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Hydraulics Research
Wallingford

BEDFORM MIGRATION IN SANDY ESTUARIES

Summary Report

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EXECUTIVE SUMMARY

Sandwaves occur extensively in tidal estuaries and coastal regions, frequently in conjunction with suspended sand transport. The two processes interact mutually, and should be considered together in predictions of their effect on engineering applications such as approach channel dredging, offshore navigation, pipeline stability, harbour and marina siltation, and cooling water intakes.

A combination of theoretical, numerical and field measurement techniques has been used in this study to improve understanding of the interactive behaviour of these processes. In particular, a unique and comprehensive field data set has been collected. This has allowed the distribution over a sandwave of the principal mean and turbulent quantities of the velocity and suspended sediment fields to be derived, providing a hitherto unavailable insight into the mechanisms involved in the sandwave/suspended sediment interactive dynamics. The importance of the region of intermittent separation above the trough is highlighted, in which high levels of turbulence and sediment concentration are generated and advected to other parts of the sandwave. Predictive models of bedform dynamics must be formulated so as to reproduce this region correctly.

The principal results of the study which should be taken into account when making engineering predictions are:

- sandwaves will alter the drag coefficient and reference concentration of a sandy sea-bed which in turn will radically affect the suspended sediment transport rate
- when analysing velocity and concentration profiles from the field in sediment laden flows, values of the bed shear stress should be obtained from Figure 2b, which take account of self-stratification effects
- suspended sediment transport enhances sandwave dynamics at moderate flow velocities, although at large velocities it generally acts to wash out the sandwave
- even at large velocities, bedload transport can be sufficient to maintain sandwaves against the flattening tendency of the suspension
- turbulence levels, shear stresses and sediment concentrations in the trough of a sandwave are all many times larger than the equivalent flat-bed values
- radical departures from flat-bed conditions occur everywhere on a fully developed sandwave, so that many of the simplified theories of small amplitude sandwave development are inapplicable.

More detailed quantitative results are presented in the collection of technical papers and reports which have resulted from this study (see References list), which can be used to provide improved predictions for engineering application.

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FIGURES

1 INTRODUCTION

1.1 Motivation

At many sites in sandy estuaries and coastal areas the movement of sand in response to tidal currents can be a major factor in the design and construction of engineering works. At the most active sites, which cause the most severe engineering problems, it is usual to find that sand is carried in suspension and that the bed is deformed into large sandwaves. The development and migration of the sandwaves can constitute a navigational hazard, and may cause spanning of pipelines leading to possible fracture. The combined effect of the sediment transported in suspension and by sandwave migration gives rise to siltation of navigation channels, harbours and cooling water intakes.

Sand is transported by a current partly as bedload (rolling, sliding and hopping of the grains along the bed) and partly in suspension. Where large quantities of sand are transported by strong tidal currents the suspended load is far greater than the bedload, and this mode of transport is thus the most important from a practical view point. In the past it was believed that sandwave growth and migration was entirely caused by bedload transport, and that suspended sand would flatten out the sandwave. However, in nature it appears that suspension of fine to medium sand is almost always accompanied by sandwaves, suggesting that the two can co-exist and may indeed reinforce each other. Previous field measurements (Soulsby et al, 1983) indicated that only 40% of the volume of sand transported by sandwave migration was due to bedload transport, and the remaining 60% must therefore have been due to suspended transport. In addition, the presence of the sandwaves appeared to modify the suspension process strongly, so that the usual sediment transport prediction methods (which assume a flat bed) would be inapplicable.

The present study is aimed at elucidating the role played by suspended sand in the development and migration of sandwaves, and the converse role played by the sandwaves in modifying the suspension process.

1.2 Detailed study topics

In order to understand the complex interaction between sand suspension and sandwaves a number of individual topics need to be addressed. These include:

- the sediment pick-up mechanism
- the sediment diffusion mechanism, and associated patterns of turbulence
- the effect of large eddies (bursting) on the above mechanisms
- the streamwise and vertical variation of the above mechanisms over sandwaves
- the turbulence damping caused by density stratification of the suspended sediment
- the effect of damping on velocity and concentration profiles
- the streamwise variation of the suspended sediment transport rate over sandwaves
- the response of the shape and migration of the sandwave to the above variations
- comparison of the transport rates associated with ripple migration, total bedload transport, sandwave migration, and suspended transport.

These topics have been investigated in this study through a combination of field measurements, analytical theory, and numerical modelling.

Many of the results obtained have been reported in the open literature during the course of the study. The most significant findings of these papers are summarised in this report, and the reader is referred to the individual papers for more detailed accounts. The results are drawn together here, and their engineering significance is discussed.

2 THEORETICAL STUDIES

2.1 Suspended sediment transport

As a preliminary to understanding the nature of the sand suspension process over bedforms it is necessary to investigate the parameters controlling suspended sediment transport over a flat bed. Many different theories have been advanced over the past forty years to predict the suspended sediment transport rate q_s. Their predictions sometimes disagree by a factor of 100 or more. A general theoretical framework into which most of these theories can be fitted has been devised in the present research programme, and was reported by Dyer and Soulsby (1988). It was shown that q_s (mass of sediment transported per unit width of seabed per unit time) can be written in the general form

$$q_s = C_o \bar{U} h I \tag{1}$$

where C_o is a reference concentration of suspended sediment at the seabed, $\bar{U}$ is the depth-averaged velocity and h the depth of the water, and $(\bar{U}h)$ is thus the water discharge. The function I depends on the shapes of the vertical profiles of velocity and concentrations, but not on their absolute values.

Because $(\bar{U}h)$ is regarded as an input variable, differences between alternative sediment transport theories must lie either in the treatment of C_o or of I. The mechanisms underlying the functional forms of C_o and I are largely independent, so that writing q_s in the form of eq (1) allows a clearer understanding of the sensitivity of q_s to various theoretical assumptions to be gained.

