

R Whitehouse

# Seabed Roughness in Tidal Flows

## A Review of Existing Measurements

R J S Whitehouse  
T J Chesher

Report SR 360  
January 1994



*HR Wallingford*



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Approved by R L Soulsby Project Manager

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## Summary

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### Seabed Roughness in Tidal Flows

#### A Review of Existing Measurements

R J S Whitehouse  
T J Chesher

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This report describes a review of field measurements concerning the variation of the seabed roughness length throughout a tidal cycle, as part of a two year research study funded by MAFF to investigate sediment transport under real sea conditions.

Specifying the bed roughness is a major source of uncertainty in the computation of coastal flows and sediment transport, especially since there is some evidence that the roughness varies with time. This question prompted the present review.

The review highlights two main aspects relating to the variations in roughness:

Firstly, there is much conflicting evidence in existing field data sets for how the seabed roughness length varies through a tidal cycle. Some field experiments indicate an increase in the roughness length of a rippled sandy seabed with time (or increasing velocity) whilst others show that the roughness length decreases. The causes of this variation are attributed to, variously, the influence of bed load transport by saltation, the changes in seabed ripple geometry, the influence of topography on the flow, non stationarity in the flow, or the stratifying effect of sediment in suspension. There is also the possibility that errors in the data collection or insufficient data coverage (both temporally and spatially) may mask the real trends.

Secondly, in specific cases where the field data coverage is extensive (both temporally and spatially) the variation in the roughness length cannot be accounted for by the existing theory.

The report reviews the results of 14 published sets of field measurements to determine how the roughness length varies at a given location. Following a discussion of the main issues the report discusses the setting up of laboratory experiments to study this phenomenon in a controlled environment, so that a more complete understanding of the physical conditions associated with the coastal bottom boundary layer may be achieved.





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## 1 Introduction

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This report describes a review of field measurements concerning the variation of the seabed roughness length,  $z_0$ , throughout a tidal cycle. The review covers field exercises that were designed specifically to measure the variations (if any) in roughness using measurements of the vertical structure of the tidal boundary layer, as well as other studies where the variation in roughness has been obtained by other methods.

The report is structured as follows. In Section 2 a short background to the study is presented. Section 3 contains the main field data review, and in Sections 4 and 5 the findings of the review are discussed and a number of recommendations for future research are presented.

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## 2 Background

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In shallow coastal waters the flow and the sediment transport are largely controlled by friction. Consequently, computations of these quantities are found to depend strongly on the bed roughness, parameterised by the seabed drag coefficient, the Nikuradse equivalent roughness, or (as here) the bed roughness length  $z_0$ . The specification of the roughness is, however, a major source of uncertainty, and there is furthermore some evidence that it varies through the tidal cycle. This latter question is the subject of this review.

For a turbulent tidal flow over the seabed the velocity profile in the near-bed region can be represented by the familiar von Karman-Prandtl equation:

$$u(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \quad (1)$$

where  $u(z)$  is the fluid velocity at height  $z$  above the bed,  $\kappa$  is von Karman's constant ( $\sim 0.4$ ) and  $u_*$  is the friction velocity. Generally speaking, velocity profile measurements made near to the seabed are found to fit Equation 1 by plotting as a straight line on  $u$  versus  $\ln z$  axes. A least squares technique can then be used to obtain the best fit of Equation 1 to the measurements (Wilkinson, 1984). The gradient of the fitted profile gives  $u_*$  and the intercept of the profile with the  $z$ -axis yields the roughness length,  $z_0$ , the height above the bed where the velocity extrapolates to zero.

The value of the roughness length  $z_0$  was established many years ago in the laboratory for a single size,  $d$ , of sand, or a flat bed of uniformly sorted sand (where the value of  $d$  is taken to be the median grain size  $d_{50}$ ), in terms of the roughness Reynolds Number  $Re_* = \frac{u_* d}{\nu}$ , where  $\nu$  is the kinematic viscosity of the fluid. Laboratory experiments have shown that for smooth turbulent flow ( $Re_* < 3.5$ ) the roughness length is related to the thickness of the viscous sublayer, and not the grain roughness. The thickness  $\delta$  of the viscous sublayer is equal to  $c_1 \nu / u_*$  where  $c_1 = 11.6$  from experimental measurements (Sleath, 1984, p34). The apparent hydraulic roughness length  $z_0$  is related to the thickness  $\delta$  and experiments have shown that  $z_0 = \nu / (c_2 u_*)$  where  $c_2 = 9$  (Sleath, 1984, p35). For rough turbulent flow ( $Re_* > 68$ ) the value of  $z_0$  assumes a constant value of  $d/c_3$ . Values of  $c_3$  between 15 and 30 have been found by various experimenters (Sleath, 1984; Soulsby, 1990, p546). The value of  $z_0$  in the intermediate range of  $Re_*$  varies as a function of  $d$  and  $\nu$ .

The uncertainty of applying laboratory derived values or relationships for  $z_0$  to seabed sediments has meant that in practice it is probably safest to estimate  $z_0$  from velocity profile measurements made in the sea and classified in terms of a description of the seabed (Table 1). The data in Table 1 are representative of the typical flow conditions and hence  $Re_*$  associated with each type of substrate. A more detailed discussion on specifying bed roughness and the intercomparison of laboratory and field measurements is contained in Heathershaw and Langhorne (1988, pp477-478) and in Soulsby (1990, Section 4).

If we examine the two values in Table 1 for sand beds in more detail the roughness length on rippled sand is seen to be 15 times larger than that for unrippled sand. Over the unrippled sand bed the roughness length  $z_0'$  is determined by the thickness of the viscous sublayer, as has been verified in the sea by Chriss and Caldwell (1982), whereas over the rippled sand bed there is an additional form drag roughness  $z_0''$  due to the variation in the normal pressure over the bedforms and the possible occurrence of flow separation downstream of the ripple crest. Therefore the total roughness length of a rippled sand bed is given by

$$z_0 = z_0' + z_0'' \quad (2)$$

Hence over rippled beds the total drag  $\tau = \rho u_*^2$ , where  $\rho$  is the fluid density, will in simplest form be comprised of two parts

$$\tau = \tau' + \tau'' \quad (3)$$

where  $\tau'$  is the skin friction related to the sediment particle roughness or the viscous sublayer thickness and  $\tau''$  is the form drag component. Other authors have suggested that the motion of sand as bedload adds an additional roughness component  $\tau''$ . Smith and McLean (1977) proposed the formula for sediment transport over a flat bed

$$z_0 = \frac{c_4(\tau - \tau_{cr})}{(\rho_s - \rho)g} + z_N \quad (4)$$

where  $\tau_{cr}$  is the value of  $\tau$  at the threshold of motion,  $\rho_s$  is the mineral density of the bed material,  $g$  the gravitational constant and  $z_N$  assumed equal to  $d/c_3$ , with  $c_3 = 30$ . Estimates of  $c_4$  obtained in the field over rippled beds are 26.3 by Smith and McLean, 26.4 (Dyer, 1981) and 21.4 (Wilkinson, 1986).

Measurements in the sea (Chriss and Caldwell, 1982) and in the laboratory (Kapdasli and Dyer, 1986) have shown that the values of  $(z_0', \tau')$  and  $(z_0'', \tau'')$  are related to two logarithmic velocity profiles which intersect at about 3-4 ripple heights (or 1/2 to 1/3 of a ripple wavelength) above the bed (ie about 10cm above the spatially averaged bed level, Figures 1 and 2). Therefore, most velocity profile measurements made over rippled beds in the sea will provide information on the total  $\tau$  and  $z_0$  because of the physical constraint of fixing the current meter no closer than about 10cm to the bed in a frame for deployment on the seabed. It is the total drag  $\tau$  which controls the fluid motion near to the boundary and the mixing of sediment into the water column, and the value of  $\tau'$  which is responsible for moving the sediment at the bed. Therefore, over a gravel bed with an irregular topography, a flat sand sheet with topographic influences on the flow from upstream, or a rippled bed the major problem for sediment transport calculations is how to partition the total

stress into  $\tau'$  and  $\tau''$ . Over a rippled sand bed this problem is greatly complicated by the fact that the contribution of  $\tau''$  to  $\tau$  varies through the tide as the bedforms change their geometry.

According to Wilkinson (1986), 'the concept of roughness length... is defined in terms of the *steady, uniform* flow of an *unstratified* fluid over an *immobile* bed.' Departures from these conditions can result in curvature of the logarithmic velocity plot, which can in turn be misinterpreted as an apparent change in  $z_0$ . However, if the cause of the departure is known (and monitored) its effect can be taken into consideration, by an appropriate adjustment to the theory, to yield an estimate of the correct unstratified and quasi-steady value for the roughness length.

Therefore, the factors that influence the shape of the velocity profile in a coastal environment include temporal acceleration and deceleration effects, large scale bed features and the corresponding flow non-uniformity (including separation), and sediment motion and the associated changes to small scale features (ripples).

The averaged values of  $z_0$  given in Table 1 do not explicitly indicate how  $z_0$  varies in a tidal cycle. The complications in determining  $u_c$  and  $z_0$  once sediment is in motion have been summarised previously by Soulsby et al (1983):

- (a) the ripple geometry may change with time causing tidal variations in  $z_0$ ,
- (b) the saltation of grains along the bed enhances the momentum transfer from the flow to the bed, causing an increase in  $z_0$  (Equation 4),
- (c) the suspended sediment in the water column produces a vertical density gradient and hence a departure from Equation 1.

Studies involving near bed velocity profiling over a period of a tidal cycle (Dyer 1980, Wilkinson 1986) have indicated variations in the roughness length of more than an order of magnitude. The phenomenon observed, that of a steady increase in  $z_0$  through the tide (see Figures 3 and 4), could not be explained satisfactorily in terms of (a), (b) or (c) above or with existing theory based upon adjustments to Equations 1 for non-stationary flow (profile curvature).

Consequently in the present study laboratory experiments will be performed to investigate the variation in roughness length, and other relevant parameters, through a tidal cycle so that a more complete understanding of the physical conditions associated with the bottom boundary layer may be achieved. The next section of this report presents the findings of a literature search to determine the scale of variability in  $z_0$  from field data sets.

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### **3 Literature review**

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An accurate determination of the roughness length,  $z_0$ , is only strictly possible by the method of vertical current profiling, and therefore the majority of field study data sets reviewed involved current meter profiling. However, two data sets are included (Washbrook, Knight) which describe an assessment of the bed roughness according to a balance of terms in the 1-D equation for continuity of momentum, as they are directly relevant to the review.

The reviews have been ordered chronologically, according to the date of publication of the source, and contain information on the location of the study, the instrumentation used and the main findings. A summary of the velocity profile study findings regarding  $z_0$  and information on the bed type are given in Table 2.

### 3.1 Anglesey, UK

Author: Charnock H, 1959

Location: Menai Straits and Red Wharf Bay, UK

Bed Description: Firm sand, ripples, some shingle

Water Depths: Not Specified

Data: Velocity profiles using three to five cupwheels on vertical tube (analogous to anemometry).

Measurement Heights: Menai Straits 0.315, 0.62 and 1.99m  
Red Wharf Bay 0.3, 0.61, 0.78, 1.37 and 2.0m

Review: Charnock measured velocity profiles in tidal streams at two locations off Anglesey, in the Menai Straits in 1955, and in Red Wharf Bay in 1955 and again in 1957.

For the first data set, lines through only two points in the vertical indicated 'roughly logarithmic' profiles and a corresponding roughness length of 0.1cm was quoted.

For the second data set five measuring points in the vertical were obtained and  $z_0$  was calculated from 12 velocity profiles covering a two hour period (Table 3). Values varied between 0.1cm and 2.4cm (Table 3, although this last value was obtained from a fit to the top three points only - all but one other  $z_0$  value out of 12 were less than 0.45cm). A mean value of 0.3cm was quoted, and an explanation for this large value was attributed to the presence of a rippled bed. The data set indicates some evidence for reduced  $z_0$  after 'peak' current.



### 3.2 Puget Sound, USA

Source: Sternberg RW, 1968

Location: Puget Sound and Strait of Juan de Fuca, USA

Bed Description: Rock, shell, gravel, and sand formed into irregular roughness and small ripples

Water Depth: Not Specified

Data: Profiles using Six Savonius rotor current meters  
Television monitoring and oriented stereophotography of the bed  
Bed samples

Measurement Heights: Not Specified

Review: Sternberg assessed data for six sites on the NW coast of USA, near Seattle, comprising velocity profiling and visual observation of the sediment-water interface. Plots of roughness length versus a Reynolds number,  $Re$  based on the velocity at 1m were presented for those profiles that exhibited a logarithmic behaviour. The main conclusion to be drawn from the data was one of an increase in *variance* in  $z_0$  with reducing  $Re$ . No systematic trend between these two variables could be discerned, but significant variations in  $z_0$  over six orders of magnitude were recorded.

The data for the six sites were merged and divided into two flow regimes (Figure 5): hydrodynamically rough and hydrodynamically transitional flow according to a dividing  $Re$  of  $1.5 \times 10^5$ . For relatively low  $Re$ , a high variance in  $z_0$  was recorded, which was attributed to influences of the fluid motion giving rise to a complicated coupling between the boundary and the flow for different flow conditions and roughness elements. At larger  $Re$  numbers the data is expressed as conforming with theory in that the  $z_0$  value tends to a 'relatively constant value' with low variance, provided the bed is not being deformed. The total variation of the drag coefficient in the rough regime varied by less than a factor two, and the author questioned whether this was significant on the basis of the available data. An ensemble average for  $z_0$  of about 0.1cm was determined.



