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A traversing system to measure bottom boundary layer hydraulic properties

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ABSTRACT

This study describes a new convenient and robust system developed to measure benthic boundary layer properties, with emphasis placed on the determination of bed shear stress and roughness height distribution within estuarine systems by using velocity measurements. This system consisted of a remotely operated motorised traverser that allowed a single ADV to collect data between 0 and 1 m above the bed. As a case study, we applied the proposed traversing system to investigate bottom boundary layer (BBL) hydraulic properties within Coombabah Creek, Queensland, Australia. Four commonly-employed techniques: (1) Log-Profile (LP); (2) Reynolds stress (RS); (3) Turbulent Kinetic Energy (TKE); and (4) Inertial Dissipation (ID) used to estimate bed shear stresses from velocity measurements were compared. Bed shear stresses estimated with these four methods agreed reasonably well; of these, the LP method was found to be most useful and reliable. Additionally, the LP method permits the calculation of roughness height, which the other three methods do not. An average value of bed shear stress of 0.46 N/m^2, roughness height of 4.3 mm, and drag coefficient of 0.0054 were observed within Coombabah Creek. Results are consistent with that reported for several other silty bed estuaries.

1. Introduction

Estuaries are of immense importance to many communities. It has been estimated that 60–80 per cent of commercial marine fishery resources depend on estuaries for part of or all of their life cycle (Klen, 2006). The flow and sediment transport patterns within estuaries are important as they play an important role in the functionality and health of these systems. Due to knowledge gaps, most numerical models used for predicting sediment transport (and related pollutant transport) rely on the use of approximations when determining bottom boundary conditions and sediment transport dynamics.

It is well recognised that the hydrodynamic properties of the bottom boundary layer (BBL) affect sediment resuspension. The shear stress near the bed directly causes sediment erosion, affects vertical mixing, and relates to conditions conducive to sediment deposition. Therefore, to accurately predict and numerically model the flow and sediment transport patterns within estuarine systems, it is important to obtain detailed velocity data near the bed (Soulsby and Dyer, 1981).

It is very difficult to directly determine the bed shear stress in the field as its determination requires the measurement of forces very close to the bed, within the viscous sub-layer (see Fig. 1) (Ackerman and Hoover, 2001). However, several indirect methods have been developed (see Section 3.1) that use more readily measurable velocity data to estimate bed shear stress. Previously, point source current meters, such as the S4 or Acoustic Doppler Velocimeter (ADV) (Gross et al., 1994; Jing and Ridd, 1996; Black, 1998; Stips et al., 1998; Osborne and Boak, 1999) have been used to derive BBL properties. However, in traditional fixed mooring arrangements they cannot usually fully resolve the boundary layer as they are restricted to a single point measurement. Additionally, if a detailed boundary layer profile is to be determined, then a number of devices must be deployed at one location (Gross and Nowell, 1983; Grant and Madsen, 1986; Feddersen et al., 2007), which is usually beyond the scope of most researchers due to the high cost of equipment and installation. More recently, Acoustic Doppler Current Profilers (ADCPs) have been used to record velocity data near the bed (Cheng et al., 1999; Thomsen, 1999), as they can provide near instantaneous three-dimensional velocity profile data that can be used to estimate shear stress. However, ADCPs have limitations in that they have a large (>10 cm) and wide spread (an order of 1 m) sampling volume, and are unable to sample close to the bed (approximately 10 per cent of the distance from the transducer to the bed), which is the most important region for assessing BBL properties within shallow estuarine systems.

In addition to the bed shear stress, the bed roughness is an essential parameter for modelling current circulations, wave height

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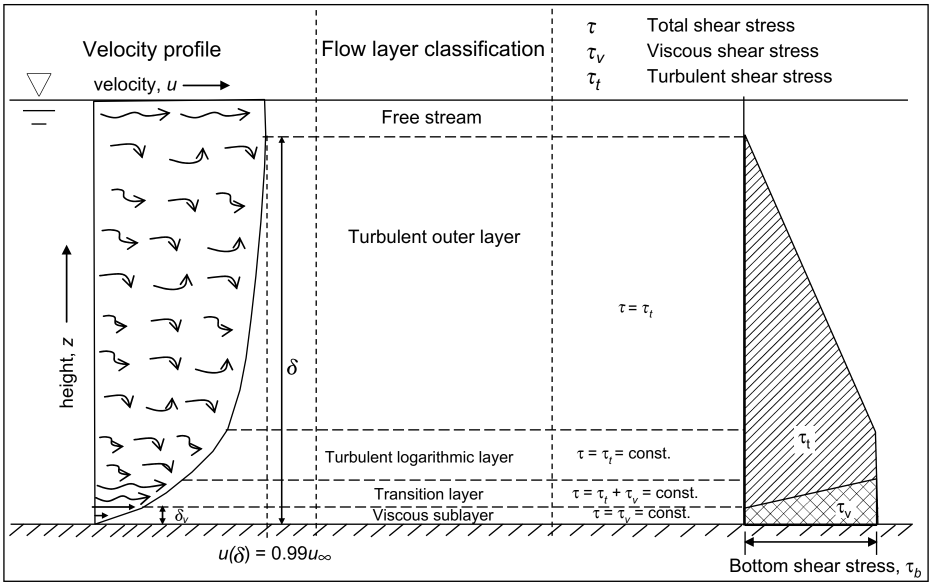