Examining C_o first, we find a wide range of methods have been proposed for relating C_o to the two quantities on which it primarily depends: the local bed shear stress, τ_o, and the sediment grain diameter d. Because different authors have chosen different ways of defining the reference height at which C_o is measured, and because the concentration decreases very rapidly with height near the bed, it is difficult to make an intercomparison of the proposed relationships. However, various power-law relationships of the form $C_o \alpha (\tau_o - \tau_c)^n$, where τ_c is the threshold value of τ_o for sediment motion, have been proposed. The degree of uncertainty in the formulation is demonstrated by the fact that different authors have suggested values of $n = 0.5$, 1.0 and 1.5. Since τ_o is proportional to $\bar{U}^2$, the different formulations predict C_o varying as anything from the 1st to the 3rd power of velocity. With these uncertainties for a flat bed, the corresponding relationship for wavy beds is clearly not at all well understood.

The general theoretical framework allows the shape-function I to be written as a double integral involving the turbulent eddy diffusivity K_m, which relates the Reynolds shear stress to the velocity gradient. Calculations of the functional form of I were made for several proposed forms of eddy viscosity distribution (Fig 1). They showed that I is relatively insensitive to the shape of the K_m-distribution. Previous authors have devoted considerable effort to selecting their K_m-distribution, but Figure 1 show that this is not necessary for a flat bed, although the more complicated distribution of K_m over bedforms could possibly lead to larger variations. By contrast, I is a strong function of the quantity $s = \beta C_D \bar{U}/3w_s$, where β is the eddy diffusivity/viscosity ratio, C_D is the drag coefficient of the seabed, and w_s is the settling velocity of the sand grains. The variation of w_s with d is reasonably well established, but the behaviour of β is not at all well understood. Furthermore, the behaviour of C_D in the presence of bedforms is poorly understood. A small error in any of these quantities leads to a corresponding error in s, which causes a large error in I and hence in q_s.

Thus, in summary, accurate prediction of the suspended sediment transport rate over bedforms requires improved knowledge of: the relationship between C_o and τ_o; the behaviour of β as a function of τ_o and w_s; the dependence of C_D on bedform geometry.

2.2 The effect of self-stratification on profiles

It has long been recognised that the presence of suspended sediment modifies the shape of velocity and concentration profiles from their sediment-free form. However, the extent of the effect, and the range of grain-sizes and flow velocities for which it is important, had not been determined. These were investigated as part of an earlier DoE-funded study, and were reported by Soulsby and Wainwright (1987) within the duration of the present contract.

The effect arises because the concentration of suspended sediment decreases with height above the bed, so that the density of the sand-water mixture also decreases with height. Since work must be done by the turbulent mixing in order to lift dense mixture from near the bed to higher levels, thereby increasing the potential energy of the water column, energy is extracted from the turbulent eddies. This reduces the eddy viscosity and diffusivity, which in turn reduces the friction at all levels and modifies the profiles of velocity and concentration. The net effect is complicated by the fact that an increase in velocity increases both the input of mixing energy, and, by entraining more sediment, also increases the damping effect. Likewise an increase in grain-size decreases the absolute concentration, but increases the concentration gradient, of suspended sediment.

Using a combination of various well-established relationships, Soulsby and Wainwright (1987) were able to map out the severity of the stratification effect as a function of grain-size and friction velocity u_* (Fig 2a). This shows that the modification of velocity and concentration profiles increases for all grain sizes with current velocity. The effect is most marked for grains in the fine and very fine sand ranges ($63 < d < 250\mu m$), and decreases for both finer and coarser sizes. For silts ($d < 63\mu m$) the modification occurs most strongly in the upper part of the profile, whereas for medium and coarse sands ($250 < d < 1000\mu m$) it occurs most strongly near the bed. Over a small range of low current velocities in the fine sand range ($125 < d < 250\mu m$) the modifications are insignificant.

A direct method is given in Figure 2b for obtaining the friction velocity u_* from velocity profiles measured under mobile sediment conditions, which takes account of the suspended sediment effects. The only inputs required are the velocity U_{100} at a height of 1m, and the grain size. This method should be used in place of the standard logarithmic profile method, which is not applicable in sediment-laden flows.

The predicted behaviour was confirmed by comparisons with field data. The above results apply above flat beds, but a similar effect is expected to apply above bedforms, where it will compound the complexity of the velocity and concentration profiles produced by topographic variations.

3 NUMERICAL MODELLING

Although some success has been achieved with analytical models of suspended sediment over bedforms (eg Smith and McLean, 1977), these are extremely complicated because of the many interacting processes taking place. Numerical models offer a more versatile method of obtaining insight into the phenomenon, and offer the additional opportunity of allowing the shape of the bedforms to change in response to the sediment transport dynamics. Consequently a numerical modelling study, undertaken by Reading University in collaboration with Hydraulics Research Ltd, was included within the present programme, and was jointly funded by SERC.

The results have been reported in detail by Johns, Soulsby and Chesher (1989). The numerical model uses a sophisticated turbulence-energy closure to calculate the hydrodynamics of the flow over a series of sandwaves of any chosen shape. The hydrodynamic quantities are used to drive bed load and suspended transport of sand, which vary over the sandwaves. The sediment budget is applied to obtain the erosion and deposition pattern over the sand waves, and the sandwave morphology is allowed to evolve with time.

The hydrodynamic predictions of the model were validated against fixed-bed laboratory tests of flow over bedforms, and the suspended sediment predictions were validated against "leading edge" laboratory flume measurements over a sand bed, both laboratory data sets being obtained from the literature. Reasonable agreement was also obtained with field data on velocity and suspended sediment measurements over the crest of a sandwave made in an earlier phase of this DoE funded study.

The changes in bed morphology resulting from 60 minutes of flow are illustrated in Figure 3, where the effects of independent runs with bedload transport and suspended transport only are compared. This shows that bed load tends to make the crest less peaked, whereas suspended load tends to make it more peaked. The trough-crest height remains almost constant for suspended transport, and is slightly reduced for bed load transport. Both modes of transport lead to an overall downstream migration of the bedform, with that due to suspension being the larger.