### 3.3 Solent, UK

Source: Dyer KR, 1970

Location: West Solent

Bed Description: Coarse sand and gravel with dunes

Water Depth: 14m approximately

Data: Profiles using Eight Braystoke current meters

Measurement Heights: 0.15, 0.3, 0.61, 1.22, 2.29, 3.81 and 6.86m above bed, 2m below surface

Review: Dyer carried out velocity profiling in the West Solent, where the bed was known to have large bedforms ranging in height from 0.25-2m and in length from 5-18m. The measurements were made over different positions on these bedforms in an attempt to gain information on the form drag. Hence the vertical profiles did not always fit on a single straight line logarithmic plot, which was attributed to the effect of the bedforms.

For the determination of the roughness length it was found that the most consistent values were obtained by considering the lowermost two levels (of the 8 meter levels) This was attributed to the skin friction being less sensitive to the flow strength and direction than the higher levels of the flow. Values of  $z_0$  between 0.001-5cm were obtained (Figure 6), though not at a fixed location, which were considered realistic for the bed material (coarse sand to gravel).

### 3.4 Great Ouse Estuary, UK

Source: Washbrook JD, 1974

Location: Canalised section of Gt Ouse Estuary, UK

Bed Description: Very fine sand, presumably rippled

Water Depths: Approximately 0.2 to 4.2m

Data: Three velocity profiles across the channel comprising four Braystoke current meters (NB not analysed for  $z_0$  variations).  
Tidal levels  
Bed samples and configuration

Measurement Heights: 0.2h, 0.3h, 0.55h and 0.9h (h = water depth)

Review: Washbrook describes an analysis of the measurements made in a canalised section of the Gt Ouse Estuary, UK in 1968, to determine the frictional resistance in a channel with a fine sand bed. Current meter profiling data was integrated to yield the instantaneous discharge. Using this, and other measurements of local water depth and free-surface gradient and channel dimensions, the bed shear stress was estimated by appealing to the 1-D equation for continuity of momentum.

The effective roughness of the bed was evaluated along the length of the channel according to the Colebrook-White law for transitional flow. For conditions of gradually varying flow the effective roughness of the bed was seen to decrease monotonically with increasing velocity (Figure 7). This behaviour was attributed to the changing geometry of the ripples on the bed, whereby as the transport of sand increased the ripples became smoother, thus creating less drag, until their effect disappeared altogether. However, as the geometry of the bed was not surveyed, the ripple dimensions were expressed according to the Mobility number referring to Yalin (1972), and a relationship between Mobility number and effective roughness was established.

Clearly, the analysis described will only yield a determination of the 'bulk' frictional resistance. However, if the profile data is still available it could perhaps be re-analysed for  $z_0$  variability.

### 3.5 Start Bay, UK

Source: Dyer KR, 1980

Location: Adjacent to Skerries Bank, Start Bay, Devon, UK

Bed Description: Medium sand with fine shell, rippled

Water Depth: 14m

Data: Velocity profiles using four Braystoke rotor flowmeters in the lowest 2m of the water column.  
Two electro-magnetic current meters (for turbulence measurements)  
Television monitoring of the bed layer  
Suspended sediment profiles (pumped samples)

Measurement Heights: Not Specified

Review: Dyer carried out velocity profile measurements over a rippled bed in Start Bay, South Devon in September 1975, and found considerable variations in  $z_0$ .

During 1.5 tidal cycles  $z_0$  varied from about 0.01cm to about 5cm. As the profiles fitted well to a logarithmic distribution over most of the monitoring period, with acceleration/deceleration effects being small, all variations in  $z_0$  were attributed to moving grains of sediment near the bed and ripple size and orientation changes. Using the slopes of the profiles Dyer derived a relationship between  $z_0$  and  $u_*$  of the form  $z_0 \propto u_*^4$  for the period of initial ripple growth (Figure 8a). The lowest value of  $z_0$  occurred at the threshold of motion and was associated with the onset of flow separation. There was also some evidence for the occurrence of ripple flattening at peak tidal flow. Wilkinson (1986) included a time series plot of Dyer's  $z_0$  data (see Figure 3), highlighting the monotonic increase in  $z_0$  from one slack water to the next, spanning the ebb tide.

However, it is important to note that this measured variation represents a change in the form drag, since the lowest current meter rotor height was about 10cm (the ripple height was 2-3cm). Sediment transport measurements were also made, and this factor, and the associated effects of ripple formation are given as the reasons for the variation in  $z_0$ . Based on calculations for the variation in roughness due to a moving layer of grains, for the period of increase of roughness on the ebb tide the mechanism for increase was attributed roughly half to ripple geometry variations and half to the layer of moving grains close to the bed.

Dyer also observed an increase in  $z_0$  with a reduction in tidal range which he attributed to the formation of steeper ripples during less strong tidal conditions. The value of  $z_0$  was approximately constant during neap tide conditions where the sediment transport rate was low and hence the bedforms did not change their geometry during the tide.



### 3.6 Conwy Estuary, UK

Source: Knight DW, 1981

Location: Tal-y-Cafn, Section of Conwy Estuary, UK

Bed Description: Fine sand bed with some rocks, fine cohesive silt bank with grass near the HW mark

Water Depth: 1-6m

Data: Bed type and configuration  
Water levels and salinity  
Velocity profiles (not analysed for  $z_0$  variation), measured sequentially using a single Braystoke current meter, at 0.5-1.0m vertical intervals.

Measurement Heights: Not Specified

Review: Knight carried out field studies in a 1.2km reach of the Conwy Estuary, UK, measuring water level, velocity, salinity and water quality parameters. The velocity profiles were integrated to yield the depth-averaged velocity in the tidal reach. Manning and Darcy-Weisbach resistance coefficients were determined via an estimation of the energy slope from the data, and these were found to vary significantly with the stage of the tide, in agreement with the findings from Washbrook (1974). The effective roughness  $k_s$ , obtained from the Colebrook-White resistance equation, was shown to vary with water level (Figure 9) as well as flow speed, and also, though to a lesser extent, with the flow direction. However, the author conceded that without an analysis of the geometry of the bed it was impossible to give a more realistic determination to  $k_s$ . Hence the exact cause of any variation in  $z_0$  was equally indeterminate.



### 3.7 Oregon Shelf, USA

Source: Chriss TM and Caldwell DR, 1982

Location: Oregon Shelf, USA

Bed Description: Flat silty sand

Water Depth: 200m

Data: Velocity profiles over bottom 20cm using thermistor sensors  
Temperature  
Savonius current metering  
Suspended sediment using a beam transmissometer  
Pressure transducer  
Television monitoring of near bed.

Measurement Heights: Not Specified

Review: Chriss and Caldwell carried out velocity profiling in the lowest 20cm of the water column in 200m of water on the Oregon Shelf, USA, in a regime that exhibited marked form drag (confirmed by the existence of two distinct logarithmic profile regions (Figure 1)).

Evidence of a viscous sublayer in the lowest few centimetres was detected. Details of bed forms and other small scale features were not collected due to operational difficulties, but the roughness length  $z_0$ , calculated from the lower part of the profile varied from  $2.5 \times 10^{-4}$ cm to  $2.5 \times 10^{-3}$ cm. However, due to the existence of the laminar sublayer,  $z_0$  was quoted as a measure of the sublayer thickness and was not related to the grain size of the sediment.

The value of  $z_0$  obtained for the upper logarithmic profile was much larger (0.08 - 1.39cm) and was related to the additional influence of form drag.



### 3.8 Puget Sound, USA

Source: Gross TF and Nowell ARM, 1983

Location: Skagit Bay Estuary, Puget Sound, USA

Bed Description: Flat bed with silt, shell and stones

Water Depth: 12m minimum

Data: Bed configuration and sediment type  
Bed core samples  
Suspended sediment using transmissometer and sampling  
Profiling using ten fixed current meters up to 3.6m from the bed  
Conductivity and temperature

Measurement Heights: 0.19, 0.32, 0.42, 0.55, 0.70, 1.01, 1.58, 2.1, 2.72 and 3.6m

Review: Gross and Nowell made near-bed velocity profile measurements in Skagit Bay, an estuary in Puget Sound, and found that 'ten-minute averaged profiles had well-defined logarithmic regions throughout the tidal cycle, with a constant value of  $z_0$ .' The water depth was 12m, with a sharp thermocline and well-mixed bottom region.

The  $z_0$  and  $u_*$  calculations were based on the seven lowest meters, covering the bottom 1.5m of the flow. The lowest meter was 19cm above the bed and, due to the stony bed, an appreciation of only the total drag on the bed was expected (i.e. a segmented profile was not expected). Analysis of the results yielded curvature of the profiles in the upper part of the flow, associated with the wake flow region found in depth-limited flow, and hence logarithmic profiles were fitted to the lowest 1m.

It was found that 600 second averaging of the profiles was necessary and sufficient to obtain reasonable confidence intervals for the estimates of  $z_0$  (Figure 10): shorter averaging periods reduced the confidence, and longer intervals increased the variance due to the non-stationarity of the flow. Sediment transport was not detected and the morphology of the bed was not changing. Gross and Nowell also highlighted the 'great uncertainty' in the estimates of  $z_0$  as a result of extrapolation over two decades in the  $z$  level. 'The average value of  $z_0$  was 0.15cm and no systematic trend in  $z_0$  could be discerned within the error bands.'

### 3.9 The Jade Inlet, North Sea

Source: McLean SR, 1983

Location: Main entrance channel to Jade Inlet, North Sea

Bed Description: Fine and medium sand formed into ripples, megaripples and dunes

Water Depth: 20m, tidal amplitude 4m

Data: Current profiling using fifteen flow meters (rotors) grouped into seven levels, up to 2.1m above the bed  
Echo sounding of the bed along a 6m traverse

Measurement Heights: 0.12, 0.22, 0.36, 0.6, 1.0, 1.6 and 2.14m

Review: McLean presents an analysis of data collected over eight half-tidal cycles in 20m of water in The Jade Inlet, North Sea. The field exercise was in an area of known bed features comprising dunes, mega-ripples and ripples, although the true bed configuration was not surveyed. However, changes in form drag were not expected (as 'variations over the waveforms would be negligible'), and it was assumed that the horizontal positioning of the instrument frame was not important.

A number of potential errors in the data due to spatial variations were identified. The frame was lifted every 1-3 hours to remove fouling, and the ship position was known to alter by up to 10m, and furthermore orientation of the frame to the dominant current was not always achieved.

The analysis of the data indicated a variation in bed roughness length,  $z_0$ , giving rise to a minimum near the middle of the tidal cycle ( $z_0 \sim 0.1\text{cm}$ ), when the velocities were highest (Figure 11). Curvature of the profile was suspected due to the development of the boundary layer, and the data was re-assessed taking the lowest values only. This reduced the variation, but the minimum was still evident. The direct influence of sediment transport was ruled out as a valid mechanism for this effect since it would predict higher roughness at mid cycle (high velocity), and lower roughness at slack water.

Finally, the variations in  $z_0$  were interpreted according to the geometry of the bed topography, in particular on the orientation of the small ripples on the larger mega-ripples. Profiling of the bed appeared to indicate an adjustment of the shape of these ripples through the tide, although no attempt was made to quantitatively correlate the scale of the ripples to the roughness length and their disappearance at peak flow.



### 3.10 Start Bay, UK

Source: Soulsby RL, Davies AG and Wilkinson RH, 1983

Location: Start Bay, Devon, UK

Bed Description: Fine sand with ripples

Water Depth: 20m

Data: Profiling using six current meters up to 13m from the bed. Only 5 of 6 current meters provided useful data.  
Bed features using light-rod-camera technique  
Bed samples  
Sand transport using piezo-electric impact probe.

Measurement Heights: Not Specified

Review: Velocity profiles measurements were made in Start Bay in October 1979 in water 20m deep. Data for eight consecutive spring tides was ensemble-averaged in order to analyse the variations in  $z_0$  and  $u$ . (Figure 12). Logarithmic profiles fitted to the lowest two meters at 1.5m and 2.5m above the bed yielded a variation in  $z_0$  spanning two orders of magnitude, with a maximum of about 1cm.

Over the tidal cycle  $z_0$  remained relatively constant from 2.5 hours after high water (HW) to HW+5.5 hours, and the value of 1cm was considered reasonable for the rippled bed monitored. The periods around slack water showed a reduction in  $z_0$ , and in these cases it was assumed that the profile deviated substantially from the logarithmic relationship. Another reduction in  $z_0$  occurred around the time of peak current, which was interpreted as an effect of sediment transport.

In contrast to the findings of Dyer (1980) no relationship between  $z_0$  and  $u$  was found and  $z_0$  did not increase monotonically through the tide as shown in Figure 3.



### 3.11 Start Bay, UK

Source: Wilkinson RH, 1986

Location: Adjacent to Skerries Bank, Start Bay, UK

Bed Description: Medium sand with fine shell, rippled

Water Depth: Not Specified

Data: Profiling using six Ott impeller current meters, up to 2m from the bed  
Suspended sediment concentrations from pumped samples  
Bed features using light-rod-camera shadow technique  
Television monitoring of the bed.