Fig. 1. Typical velocity and shear stress distribution within different flow regions (layer thickness is not to scale) of a turbulent bottom boundary layer.

attenuations and sediment transport within estuarine and coastal waters – but it is often unknown and difficult to measure directly in the field. The majority of modelling software packages (e.g. MIKE21/MIKE3 and ECOMSED) use an estimated roughness height or a drag coefficient as an input parameter for describing the bed shear stress in their sediment transport formulae (e.g. DHI, 2002; HydroQual, 2002). The physical bed roughness generally consists of three roughness components: grain roughness, bedform roughness, and sediment saltation roughness (You, 2005). The total roughness can be measured from the affected velocity profiles using Prandtl's (1926) law of the wall equation, which would substantially reduce the uncertainties of numerical models.

In this study, a new simple and robust system was developed to measure the flow properties within estuarine BBLs. The system is based around a traversing mechanism used to move an ADV vertically through the water column and, importantly, near the bed, so that hydraulic properties of the BBL could be assessed. Additionally, bed shear stresses measured using four different methods were compared. Results of the successful application of this new system are presented in this paper through a case study of a shallow estuarine system.

2. Theoretical background

The flow of water near a solid boundary has a distinct structure called a boundary layer. An important aspect of a boundary layer is that the velocity of the fluid (u) goes to zero at the boundary. At some distance above the boundary the velocity reaches a constant value (Fig. 1) called the free stream velocity u_∞. Between the bed and the free stream, the velocity varies over the vertical co-ordinate. The height of the boundary layer, δ, is typically defined as the distance above the bed at which $u(\delta) = 0.99u_\infty$ (see Fig. 1) (Douglas et al., 1986).

The BBL can be subdivided into four regions (see Fig. 1): (1) viscous sub-layer (thickness δ_v) representing a thin laminar flow layer just above the bottom – in this layer there is almost no turbulence and the viscous shear stress is constant; (2) transition layer, where viscosity and turbulence are equally important and the flow is turbulent; (3) turbulent logarithmic layer, where the viscous shear stress can be neglected and the turbulent shear stress is constant and equal to the bottom shear stress; and (4) turbulent outer layer, where velocities are almost constant because of the presence of large eddies, which produce strong mixing of the flow and shear stress gradually reducing to zero at the free stream (outer edge of the boundary layer). In a well-mixed fully developed turbulent flow over a rough channel bed, the outer turbulent layer covers approximately 80 per cent of the BBL thickness (Granger, 1985).

A typical phenomenon of turbulent flow is the fluctuation of velocity. The instantaneous velocity consists of a mean and a fluctuating component, and can be written as follows:

$$U = u + u', \quad V = v + v' \quad \text{and} \quad W = w + w' \tag{1}$$

where U, V and W are instantaneous velocities; u, v and w are time-averaged velocities; and u', v' and w' are instantaneous velocity fluctuations in longitudinal, transverse and vertical directions, respectively. Shear stress in laminar flow is defined as:

$$\tau_v = \rho\nu \frac{\mathrm{d}u}{\mathrm{d}z} \tag{2}$$

where τ_v is the viscous shear stress; ρ is the density of fluid; ν is the kinematic viscosity of fluid; and z is the elevation above the bed. On the other hand, shear stress in turbulent flow is defined as:

$$\tau_t = \eta \left(\frac{\mathrm{d}u}{\mathrm{d}z}\right)^2 \tag{3}$$

where τ_t is the turbulent shear stress, and η is a turbulent mixing coefficient (often called eddy viscosity). The eddy viscosity η is not a property of the fluid like ρ and ν, but is a function of the velocity. Turbulent velocity fluctuations generate momentum fluxes resulting in shear stresses (called Reynolds stresses) between adjacent parts of a flow (Tennekes and Lumley, 1972). The Reynolds stress (turbulent shear stress) is defined as:

$$\tau_t = -\rho\overline{u'w'} \tag{4}$$

This can be measured with high precision velocity recording devices such as ADV and Laser Doppler Systems. Turbulent shear stress equals the bed shear stress when measured within the constant shear stress region (Fig. 1).