In another test, at larger flow velocity, the effects of bed load were similar though larger, but in contrast the suspended load resulted in a marked lowering of the crest and filling of the trough. The net effect is to wash out the sandwaves, as is observed to occur at high velocities in nature.

Thus the numerical model indicates that at moderate flow velocities over fine sand the suspended transport tends to maintain and translate sandwaves, but at greater flow velocities it tends to wash out the sandwaves. Both effects are in accord with experience.

4 FIELD MEASUREMENTS

One of the most important objectives of the present study was to obtain field measurements of the turbulent velocity and sediment-concentration distributions over a natural sandwave, in order to elucidate the mechanisms involved in the bedform dynamics. These were made at a site in the estuary of the River Taw in North Devon. Earlier experiments at this site were made in a previous phase of the study above the crest of a sandwave only. The principal results from these experiments, reported by Soulsby et al (1984, 1985, 1987) were:

- horizontal diffusion of sediment occurs in the upstream direction, but is small compared with the advection rate
- vertical diffusion of sediment (the sediment entrainment mechanism) occurs upwards, but is significantly smaller than the downward settling flux
- the eddy diffusion coefficient for sediment is considerably smaller than the eddy viscosity coefficient
- the sediment pick-up rate could be presented as a function of the bed shear stress
- suspended sediment moves as large clouds which are correlated over horizontal and vertical scales of order one metre, and lean in the downstream direction (Fig 4)
- the clouds of sediment are associated with ejection events in the turbulent "bursting" cycle, and these events are the dominant mechanism of the sediment suspension process
- self-stratification of the sediment-laden flow leads to damping of the turbulent kinetic energy

The new experiments, reported by Atkins et al (1989), confirmed the above results, and also provided new insight into the mechanisms occurring at all other parts of the sandwave in addition to the crest. The measurements were made from a boat connected to two instrumented masts driven into the sandwave at low tide, when the area was exposed. Both masts carried arrays of Braystoke propeller current meters and pumped sampling nozzles for obtaining sediment concentrations. One mast was always mounted at the crest of the sandwave to provide reference values of velocity and concentration. The other mast was moved day by day to five positions on the sandwave ranging from the trough to the crest. The latter mast additionally carried the main set of instruments, comprising electromagnetic current meters (EMCM) at heights of 10, 20, 40 and 80cm above the bed, and an acoustic backscatter probe (ABP) which measured the sediment concentration at the same 4 levels. The ABP was designed, built and operated by Dr P D Thorne of the Proudman Oceanographic Laboratory. These instruments provided high frequency turbulence measurements of the horizontal (u) and vertical (w) components of water velocity, and of the suspended sediment concentration. Mean values of horizontal velocity ($\bar{U}$) and concentration ($\bar{C}$) from them were calibrated against the Braystoke and pumped sampling measurements. The sandwaves at this site migrate in the direction of the strongly dominant flood tide, with ebb-directed sediment transport being small. Daily levelling surveys along a line through the instrumented sandwave pinpointed the position of the instruments relative to the topography, and allowed the migration rate of the sandwaves to be calculated.

Because the data were collected relatively late in the contract period it was not possible to perform a detailed analysis to address all the questions raised in sections 2 and 3. However, a basic analysis of all the principal mean and turbulent quantities has been made, and the resulting plots reveal many new and interesting aspects of bedform dynamics which impact on modelling and prediction techniques.

To minimise random scatter in the data the various quantities of interest were each averaged into 4 bands, where the time intervals of data going into each band corresponded to a narrow range of velocity measured at a height of 0.4m on the reference mast. The results were plotted as profiles superimposed onto a composite average shape of sandwave from the daily levelling surveys.

The mean velocity profiles (Fig 5a) show that the flow pattern over the sandwave is complex. Low mean velocities occur within trough, corresponding to a region of intermittent flow separation in which the velocity just above the bed is directed upstream for up to 40% of the time. On the flank of the sandwave and at the crest the mean velocity exhibits a low-level jet with intense shear near the bed due to speed-up over the rising topography. At no position do the profiles conform to the flat-bed logarithmic form.

The distribution of mean sediment concentration (Fig 5b) also differs markedly from the flat-bed (Rouse) form. The largest concentrations occur at a height of 0.2m within the trough. This is attributed to sand carried from the preceding crest by jetting and avalanching settling through the slower-moving water in the trough. Concentrations over the flank and crest are smaller and correspond more closely to flat-bed conditions, but still with marked features due to the topography.

The velocities and concentrations are both highly turbulent, most especially in the trough region where turbulent kinetic energy is very large. The standard deviation of concentration is typically 50 to 100% of the mean concentration everywhere. The distributions of turbulent kinetic energy and sediment concentration are rather similar, suggesting that models which link the two quantities might have some success.

The distributions of momentum flux ($-\overline{uw}$) and sediment fluxes ($\overline{uc}$ and $\overline{wc}$) give detailed insight into the turbulent mechanisms operating (Fig 6). The momentum flux $-\overline{uw}$ has large values in the trough, and elsewhere increases upwards as form drag of the sandwave becomes incorporated. The horizontal sediment flux $\overline{uc}$ is directed upstream everywhere except in the trough. The vertical sediment flux $\overline{wc}$ is upward everywhere except in the trough, but is no larger anywhere than 50% of the settling flux.

The suspended transport rates calculated by vertical integration of the mean fluxes are typically 3 to 14 times larger than the migration transport calculated from the daily levelling surveys. The sediment budget calculated by differencing the suspended transport rates would contribute a levelling of the crest and a filling of the trough (Fig 7). Thus, for these velocities and grain sizes, suspension appears to attempt to wash out the sandwaves. The observation that they maintain their shape must therefore be attributed to the effects of bedload transport.