Measurement Heights: Not Specified

Review: Wilkinson analysed velocity profile data from Start Bay at the same site as Myer (1980) over the ebb phase of three consecutive spring tides. He found a consistent trend during each tide of a progressive increase in  $z_0$  from about 0.5cm at slack water to 1.3cm at the end of the ebb (see Figure 4). The average  $z_0$  was consistent with accepted values for the bed material (from Table 1,  $z_0$  for rippled sand = 0.6cm) and a number of reasons for the variation were considered.

The effect of non-stationarity was ruled out as the profiles showed little curvature, with a correlation coefficient of 0.98. Likewise, stratification by sediment in suspension was also discounted as the variation in  $z_0$  and concentration did not correlate well. The measured changes of ripple shape (wave length, height, skewness of slope) over 0.6m of seabed did not appear to contribute to significant changes in  $z_0$ , and the effects of flow acceleration, though giving the correct qualitative response according to theory, did not account for the scale of the variation measured.

As a result this data set highlights the need for further research into the basic processes regarding velocity profiles in the bottom boundary layer, in order that a more thorough understanding may be achieved.

### 3.12 Vesjsnaes Channel, Baltic Sea and Jade Inlet, North Sea

Source: Schauer U, 1987

Location: Vesjsnaes Channel: Part way between Baltic Sea and the Kattegatt  
Jade: Main entrance channel to the Jade Inlet

Bed Description: Vesjsnaes Channel; Mud, fine sand with flints. Jade Sea;  
Sand with megaripples

Water Depth: Greater than 20m at both sites

Data: Profiling using six Savonius current meters  
Supplementary Aanderaa current meters (at Vesjsnaes)  
Four thermistors  
Four conductivity cells  
Pressure sensor

Measurement Heights: Vesjsnaes Channel, Savonius rotors 0.29, 0.44, 0.92, 1.65, 2.71 and 3.43m; Aanderaa current meters 0.15, 0.5, 0.82, 1.14, 1.69, 2.47, 3.75 and 5.0m; Jade Inlet, Savonius rotors 0.18, 0.33, 0.81, 1.54, 2.6 and 3.32m

Review: Schauer carried out field experiments in two hydrographically different regions, measuring velocity profiles in the bottom 3.5m of water (both sites were deeper than 20m). Logarithmic velocity profiles were obtained with a correlation coefficient greater than 0.9 for most of the profiles. Values of  $z_0$  were very high (of the order of centimetres) and showed a systematic reduction with increasing velocity (Figure 13), a similar result to that found in the North Sea by Vincent and Harvey (1976) and by other workers elsewhere. Notably, the bed surface was not monitored during the field exercise under review and the effects of variation in geometry of small-scale ripples on the larger bedforms was not proposed as a mechanism for the reduction in  $z_0$ , because the absolute value for the roughness was too high.

The velocity profiles were concave which made a significant difference in the estimation of  $z_0$  depending on the number of measurement levels considered, reducing it by an order of magnitude when the upper levels were ignored. The reasons for deviation from a logarithmic profile were considered, and non-stationarity, and the influence of bedforms were ruled out at both sites. At the Vesjsnaes Channel site the bed was flat and the acceleration was low. At the Jade site the profiles were concave all the time, negating the argument for acceleration being important, and the measured decrease in roughness with increasing velocity was in disagreement with the theory of Smith and McLean (1977).

### 3.12 Schauer (cont'd)

The effect of suspended sediment was investigated according to an adaptation of the Monin-Obukov theory by Taylor and Dyer (1977), using approximate values as the suspended sediment concentration was not monitored. This yielded a satisfactory reason for the concave curvature of the profiles, but did not explain the reduction in  $z_0$  with increasing velocity.

Finally, a mechanism for the large reduction in  $z_0$  with increasing velocity and the concave profiles was given by a modification of Prandtl's law of the wall according to Blackadar (1962), adapted for shallow water flows.

### 3.13 Solent, UK

Source: Heathershaw AD and Langhorne DN, 1988

Location: West Solent, UK

Bed Description: Sandy gravel, mainly level

Water Depth: Less than 20m

Data: Bed configuration from side-scan sonar  
 Frame 1: Profiling using six Ott current meters up to 1.8m above the bed  
 Television camera and hydrophones (for Self Generated Noise)  
 Frame 2: Profiling using four Ott current meters up to 1m above the bed  
 Television camera and gravel trap

Measurement Heights: Frame 1 0.1, 0.25, 0.4, 0.65, 1.0 and 1.8m  
 Frame 2 0.1, 0.22, 0.46 and 1.0m

Review: Heathershaw and Langhorne carried out near-bed velocity profiling measurements over a gravel bed in the West Solent. They calculated a 'relatively constant' value for  $z_0$  over a tidal cycle for weak bedload or no motion conditions, quoting a geometric mean value of 0.3cm.

Rough turbulent flow conditions were expected to prevail over most of the tidal cycle. The main channel is sheltered from the dominant wave direction and hence the site represented a predominantly tidal environment.

The gravel bed contained some irregular but small-scale topographic relief, but was devoid of organised bedforms and was predominantly level. Irregular topography, assumed to occur upstream of the monitoring positions, was given as an explanation for an internal boundary layer producing a change in slope of the velocity profiles at about 0.6m above the bed. Taking the lowest 4 or 6 points of such profiles, estimates of  $u_*$  and  $z_0$  were obtained. Successive deployments of the measuring rig indicated small changes in  $z_0$  were produced, which were attributed either to actual changes in seabed roughness (according to particle size) or to uncertainty in the meter heights relative to the bed. However, during an individual monitoring period the roughness did not vary significantly (Figure 14, 2130-0000BST).

In one deployment (Figure 14, around 1930 BST) the roughness length was observed to decrease by two orders of magnitude over a two hour period characterised by unusually intense bedload movement. This was the opposite to the behaviour predicted by the bedload model of Smith and McLean (1977), Equation 4.

### 3.14 Celtic Sea, UK

Source: Soulsby RL, 1990

Location: Celtic Sea

Bed Description: Silty sand, rippled

Water Depth: 120m

Data: Current meter profiling

Measurement Heights: 1.0, 2.5, 6.0, 15, 30, 70 and 90m

Review: Soulsby presents a data set collected above a rippled sand bed in the Celtic Sea over 11 tidal cycles (water depth 120m). The ensemble averaged data set yields a variable  $z_0$  ranging from 0.1cm to about 1.5cm (Figure 15). This variation was explained in terms of the varying orientation of the flow in the open tidal ellipse relative to the crests of the rippled bed, since the two extremes related well to average values for unrippled and rippled beds respectively. At times of maximum flow the current was flowing normal to the crests and at times of minimum flow parallel to the crests.

## 4 Discussion and conclusions

This report has presented an extensive review of currently available field measurements of the seabed roughness length  $z_0$ . Typical values of  $z_0$  can be assigned to the different types of seabed (Table 1) but in addition where the seabed sediment is potentially mobile then the value of  $z_0$  can vary in a systematic fashion. This is particularly true of tidal flow over rippled sand beds where, once threshold conditions are exceeded, the presence of bed load transport, changing ripple geometry and sediment in suspension can cause real or apparent changes in  $z_0$  through the tidal cycle. At other times when sediment is not in motion apparent changes in  $z_0$  can be produced by the influence of topography or non-stationarity in the flow. A summary of findings is given in Table 2.

Most measurements in the sea will provide estimates for the total drag and total roughness length because the current meters cannot be placed closer than about 10cm above the bed, ie outside the region of the flow controlled by the roughness of the grains or the viscous sub-layer thickness. Detailed velocity profile measurements can be made for heights of less than 10cm above the seabed but require very sophisticated instrumentation such as was used by Chriss and Caldwell (1982). Measurements in the bottom 10cm can be made in the laboratory (eg Kapdasli and Dyer, 1986).

The following observations for the behaviour in  $z_0$  have been reported for

### GRAVEL BEDS:

- (a)  $z_0$  remains constant through the tide over immobile beds of sandy gravel for conditions of rough turbulent flow (eg Dyer, 1970; Heathershaw and Langhorne, 1988; Gross and Nowell, 1983) and over rocky substrates (eg Sternberg, 1968).
- (b)  $z_0$  for sandy gravel beds can be reduced by two orders of magnitude under conditions of unusually intense bedload transport (eg Heathershaw and Langhorne, 1988). This phenomenon has not been explained satisfactorily but could be due to a reduction in the local bed level.

### SAND BEDS:

- (c)  $z_0$  increases monotonically through the period of half a tidal cycle (eg Dyer 1980; Wilkinson, 1986). No satisfactory explanation for this behaviour has been put forward.
- (d)  $z_0$  increases in proportion to the increasing shear velocity as ripples are built up (eg Dyer, 1980). This supposes a reasonable link between shear velocity - sediment transport - ripple geometry change - hydrodynamic roughness variations.
- (e)  $z_0$  is reduced at periods of peak tidal flow as ripples become washed out (eg Dyer, 1980; McLean, 1983; Soulsby et al, 1983). This phenomenon is supported by observations of the changing bedforms.

- (f) Reductions in  $z_0$  with increasing flow velocity have also been measured by Charnock (1959), Washbrook (1974), Knight (1981) and Schauer (1987). These measurements were taken without any observations of the seabed.
- (g)  $z_0$  varies with time under an open tidal ellipse as the direction of flow changes with respect to the orientation of the ripple crests (Soulsby, 1990).

Therefore, the data highlight the complex behaviour of  $z_0$  for a sand bed through a tidal cycle. The changes in  $z_0$  can be appreciable but given the complex interactions of flow, bedforms and sediment transport there is no one parameter alone that has been found yet to satisfactorily explain the variations that have been observed. In particular, Wilkinson (1986) presented the results of extensive investigations to explain the behaviour in (c) above and found no satisfactory explanation. Importantly, in relation to (c), Wilkinson questions how the value of  $z_0$  gets back to its initial value at the start of the succeeding half cycle.

A further unexplained observation is that although the value of  $z_0$  can increase by two orders of magnitude during the tide the ripple geometry will certainly not increase by this amount (Soulsby et al, 1983). It seems more likely that the interaction of all the boundary layer parameters will produce quite different behaviour above the sediment-water interface for only small changes of the controlling parameters around certain critical conditions. This means that the behaviour of  $z_0$  at slightly different sites could be very different.

## ***5 Recommendations for a laboratory experiment***

Within the present contract a series of well controlled laboratory experiments will be set up to make detailed observations of the value of  $z_0$  for a mobile sand bed through a simulated tidal cycle and to determine the causes of (c) to (f) above.

The following will be addressed in setting up the experiment:

- (a) use a quartz sand that ripples naturally, amplitude ~ 2cm, wave length ~ 20cm.
- (b) perform the experiments at prototype tidal time scales with rectilinearly reversing flows and prototype velocities to remove any scale and flow alignment effects.
- (c) perform the experiments in shallow water to reduce the influence of non-stationarity on the measured velocity profiles.
- (d) perform the experiments in deep enough water so that the Froude Number is low for the velocities used ( $Fr < 0.3$ ) and hence the bedforms produced are representative of conditions found in the sea.
- (e) perform the experiments in deep enough water so that both the skin friction and total drag velocity profiles can be measured (evidence from Chriss and Caldwell, 1982 and Kapdasli and Dyer, 1986).

- (f) keep the width to depth ratio of the flow to between 3 and 5 to minimise secondary circulation in the flow ( $>3$ ) and to avoid the development of non-uniform bed conditions ( $<5$ ).
- (g) remove the complications imposed on the velocity profile by suspended sediment induced stratification and work, initially at least, with a coarse sand that is transported only as bedload.

The following parameters will be measured in the laboratory:

- (h) the grain size distribution of the bed material.
- (i) the water temperature.
- (j) the threshold shear stress for sediment motion and roughness length over a flat bed.
- (k) the threshold shear stress and roughness length at the ripple crest and trough.
- (l) the spatially averaged total threshold shear stress and roughness length over a rippled bed.
- (m) frequent, extensive and detailed surveys of the ripple bedforms.
- (n) frequent measurements of the vertical velocity profile to determine the total drag and roughness length (and skin friction values if possible).
- (o) observations and photographs of the evolution of the sediment bed.
- (p) ripple migration rates where possible.

An experimental programme is being set up based upon (a) to (p) above and the results of the measurements will be reported elsewhere.

