from the original velocity record to give the oscillating wave and turbulent components of the velocity.

The mean tidal velocity over each ten minute period was calculated for the x and y horizontal directions. From these the magnitude and direction of the tidal flow at 0.1m and 0.5m above the bed was computed. From the tidal mean velocities at the three heights the shear stress at the bed could be calculated. A plot of velocity against log height above the bed for a particular instant in time gives a near straight line. Using the following equations the bed shear stress can be calculated:

$$u_* = k\ du/d(\ln z) \quad \text{(A3)}$$

$$\tau_b = \rho\ u_*^2 \quad \text{(A4)}$$

where

u_* = frictional shear velocity (ms^{-1})

u = horizontal velocity (ms^{-1})

z = height above bed (m)
k = von Karman's constant (0.4)
τ_b = shear stress at the bed (Nm^{-2})
ρ = water density (kgm^{-3})

The height above the bed at which the current velocity is zero is constant for a given bed roughness, this is known as the apparent bed roughness. From the apparent bed roughness, U_* and τ_b can be calculated where there is only one velocity measurement available at a known height. This apparent bed roughness was also used in calculation of the wave induced shear stress.

The direction of the waves was calculated from inspection of a probability distribution analysis of the directions of the tide reduced velocity data. The x and y components of this velocity data were first resolved to give speed and direction.

A spectral analysis of the x and y horizontal velocities of the tide reduced EMCM data was then carried out. The frequencies analysed corresponded to those used for the pressure sensor analysis and the spectral distribution of energy was broadly similar. The spectral analysis was expressed as a plot of log energy versus log frequency. This can be interpreted as comprising turbulence from the tidal current with wave induced fluctuations showing as peaks superimposed on top. Each spectrum can be split to separate the turbulent from the wave energy (Ref 4).

The RMS orbital velocity corresponds to the square root of the sum of the areas of the spectrum, on a linear plot, attributed to the waves of the x and y components. This can be used to confirm the RMS velocity found from water pressure analysis using wave theory. The direction of propagation of the waves can also be found from the ratio of the areas of the x and y components.

The kinetic energy density corresponds to half the sum of square roots of the areas of the spectrum attributed to the turbulence of the x, y and z components. This was also calculated for 0.1m and 0.5m above the bed.

3 Calculation of erosion and deposition rates

The total mass in suspension at any particular sampling time was found by summing the concentration profiles. The change in mass in suspension from one instant in time to the next will correspond to the mass eroded from or deposited on the bed assuming uniform conditions over a large area.

The rate of erosion or deposition at a point can also be calculated from the ultrasonic bed level measurements on the complex near bed frame. The mass of erosion is proportional to the bed level change times the density of the bed. The density can be measured using a gamma ray probe or by taking samples for laboratory analysis.

4 Calculation of bed shear stress vector

The friction velocity and apparent bed roughness were calculated from the best fit logarithmic line through the lower water column velocity measurements. The shear stress calculated using equation A4, however, will only represent the real bed shear stress in records which have insignificant wave activity. The direction of this stress was the same as that of the measured flow direction.

To find the peak bed shear stress due to waves the maximum bottom orbital velocity must first be found. The maximum bottom orbital velocity was calculated from the significant wave height, mean wave period and the water depth using first order linear wave theory. The peak bed shear stress can then be found by assuming a friction factor (Ref 3) or using the friction factor found from the tidal flows as above. The direction of this stress was orientated in the direction of wave propagation.

The wave and tide induced shear stress parameters can be combined to give an overall shear stress.

The high frequency velocity measurements enable the bed shear stress to be calculated from the Reynolds stress and from total kinetic energy (Ref 4). The Reynolds stress was calculated from the spectrum of the high frequency velocity data. This in turn can be used to calculate the bed shear stress. The streamwise and transverse components were calculated and combined to give the modulus and direction of the stress.

The shear stress at the bed has been found by other researchers to be directly proportional to the turbulent kinetic energy (Ref 4). This has been found to be true of a wide variety of flows including wave plus current flows and enables the shear stress to be estimated.