Several of the results from the data have implications for modelling and prediction of sandwave behaviour. Many theoretical models assume that departures from flat-bed conditions are small; the present measurements show that this is invalid for natural fully developed sandwaves. The large values of shear stress and sediment concentration observed in the trough is also in contrast with simple theories, which predict minimum values occurring in the trough. Future models may therefore need to make more realistic assumptions if they are to provide adequate predictions for engineering applications.

5 CONCLUSIONS

An improved insight into the mechanics of suspended sand transport over flat beds has been gained by the theoretical developments. These highlighted the insensitivity of the transport rate to eddy viscosity distribution, but the need for improved formulations of the drag coefficient, reference concentration and diffusivity/viscosity ratio. They also demonstrated that self-stratification can significantly affect the interpretation of measured velocity and concentration profiles.

Theoretical understanding was extended to the case of a bed of fully developed sandwaves through the development of a numerical model. This showed that at moderate velocities sediment suspension could aid the growth and migration of sandwaves, but at larger velocities it tended to flatten them.

A comprehensive set of field measurements was obtained which revealed the behaviour of the fields of velocity and sediment concentration over a natural sandwave in tidal waters, for both mean and turbulent quantities. Under the spring-tide conditions prevailing, the suspension was inferred to be acting to flatten the sandwaves, although their height was observed to be relatively constant due, presumably, to bed load transport. Marked departures from flat-bed conditions were found, with patterns of the turbulent quantities which are internally consistent and plausible, but very different from those assumed by simple models. Even the relatively sophisticated model used in the numerical study was deficient in some of these aspects.

The results aid the prediction of the mutually interacting changes in sandwave development and suspended sediment transport occurring as a result of engineering works in tidal estuaries and coastal regions.

6 ACKNOWLEDGEMENTS

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FIGURES.

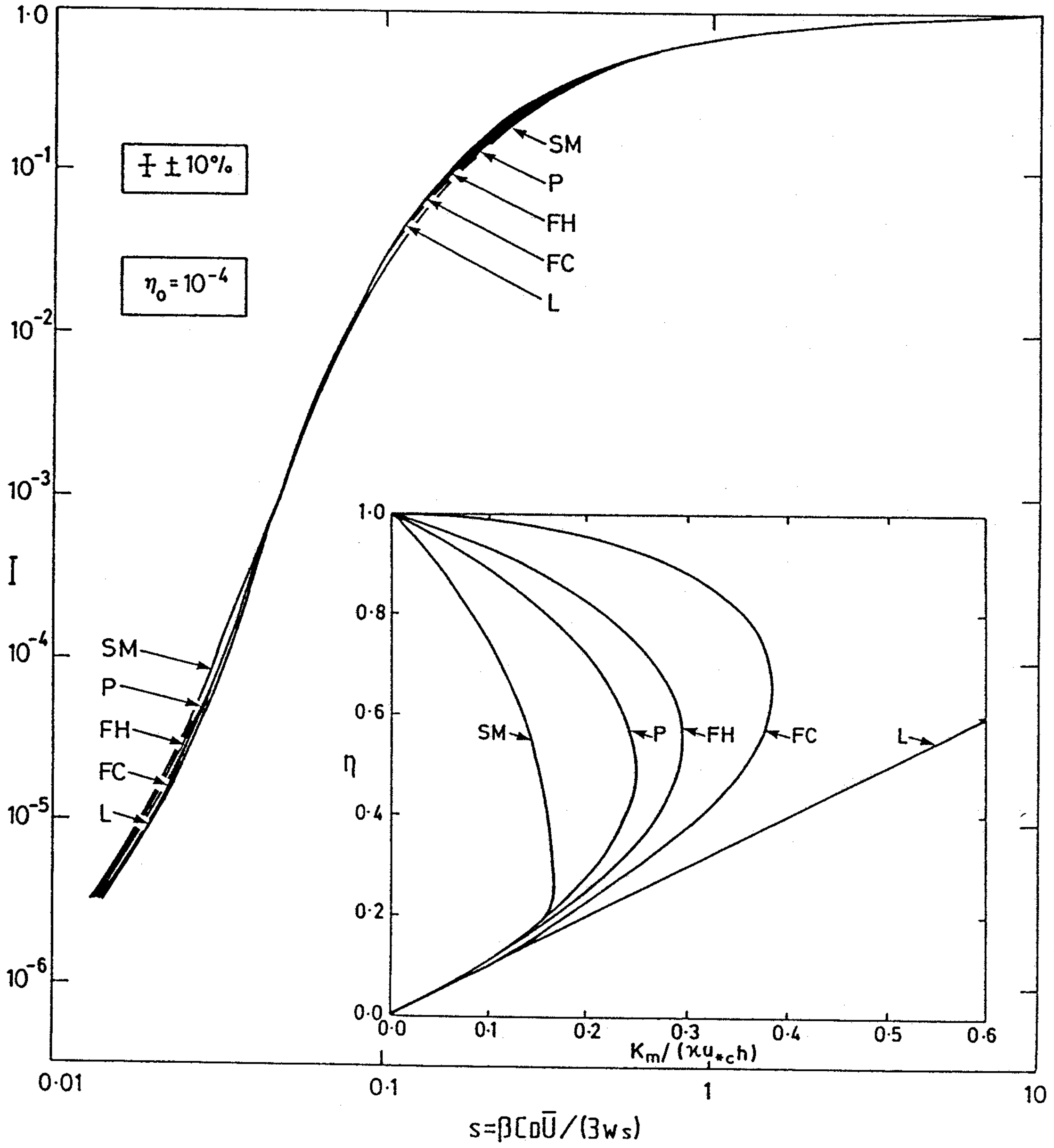

Fig 1. Shape function I (s), showing insensitivity of sediment transport rate to the choice of eddy viscosity distribution (inset), but strong dependence on current velocity ($\bar{U}$), settling velocity (w_s), and drag coefficient (C_D). For key see Ref 2.