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## Tables



**Table 1** Typical values for the roughness length  $z_0$  and drag coefficient  $C_{100}$  for different bottom types. Taken from Soulsby (1990)

Bottom Type	$z_0$ (cm)	$C_{100}$
Mud	0.02	0.0022
Mud/sand	0.07	0.0030
Silt/sand	0.005	0.0016
Sand (unrippled)	0.04	0.0026
Sand (rippled)	0.6	0.0061
Sand/shell	0.03	0.0024
Sand/gravel	0.03	0.0024
Mud/sand/gravel	0.03	0.0024
Gravel	0.3	0.0047

**Table 2 Summary of results regarding values of  $z_0$  found from near-bottom velocity profiles and the corresponding seabed conditions**

Data set	Bed type	Bed features	Mean $z_0$ (cm)	$z_0$ range (cm)	Attribution of variation by author	Trend	Other remarks
Anglesey Chamock 1959	Sand	Firm sand, ripples, some shingle	0.1, 0.3	0.1 - 2.4	Changes in ripple geometry	Constant with a reduction in $z_0$ after peak flow	
Puget Sound Stenberg 1968	Rock, shell, gravel and sand	Sand formed into irregular roughness and small ripples	0.1	$10^{-5}$ - $10^1$	Profile curvature (boundary layer growth)	No trend	Variance in $z_0$ increases with reducing Re
Solent Dyer 1970	Coarse sand, gravel	Dunes	0.15	0.001 - 5	Different bed material (variations considered realistic)		NB variations are not at fixed location - influence of bed forms apparent
Start Bay Dyer 1980	Medium sand with fine shell	Ripples		0.01 - 5	Sediment transport, ripple formation	$z_0 \propto u_*^4$ Increase in $z_0$ from 0.1-3.3cm observed on ebb tide, plotted in Wilkinson (1986)	
Oregon Shelf Chriss and Caldwell 1982	Silty sand	Flat	$6.27 \times 10^{-4}$  0.4*	$2.5 \times 10^{-4}$ - $2.5 \times 10^{-3}$  0.08 - 1.39	Viscous sublayer  Upper log region	$z_0$ dependent on sublayer depth	Roughness lengths similar to flow over sparse roughness
Puget Sound Gross and Nowell 1983	Silt, shell, stones	Flat	0.15	0.1 - 0.3	Measurement errors	No trend	$z_0$ not expected to vary
Jade Inlet McLean 1983	Fine and medium sand	Ripples, dunes, megaripples		$\approx 0.1$ - 0.6	Ripple formation	Minimum $z_0$ at mid tide (peak flows)	$z_0$ related to spatially averaged bed level

\*geometric mean

**Table 2 Continued**

Data set	Bed type	Bed features	Mean $z_0$ (cm)	$z_0$ range (cm)	Attribution of variation by author	Trend	Other remarks
Start Bay Soulsby, Davies and Wilkinson 1983	Fine sand	Ripples		0.001 - 1	Profile curvature and sediment transport	Reduction in $z_0$ around slack water. Reduction in $z_0$ at peak current	Also discusses data for Wilkinson (1986)
Start Bay Wilkinson 1986	Medium sand with fine shell	Ripples	0.6	0.5-1.3 (smoothed data)	Unresolved	General increase in $z_0$ from 0.5-1.3cm through an ebb tide	Non-stationary effects suspected
Vesjsnaes and Jade Schauer 1987	Vesjsnaes: mud, fine sand, flints Jade: sand	Megaripples	$\approx 1$	0.1 - 3	Curvature of profiles at low velocity	$z_0$ reduction with increasing velocity	
Solent Heathershaw and Langhome 1988	Sandy gravel	Mainly level	0.3*			Constant $z_0$ measured	$z_0$ was observed to decrease by nearly 2 orders of magnitude during periods of intense bedload movement
Celtic Sea Soulsby 1990	Silty sand	Ripples	$\approx 1$	0.1 - 1.5	Flow orientation, open tidal ellipse	Low $z_0$ for flow along ripple crests. High $z_0$ for flow across crests	Short review of $z_0$ variability

\*geometric mean



**Table 3** *Current profile data of Charnock (1959) observed in Red Wharf Bay, July 5 1957*

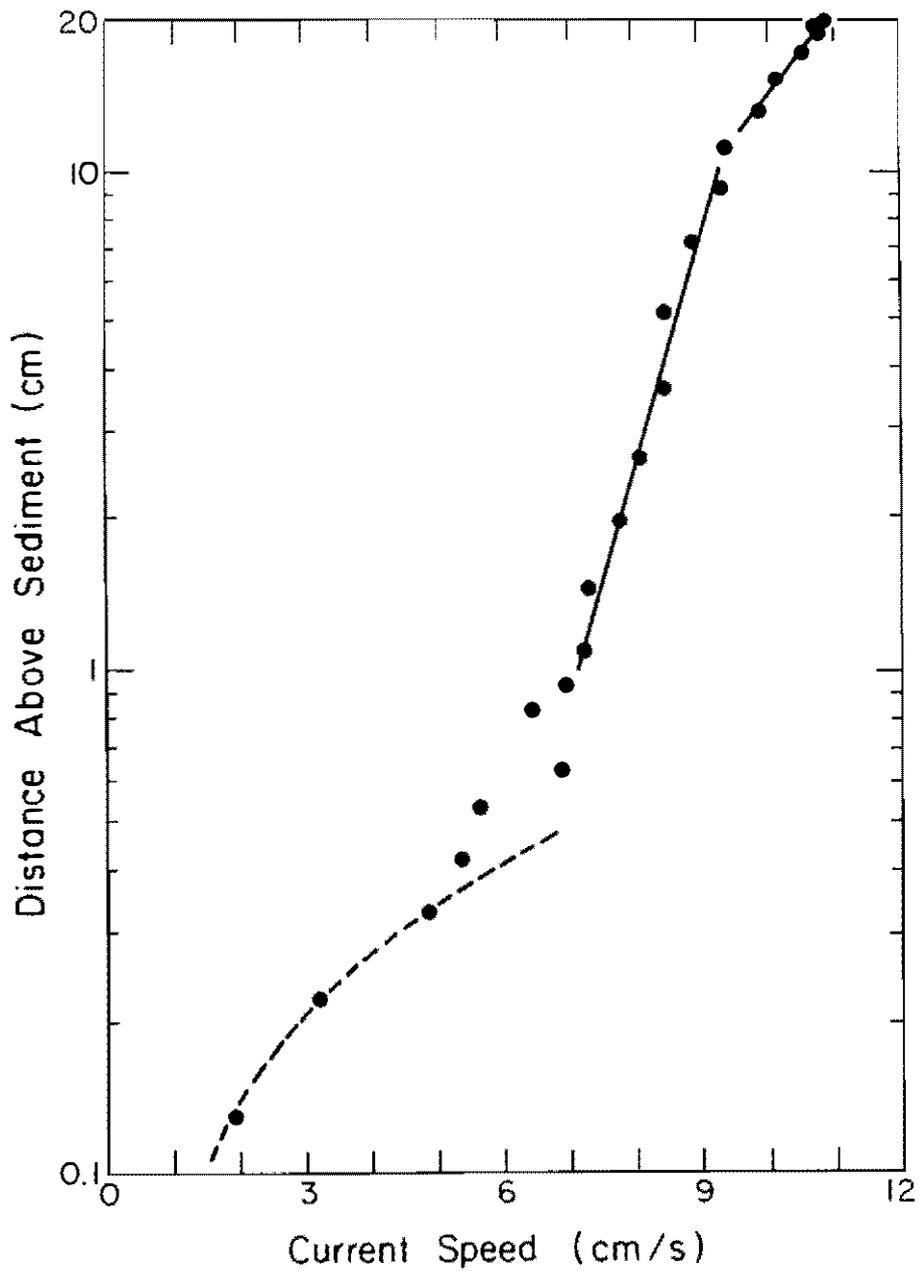
Profile	a	b	c	d	e	f	g	h	i	j	k	l
Time GMT	1820	1830	1840	1850	1900	1910	1920	1950	2000	2010	2020	2030
$U_{200}$ (cm/s)	31.2	29.8	31.0	34.6	37.3	40.8	33.4	25.9	35.6	28.1	37.3	38.9
$U_*$ (cm/s)	2.8	1.7	2.0	2.2	2.3	2.3	1.8	1.5	2.2	2.4	2.5	2.4
$z_0$ (cm)	2.42	0.16	0.39	0.39	0.34	0.19	0.10	0.23	0.30	1.83	0.45	0.33
$10^3 C_{100}$	11.6	3.9	5.2	5.2	4.9	4.1	3.4	4.3	4.8	10.0	5.5	4.9

$U_{200}$  is current speed at 2m above seabed  
 $U_*$  is friction velocity  
 $z_0$  is roughness length  
 $C_{100}$  is drag coefficient related to velocity at 1m