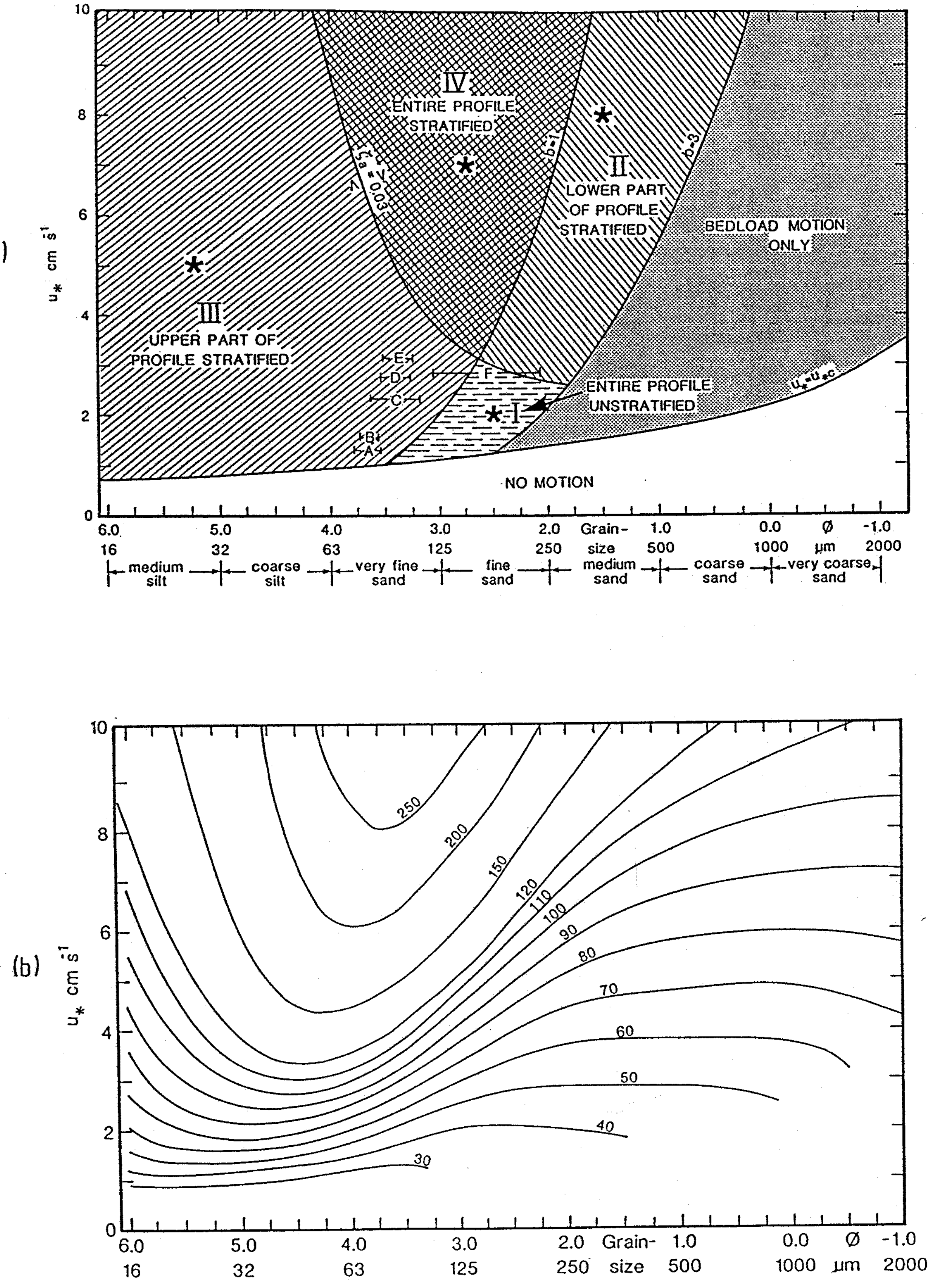

Fig 2. (a) Effect of self-stratification of velocity profile in sediment-laden flows as function of friction velocity (u_*) and grain-size. (b) Diagram for calculating u_* from velocity measurements in sediment-laden flows. See Ref 9.

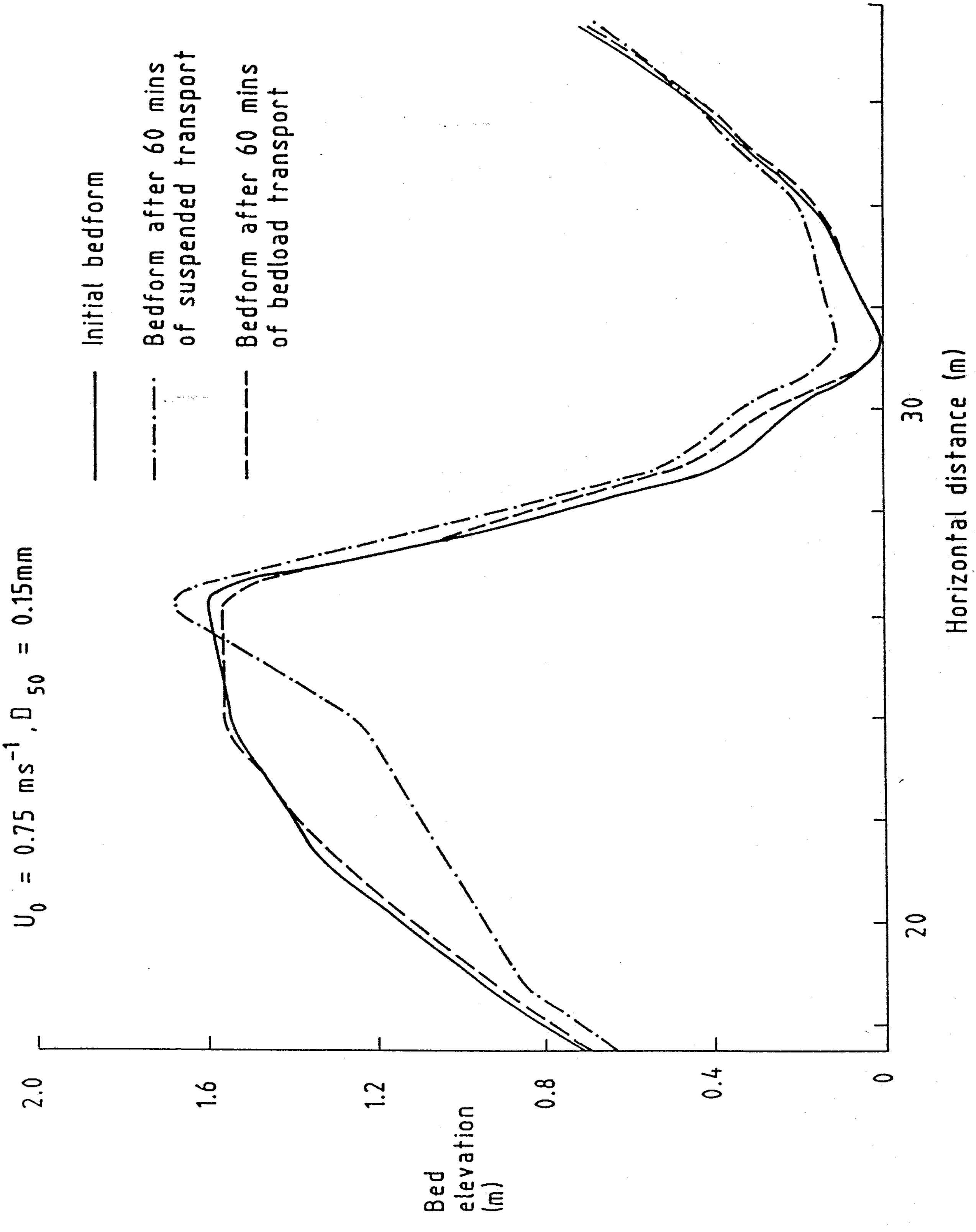

Fig 3. Numerical model predictions of evolution of sandwave morphology after 60 minutes of either bed load or suspended load transport. See Ref 3.

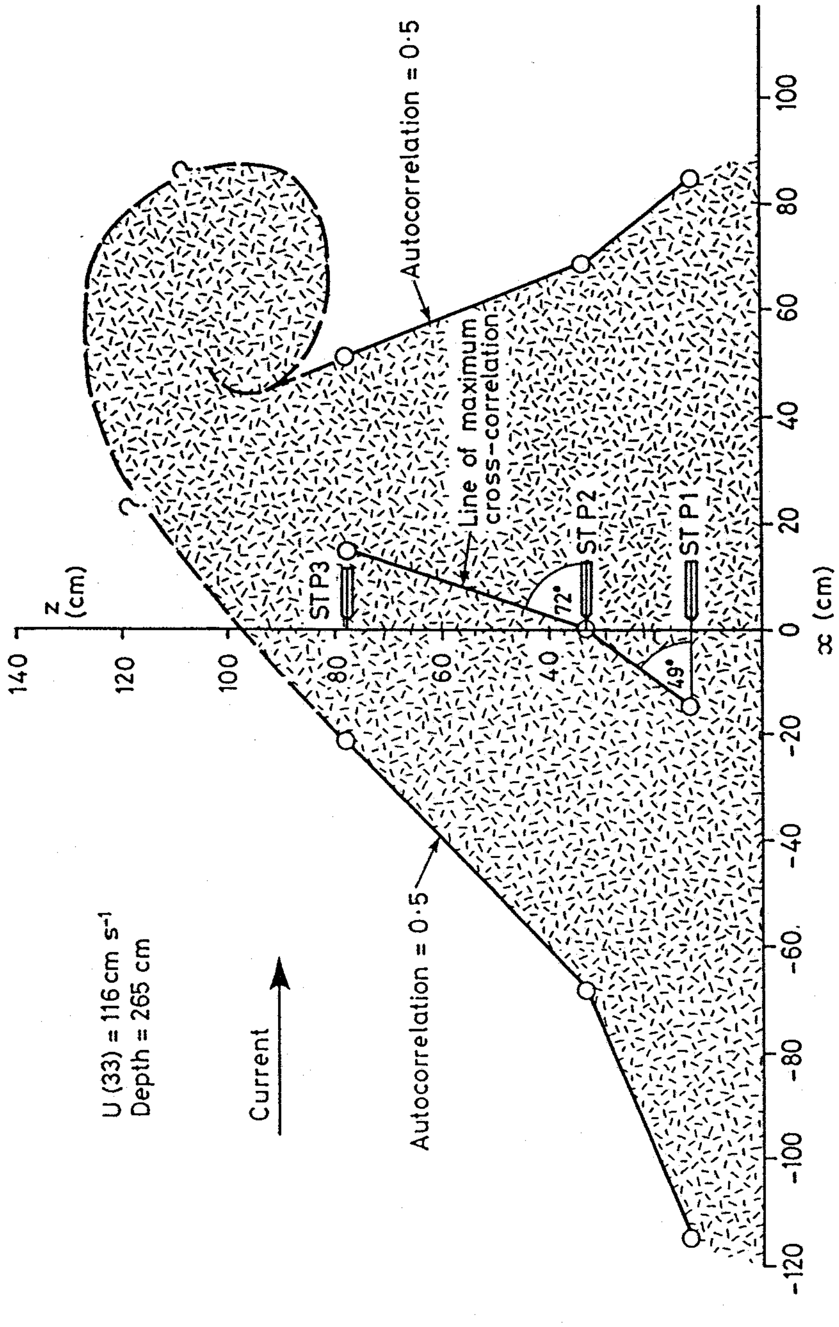

Fig 4. The shape of the average cloud of suspended sand in the Taw estuary deduced from cross-correlations and auto-correlations of concentration sensors. See Ref 8.