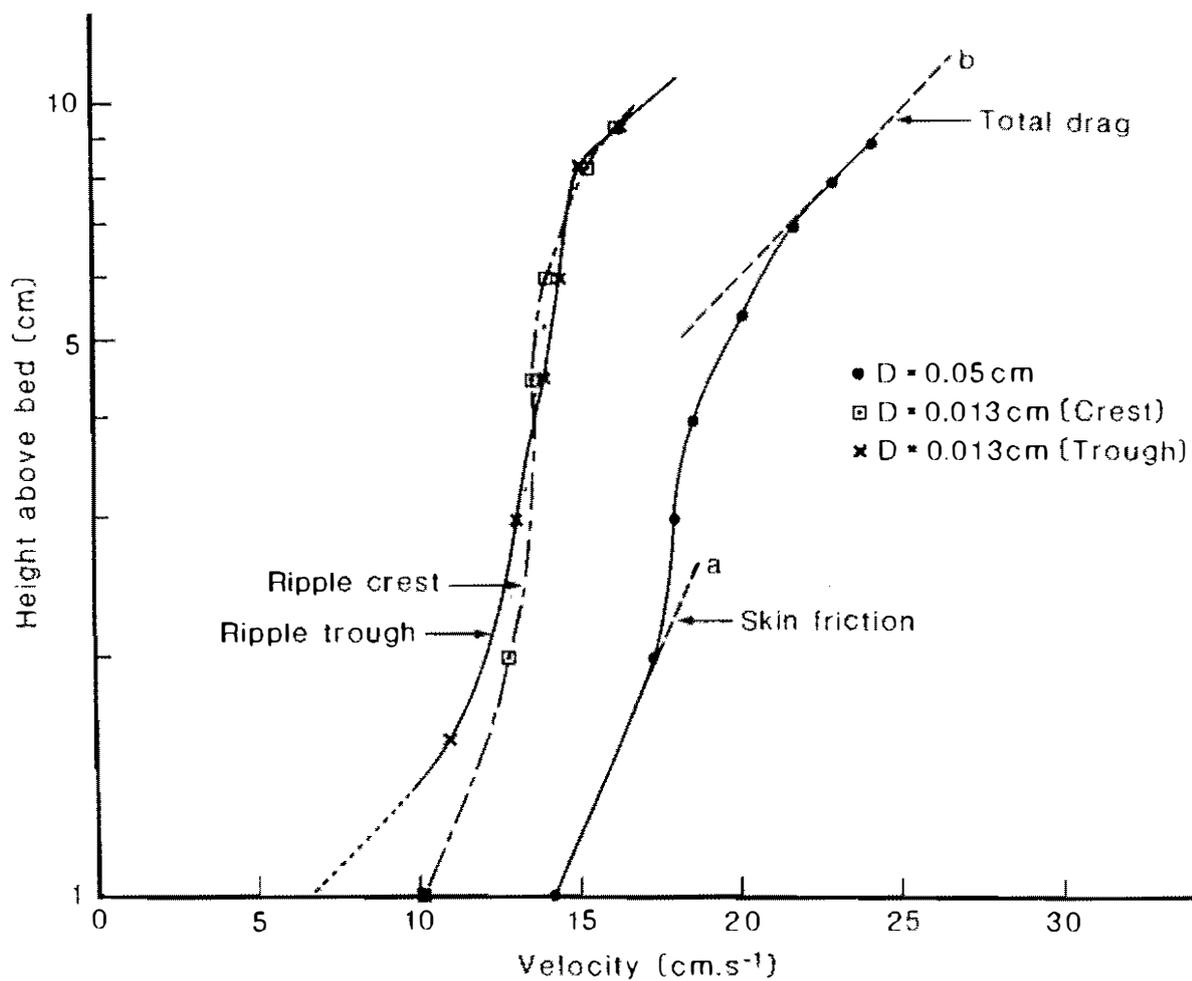
## Figures





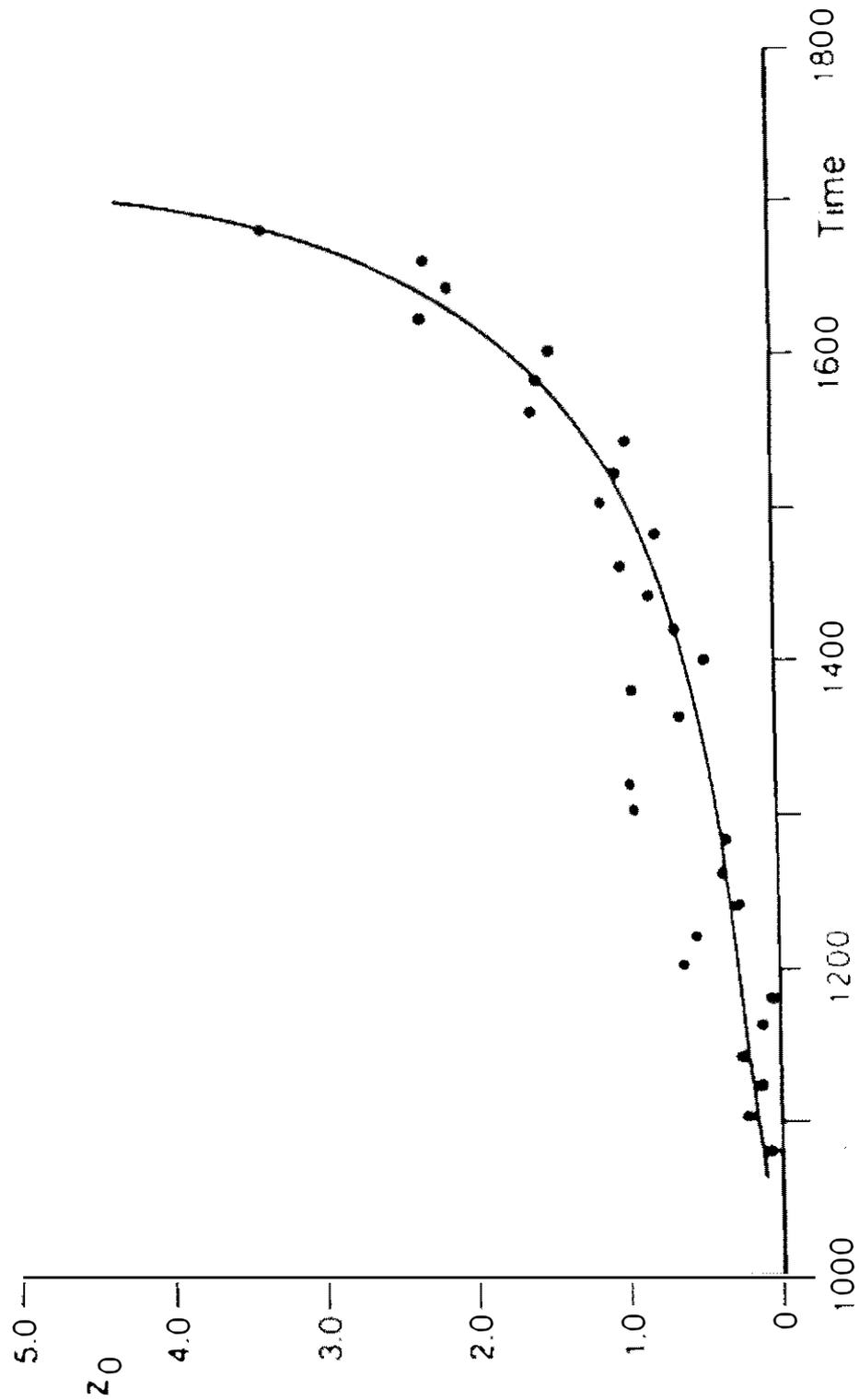
Typical mean velocity profile for the October 1978 experiment. The dashed line represents a linear fit in the viscous sublayer. The solid lines represent fits to the data in the lower and upper regions of the velocity profile. The region between the dashed line and the lower solid line is the so-called 'buffer' region where the velocity profile obeys neither a linear nor a logarithmic law.

**Figure 1** An example of the composite form of the mean velocity profile measured on the Oregon Shelf. From Chriss and Caldwell, 1982, *J. Geophys. Res.*, 87, 4148-4154. Copyright by the American Geophysical Union

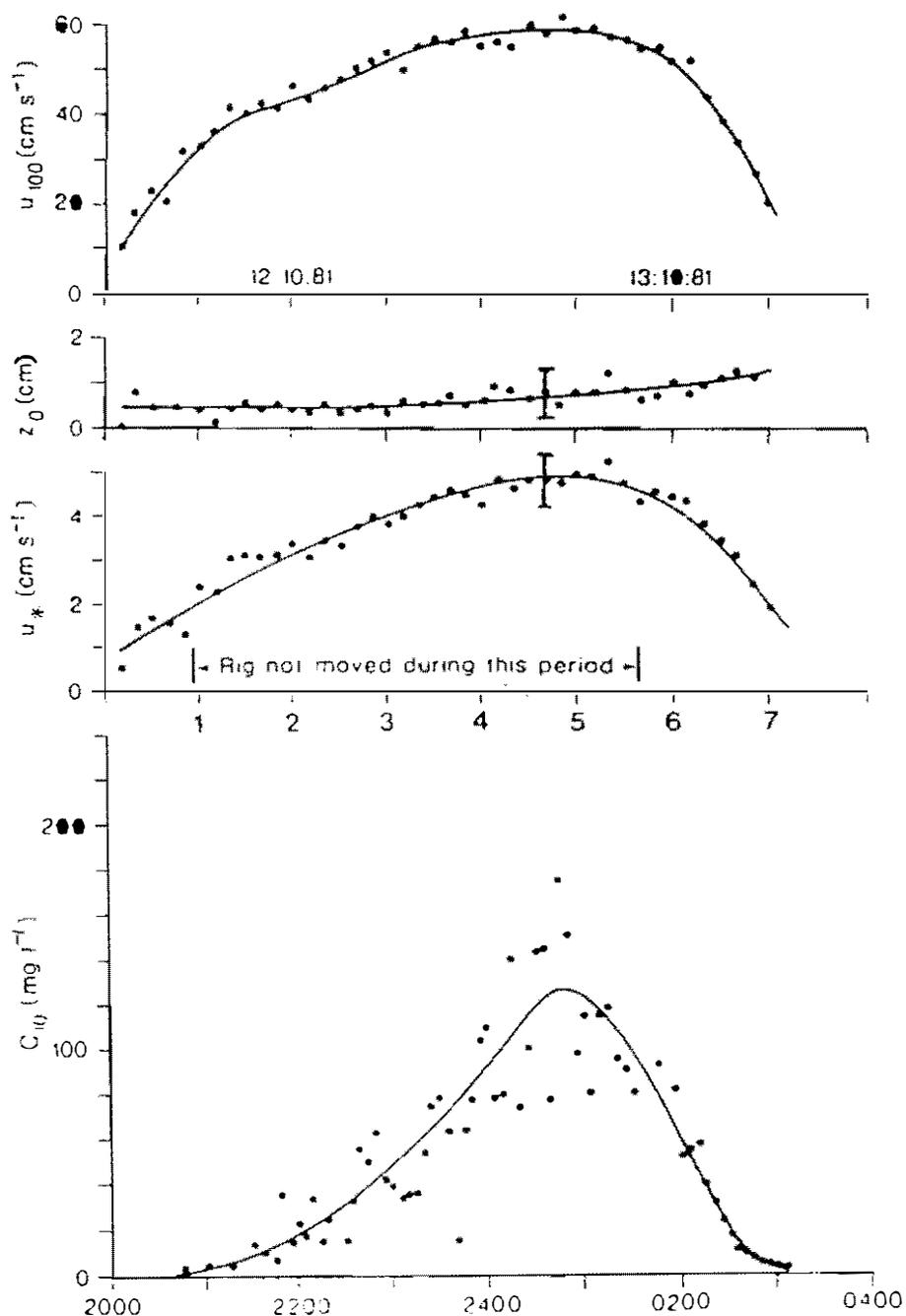


Typical velocity profiles obtained by laboratory tests on the rippled bed.  
**Curve a** = skin friction and **Curve b** total drag.

**Figure 2** An example of the composite form of the mean velocity profile measured over a rippled sand bed in the laboratory. From Kapdasli and Dyer, 1986, *Geo-Marine Letters*, 6, 161-164. Reproduced by permission of Springer-Verlag.

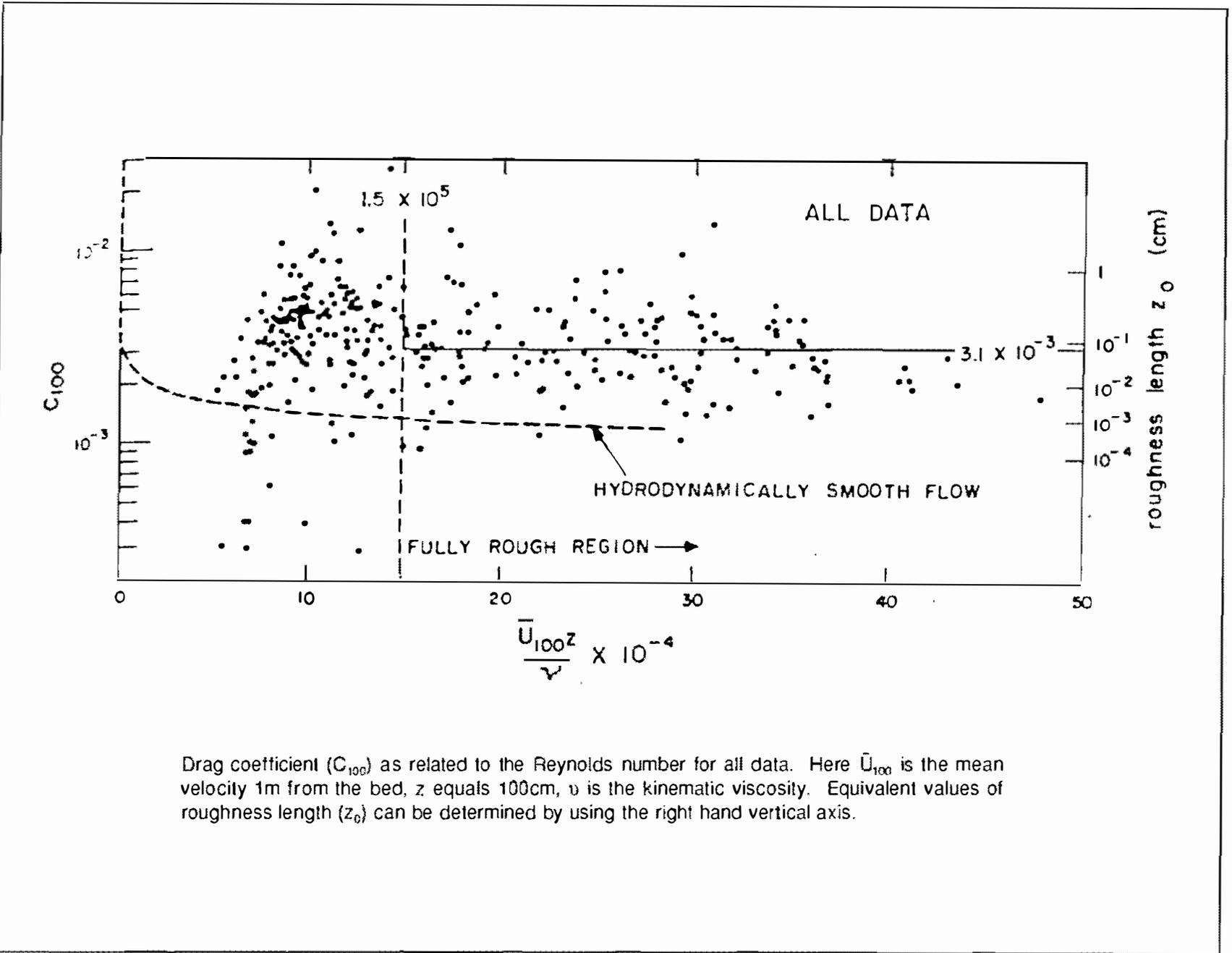


**Figure 3** Variation in  $z_0$  measured at Start Bay, Devon, 1975. From Wilkinson, 1986, *Geo-Marine Letters*, 5, 231-239. Reproduced by permission of Springer-Verlag.



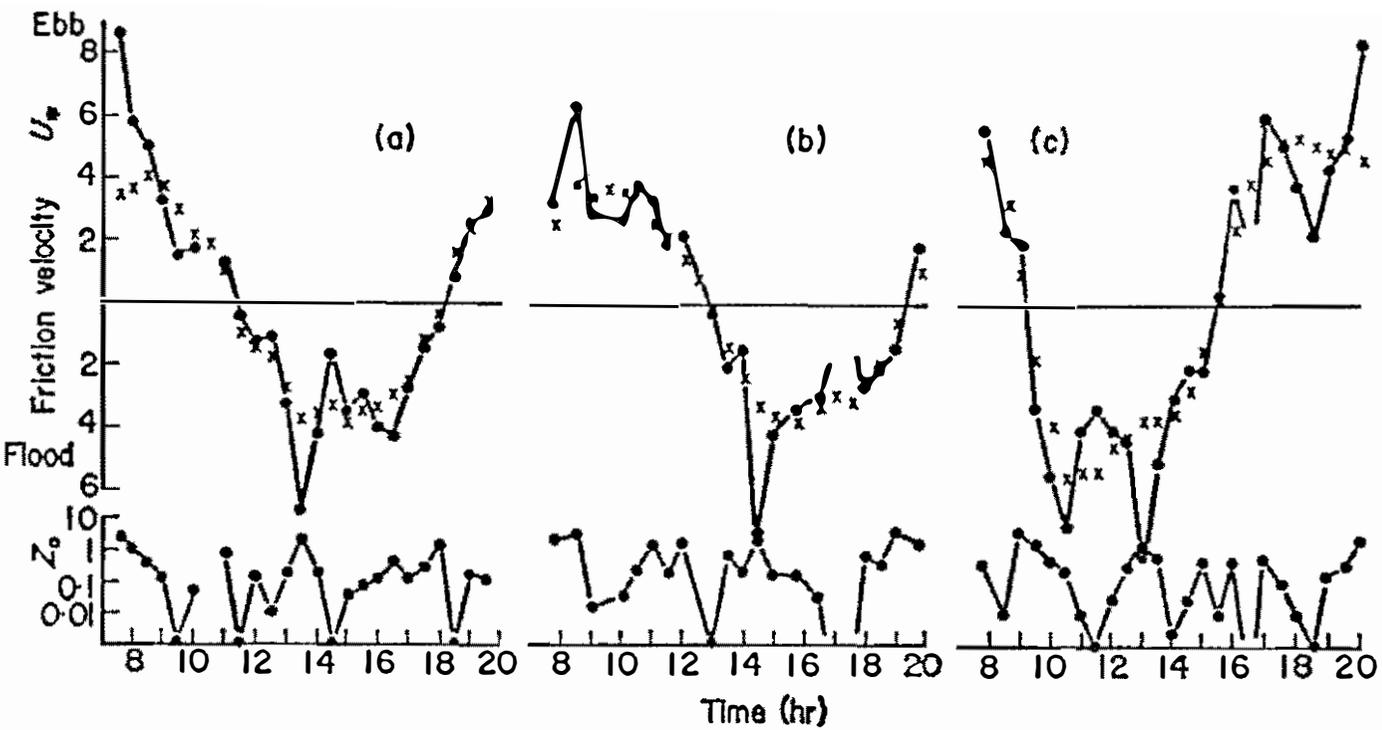
Time series of flow data and mean suspended sediment concentration.  $u_{100}$  is velocity at 1m above the bed,  $z_0$  roughness length,  $u_*$  the friction velocity, and  $C_{10}$  the suspended sediment concentration 10cm above the bed.