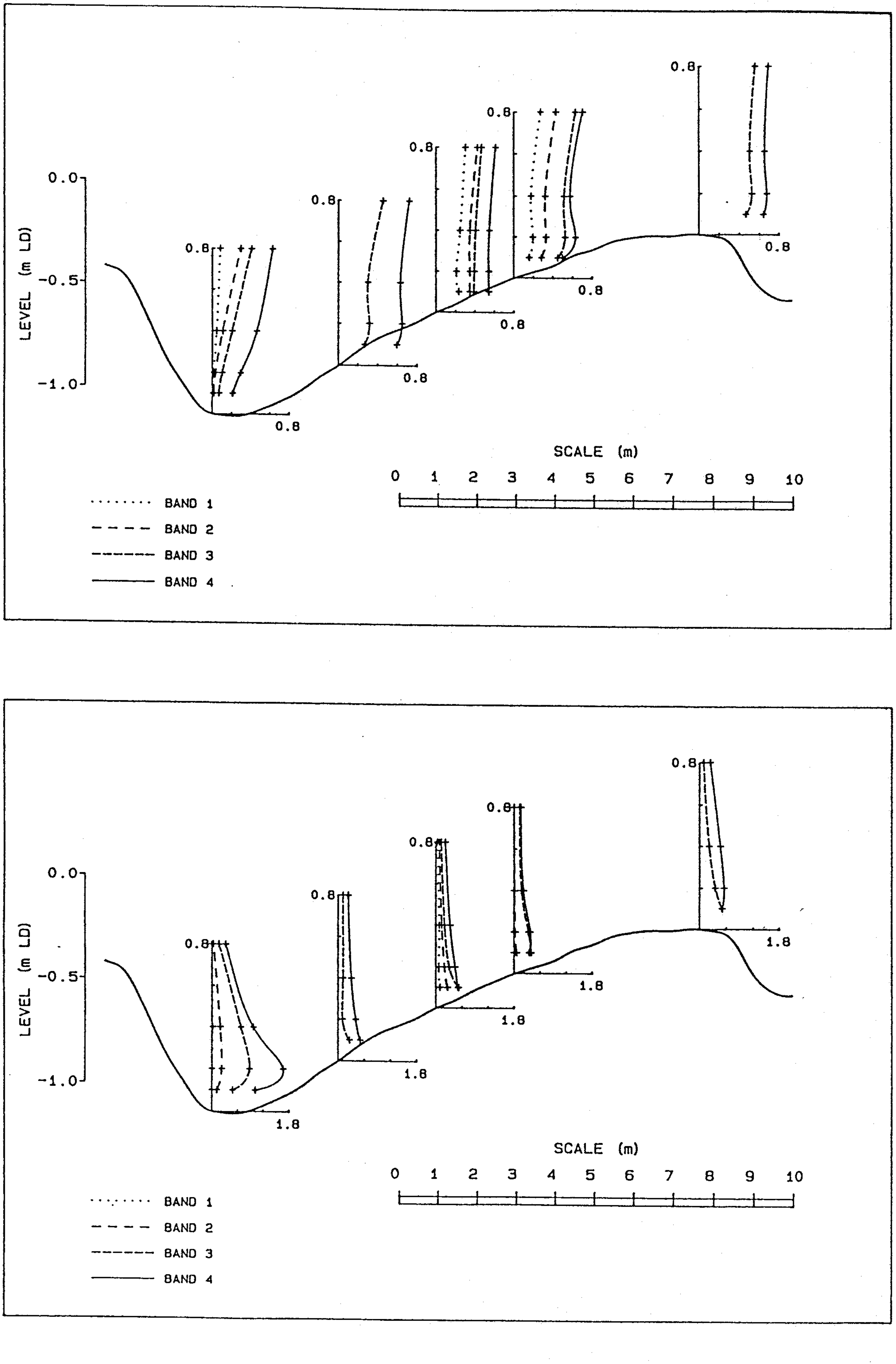

Fig 5. Distribution over a sandwave in the Taw estuary of (a) mean streamwise velocity ($\bar{U}$), (b) mean suspended sand concentration ($\bar{C}$). See Ref 1.

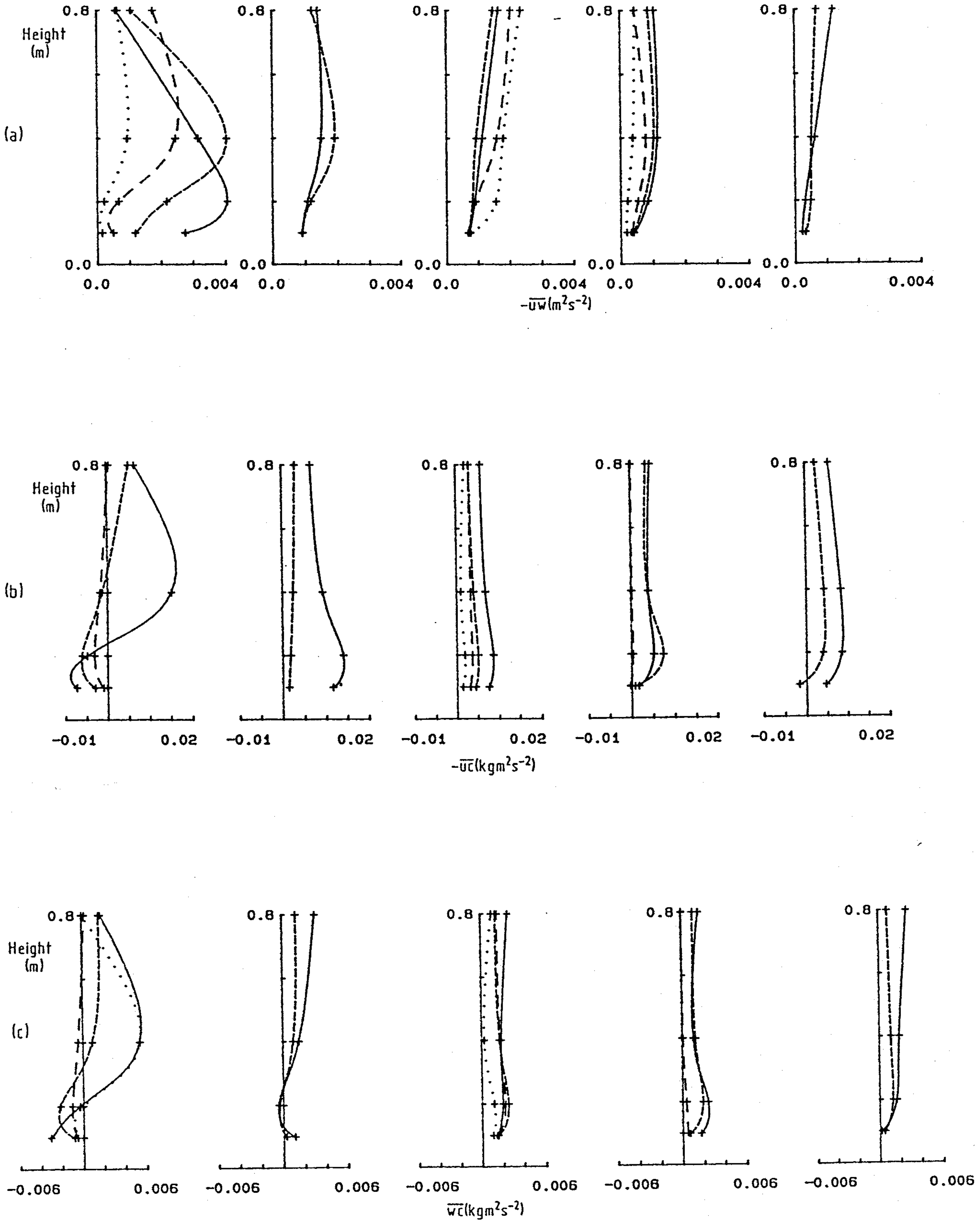

Fig 6. Distribution over a sandwave of (a) kinematic Reynolds stress $(-\overline{uw})$, (b) upstream diffusive flux of sediment $(-\overline{uc})$, (c) upward diffusive flux of sediment $(\overline{wc})$. For positions on sandwave and banding see Fig 5.

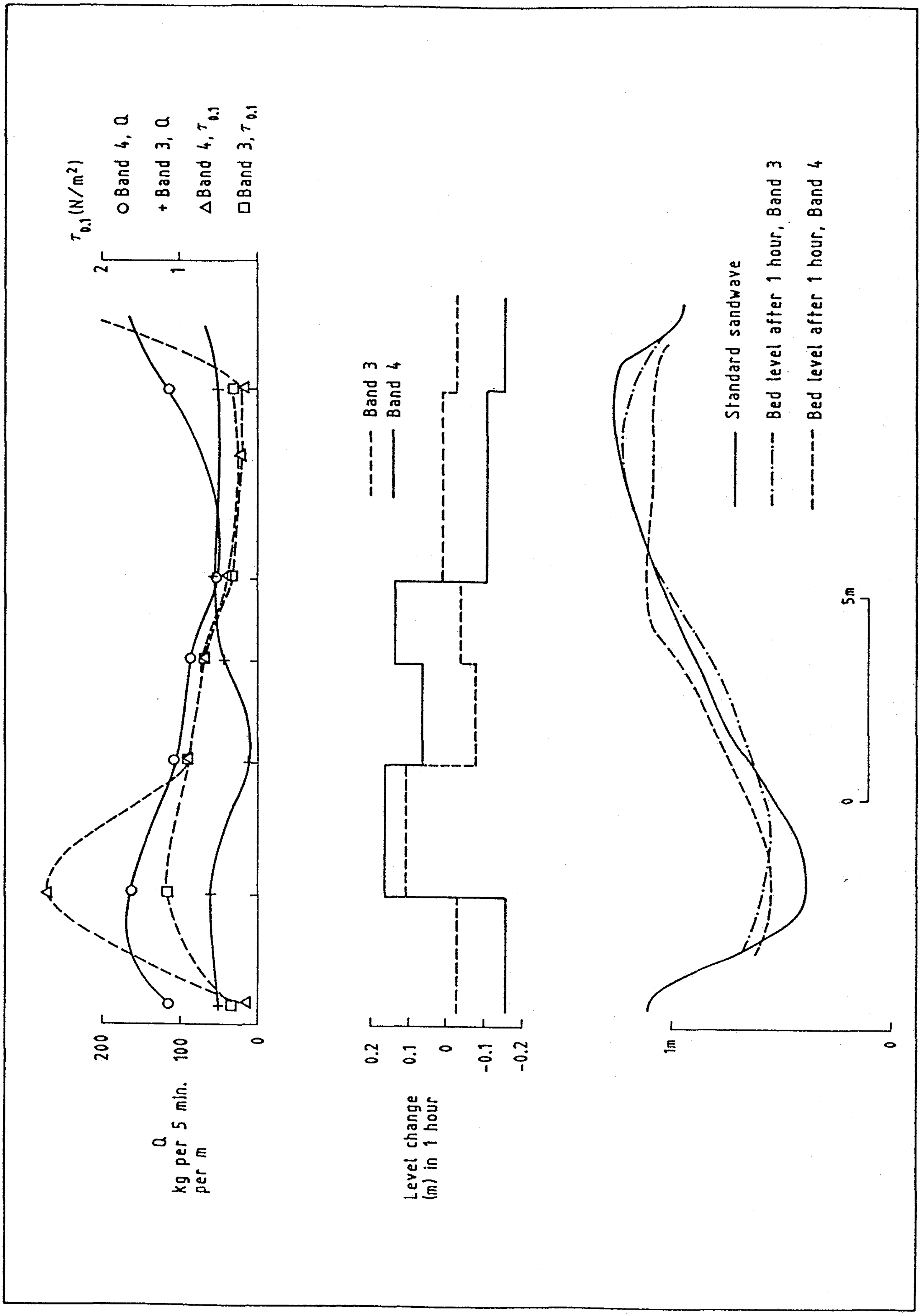

Fig 7. Bed level changes over sandwave inferred from measured suspended transport rates and sediment continuity. See Ref 1.