**Figure 4** Time series of field measurements at Start Bay, Devon, 1981, from Wilkinson, 1986, *Geo-Marine Letters*, 5, 231-239. Reproduced by permission of Springer-Verlag.



Drag coefficient ( $C_{100}$ ) as related to the Reynolds number for all data. Here  $\bar{U}_{100}$  is the mean velocity 1m from the bed,  $z$  equals 100cm,  $\nu$  is the kinematic viscosity. Equivalent values of roughness length ( $z_0$ ) can be determined by using the right hand vertical axis.

Figure 5 Variation of the drag coefficient in tidal channels with Reynolds Number. From Sternberg, 1968, Marine Geol., 6, 243-260. Reproduced by permission of Elsevier Science Publishers BV.



Variation of  $U_*$  ( $\text{cm s}^{-1}$ ) and  $Z_0$  (cm) calculated from the velocity profiles.  $\times U_*$  ( $\text{cm s}^{-1}$ ) calculated from velocity 3.81m above sea bed using  $Z_0$  of 0.15cm. (a), (b), and (c) are for 3 different locations.

**Figure 6** Time series of shear velocity and roughness length measured in the Solent. From Dyer, 1970, Geophys. J. Roy Astron. Soc, 22, 153-161. Reproduced by permission of Blackwell Scientific Publications Ltd.

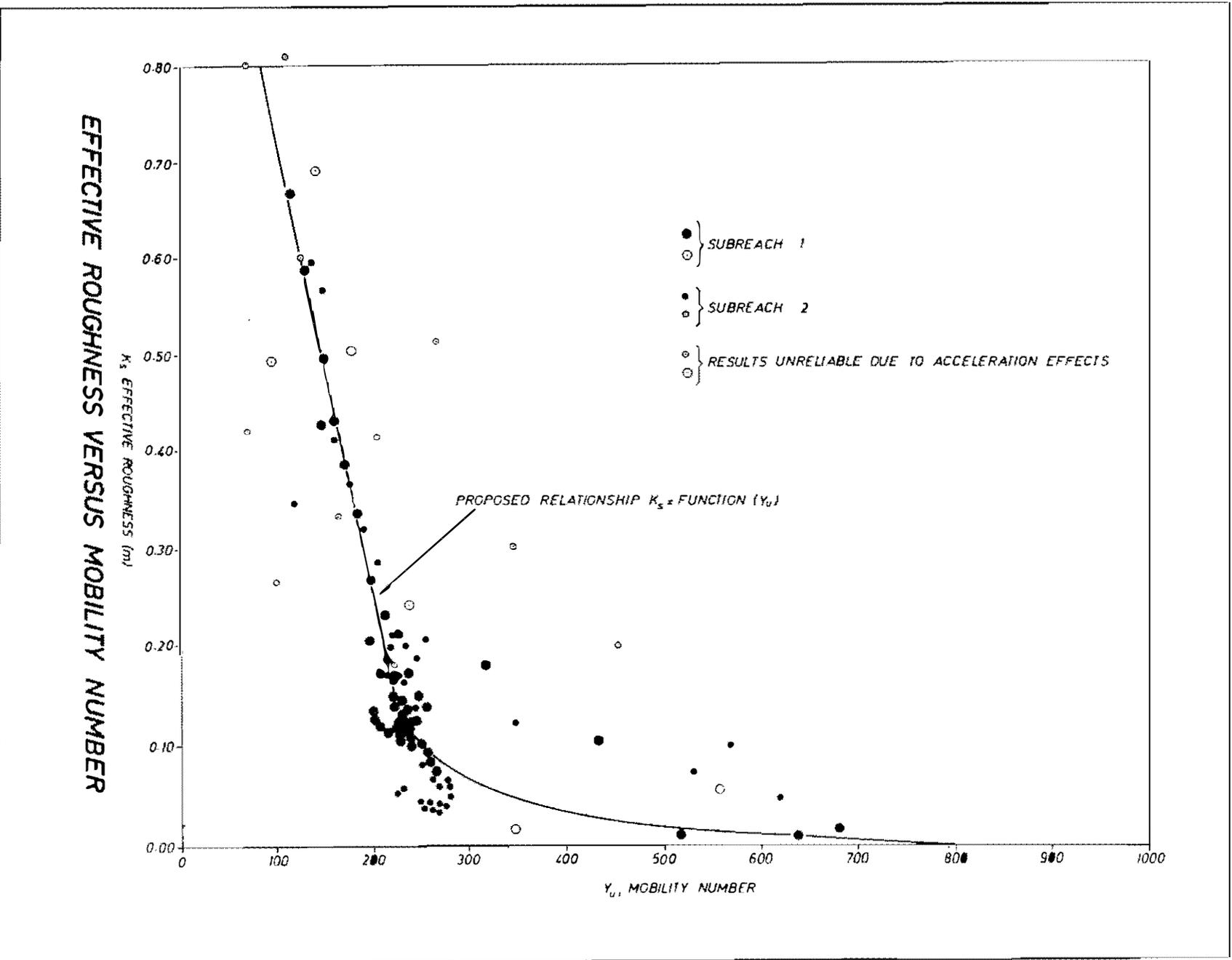
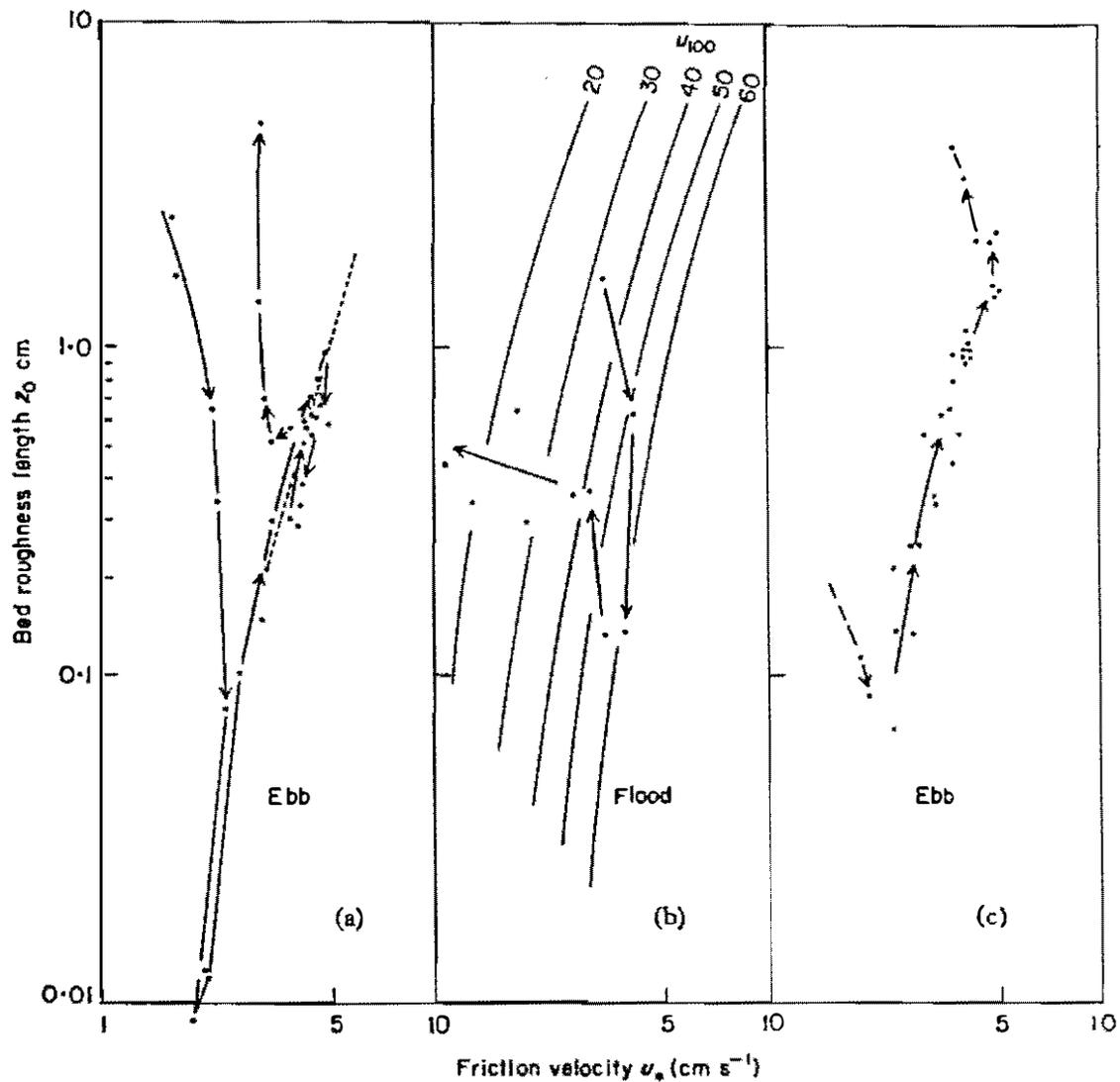
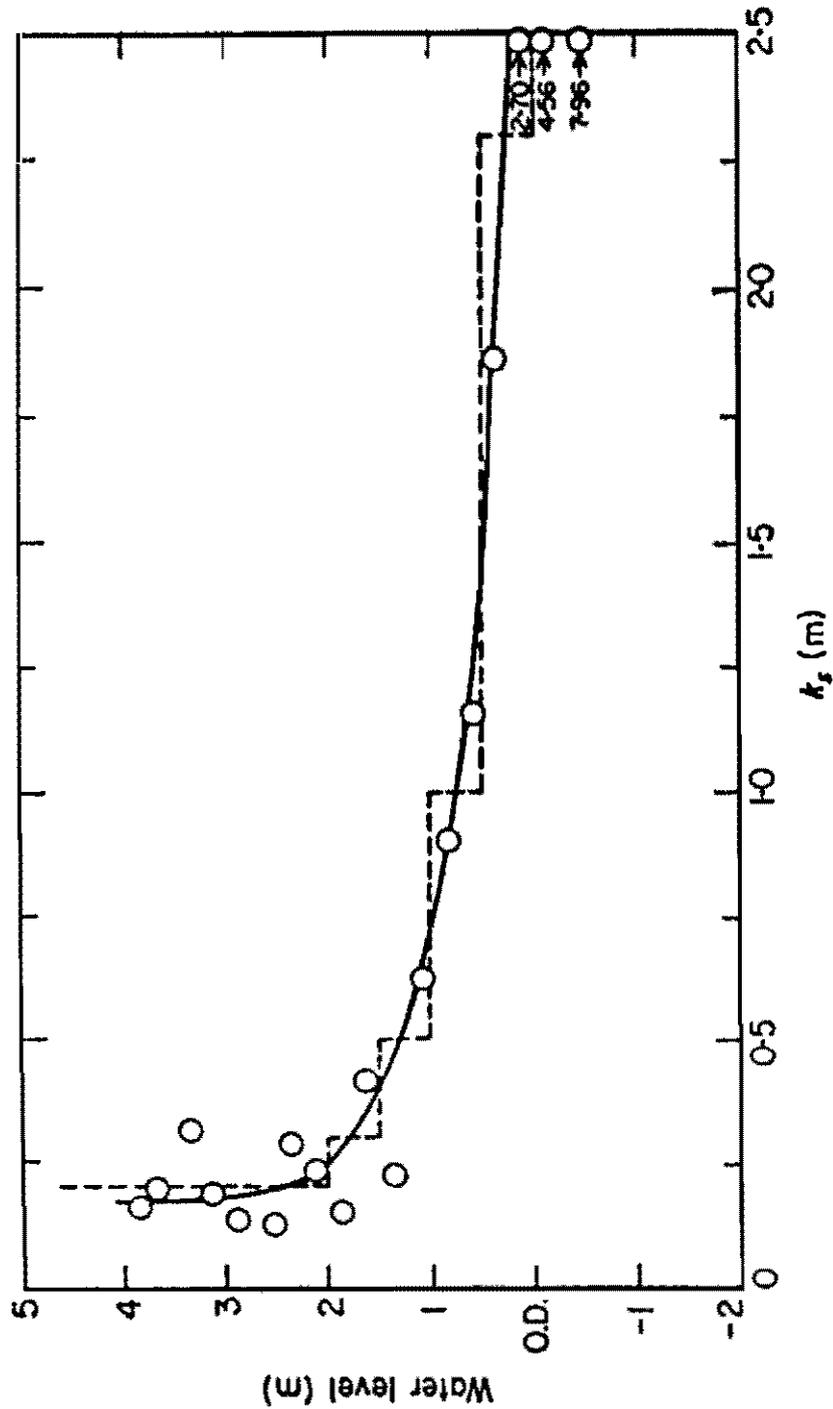


Figure 7 Variation in the effective roughness of a mobile bed with mobility number as measured in a tidal channel. Reproduced from Washbrook (1974).



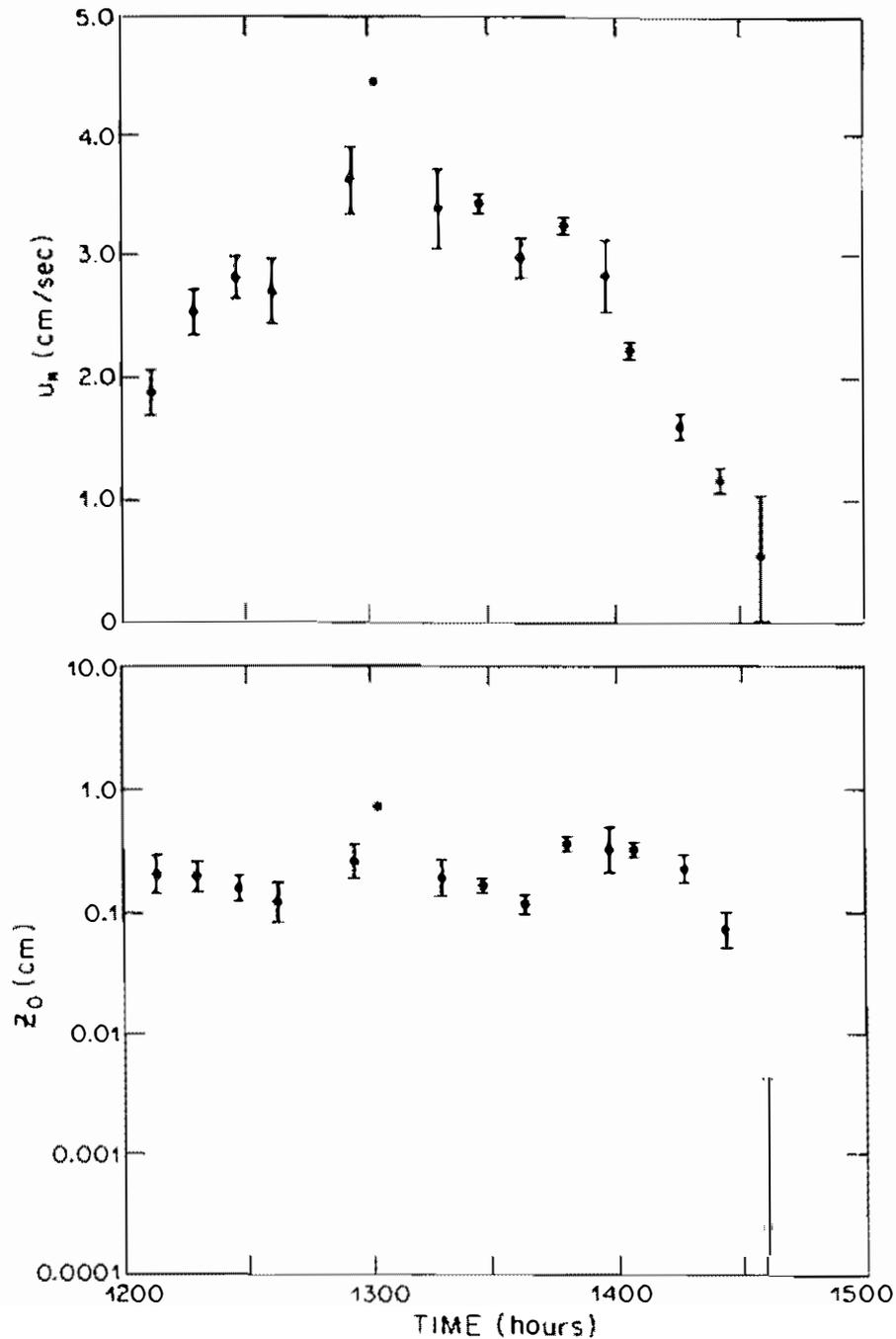
Variation of bed roughness length with friction velocity, during 1½ tidal cycles. (a) Dashed line has the formula  $z_0 = 0.0017U_*^4$ . (b) Fine lines are isopleths of  $u_{100}$  ( $\text{cm s}^{-1}$ ).

**Figure 8** Variation in the roughness of a mobile sand bed with friction velocity, Start Bay, Devon. From Dyer 1980, *Estuarine and Coastal Marine Science*, 10, 181-199. Reproduced by permission of Academic Press (London) Ltd.



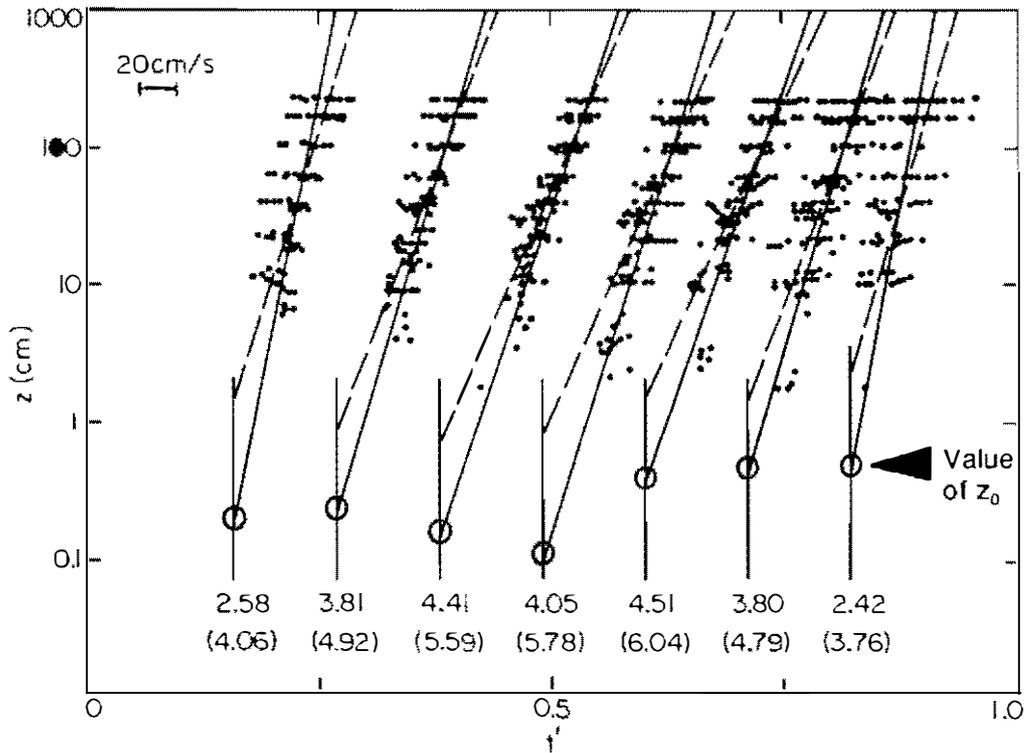
Variation in the Nikuradse roughness parameter,  $k_s$ , with water level

Figure 9 Variation in the effective roughness of a tidal channel with water level. From Knight, 1981, Estuarine, Coastal and Shelf Science, 12, 303-322. Reproduced by permission of Academic Press (London) Ltd.



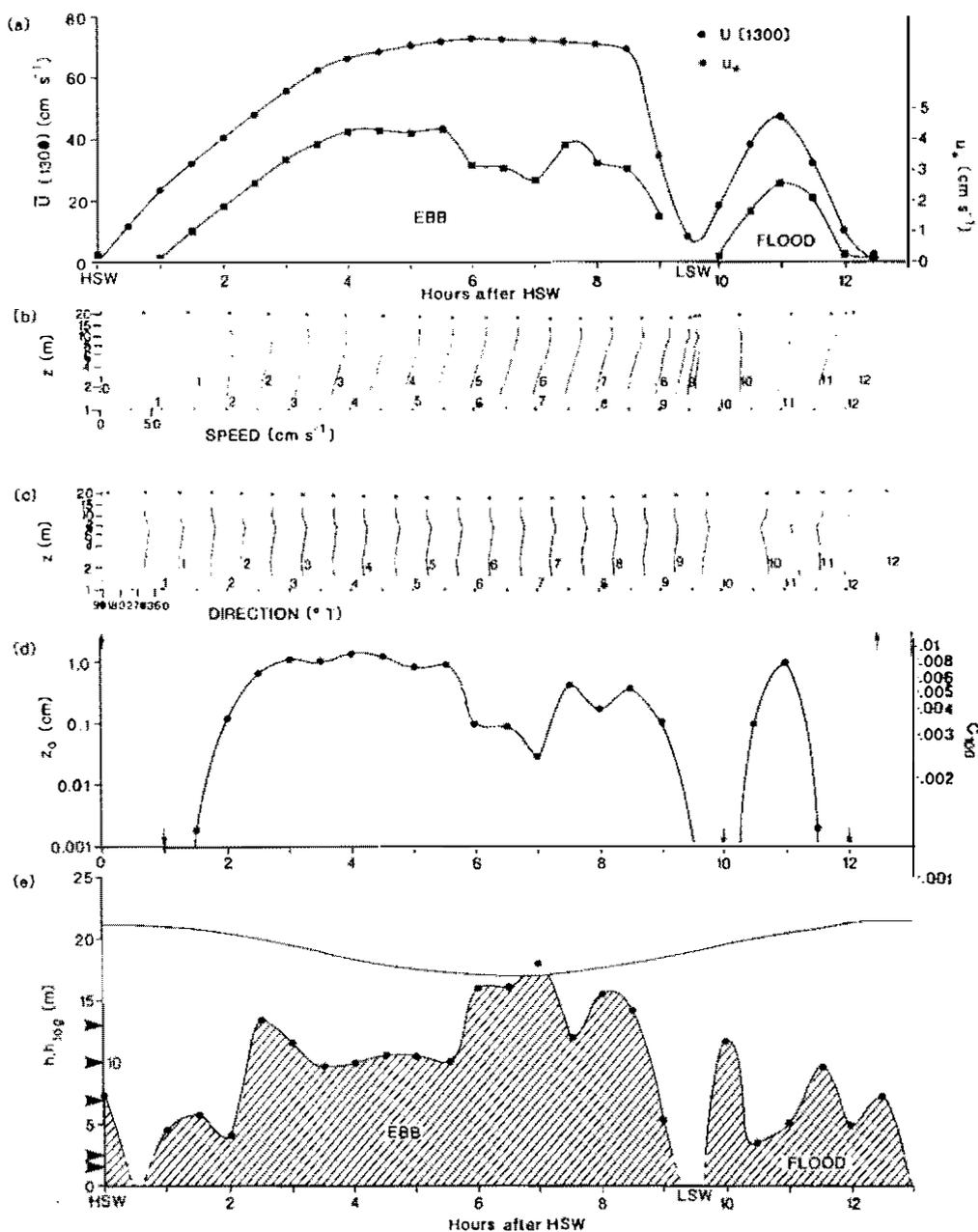
Time series of the shear velocity,  $u_w$ , and roughness length scale  $z_0$ , obtained by the least-squares regressions on 10-min averaged profiles of vertical velocity. Confidence intervals are 95% level based on the number of points that went into the regression and the goodness of fit. Least-squares regression confidence intervals could not be computed for the point at 1302 because only two velocity measurements were available. A value of 0.4 was used for Karmans constant to estimate  $u_w$  from the slope of the logarithmic profile.

**Figure 10** Time series of shear velocity and roughness length from measurements in Puget Sound. Reprinted from Gross and Nowell, 1983, *Continental Shelf Res.*, 2, 109-126. With kind permission from Pergamon Press Ltd, Headington Hill Hall, Oxford OX3 0BW.



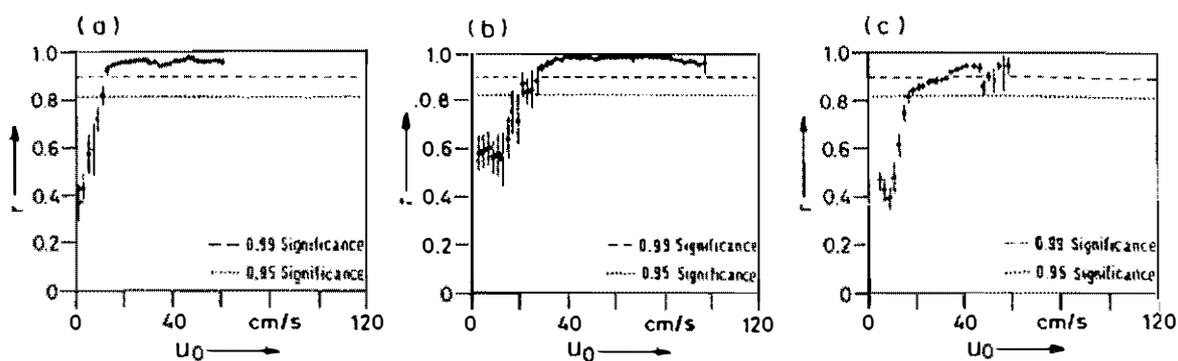
Velocity profiles as a function of time within the tidal cycle. Individual mean velocity profiles, grouped according to phase of the tidal cycle, are plotted semi-logarithmically and displaced so as to make the differences obvious. The solid lines are least-squares fits to the data with vertical positions corrected using spatially averaged bottom topography. The dashed lines are fits without correcting. The numbers below are the shear velocity in  $\text{cm s}^{-1}$ , with those in parentheses being the uncorrected values. It is evident that not correcting the profiles yields much larger stress estimates.

**Figure 11** Velocity profiles measured over a mobile sand bed in a tidal inlet. From McLean, 1983, in *North-Sea Dynamics*, edited by Sündermann and Lenz. Reproduced by permission of Springer-Verlag.



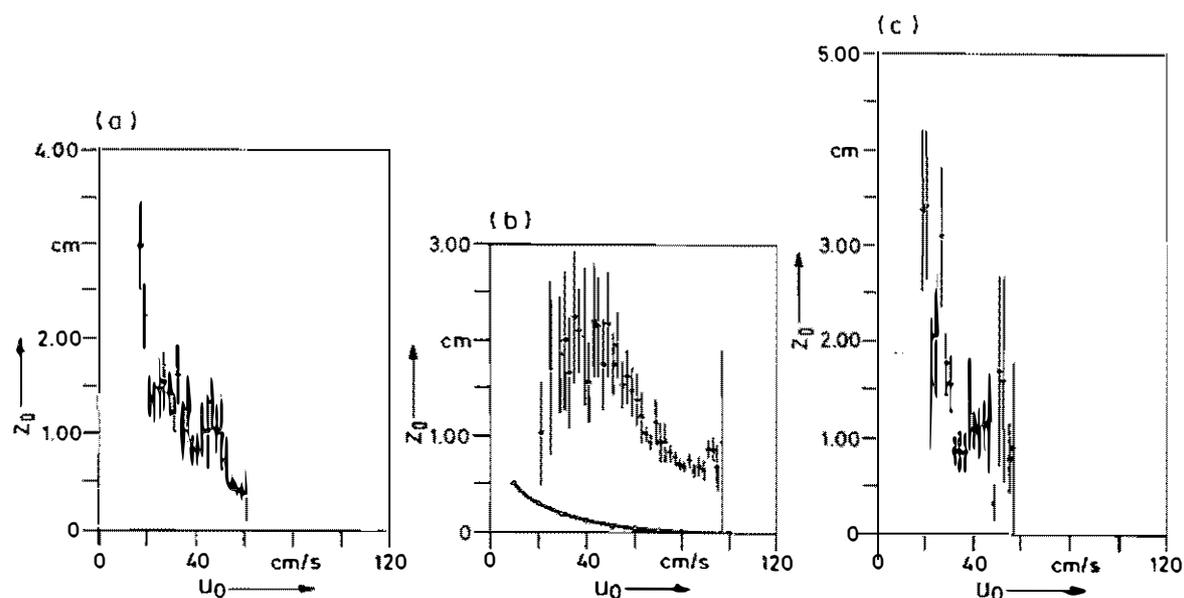
Flow parameters through an ensemble-average tidal cycle measured in Start Bay. (a) Current speed at 13m above the bed, and the friction velocity  $u_*$ . (b) Vertical profiles of current speed averaged over half-hourly intervals. Crosses indicate the origin of the correspondingly numbered profile, and asterisks the water surface. (c) As for (b) but current directions. Crosses indicate  $90^\circ$  for the correspondingly numbered profile. (d) The roughness length  $z_0$ , and drag coefficient  $C_{100} = \{0.4/\ln(100/z_0)\}^2$ . (e) The water depth  $h$ , and height of the logarithmic layer  $h_{10g}$  as defined in the text. Arrows against the  $h$  axis indicate the heights of the current meters.

**Figure 12** Variation in boundary layer characteristics through the tide, Start Bay, Devon. From Soulsby, Davies and Wilkinson, 1983, Institute of Oceanographic Sciences Report No.152. Reproduced with permission.



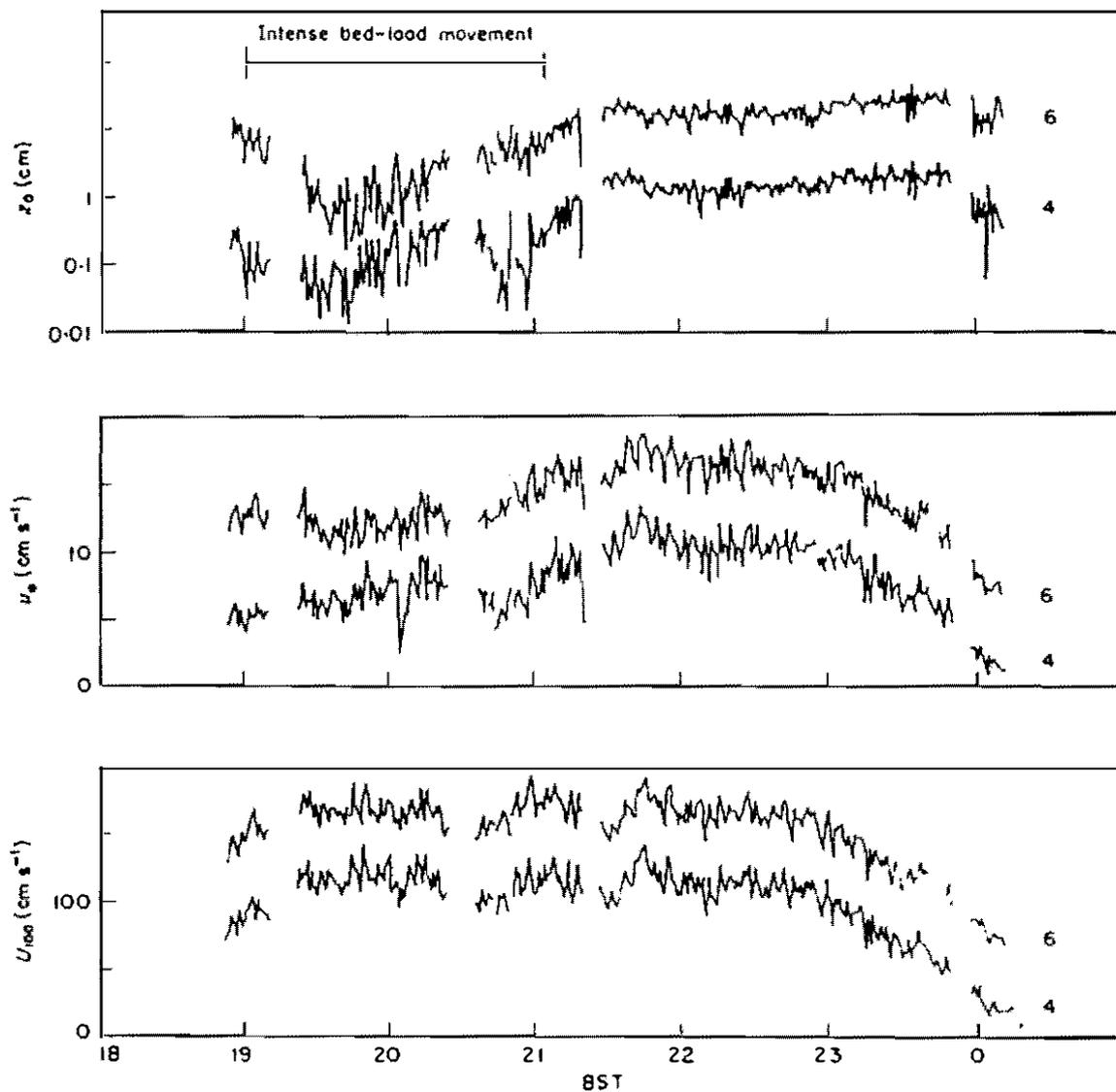
Correlation coefficient vs reference velocity in the uppermost level,  $U_0$ . Mean values for  $2\text{ cm s}^{-1}$  intervals with bars for the 95% significance level. (a) Vejsnaes Channel, PMD; (b) Jade Inlet; (c) Vejsnaes Channel, A-PMD.

NB: PMD = Profile Measuring Device (Savonius rotors), A-PMD = PMD with Aanderaa current meters.



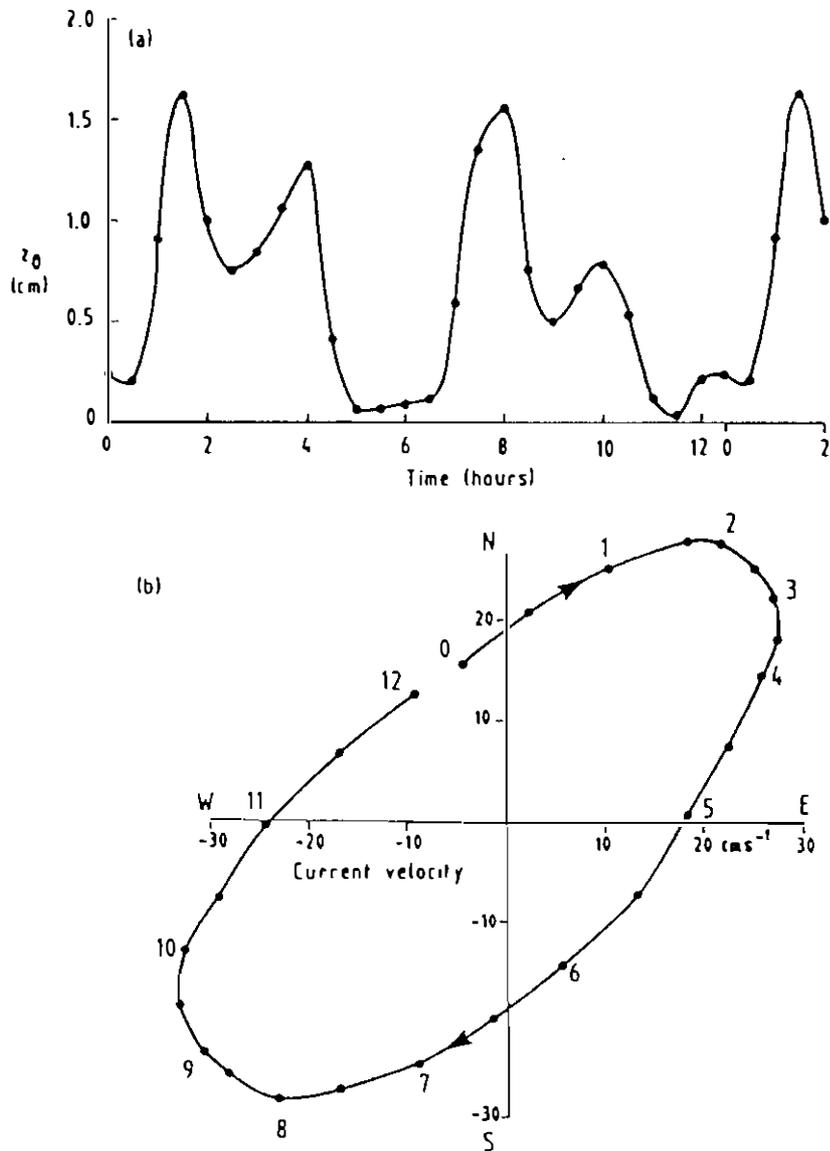
Roughness length reference vs reference velocity (for details see above). (a) Vejsnaes Channel, PMD. (b) Jade Inlet. The heavy line is the roughness length vs reference velocity after Vincent and Harvey (1976). (c) Vejsnaes Channel, A-PMD.

**Figure 13** Variation in the roughness length of the bed of a tidal inlet with velocity. Reprinted from Schauer, 1987, *Continental Shelf Res.*, 7, 1211-1230. With kind permission from Pergamon Press Ltd, Headington Hill Hall, Oxford OX3 0BW.



Variation of  $U_{100}$ ,  $u_*$ , and  $z_0$  during flood tide on 18-19 September 1982 showing reductions in  $z_0$  which are believed to be associated with intense bed-load movement. Results are shown for the six-rotor and four-rotor data sets in the upper and lower traces, respectively. The six-rotor data set results have been displaced vertically upwards by  $50 \text{ cm s}^{-1}$  in  $U_{100}$ , by  $5 \text{ cm s}^{-1}$  in  $u_*$ , and by a factor of 10 in  $z_0$ . These observations were obtained with the large rig. Numbers adjacent to traces indicate six-rotor and four-rotor data sets respectively.

**Figure 14** Time series of the roughness length measured over a sandy gravel in the Solent. From Heathershaw and Langhorne, 1988, *Estuarine, Coastal and Shelf Science*, 26, 459-482. Reproduced by permission of Academic Press (London) Ltd.



(a) Variation of  $z_0$  through the tide for the mobile sand bed of the Celtic Sea currents data. (b) The tidal ellipse at  $z = 2.5\text{m}$ , showing times plotted in (a).

**Figure 15** The variation of the roughness length of a mobile sand bed under an open tidal ellipse, Celtic Sea. From Soulsby, 1990, in *The Sea*, volume 9, edited by Le Mehaute and Hanes. Copyright © 1990 by John Wiley & Sons Inc. Reprinted by permission of John Wiley & Sons Inc.

