The role of near-bed turbulence in sediment resuspension

Md Sarik Salim
B.Sc., M.Sc. (Civil Engineering)

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School of Civil Environmental, and Mining Engineering
The UWA Oceans Institute
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ABSTRACT

Classical sediment transport theory postulates that sediment is transported when a critical mean velocity is exceeded. However, other studies have observed sediment transport below critical values and have suggested that near-bed turbulence may contribute to sediment resuspension and transport. Sediment transport has significant implications for the management of societal issues such as coastal erosion, changing seabed morphology influencing marine ecosystems and therefore their successful management require a comprehensive understanding of sediment transport process. In this study, laboratory and field measurements were used to examine the intermittent nature of bottom turbulence and its relationship to sediment resuspension in the laboratory and in the field. In particular, the relationship between intermittent coherent events of strong turbulence production (‘bursting’ events) and sediment resuspension was examined. The measurements were undertaken in four contrasting flow regimes that included unidirectional currents (open channel flow in the laboratory, continental slope region, tidal inlet) and oscillatory flow conditions (nearshore beach). The results indicated that the mean critical velocity alone was not an accurate predictor of the episodic initiation of sediment motion. Turbulent events were able to transport sediment even at mean flow conditions below the predicted threshold defined by time-averaged stress. The pattern of turbulent bursting events was similar for all flow conditions with ejection and sweep events dominating the re-suspension process. In the beach experiment, turbulent events were mainly observed during the backwash. It is concluded that sediment transport is an event based process with bulk sediment resuspension events related to turbulent velocity fluctuations.
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AUTHORSHIP DECLARATION: CO-AUTHORED PUBLICATIONS

This thesis contains work that has been published and prepared for publication.

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I, Charitha Pattiaratchi certify that the student statements regarding their contribution to each of the works listed above are correct

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Chapter 1: Introduction

1.1 Overview

In the field of sediment transport research, various problems such as local scouring, sedimentation in reservoirs, erosion due to coastal and river floods, dam breaching flows, aggradations and degradations of riverbeds are of fundamental importance for engineers, geophysicists, decision makers and environmentalists. In ecosystem of coastal zones, transport of sediment play an important role in maintaining water health, influencing biological production. It is also responsible for providing nutrients to aquatic plants, as well vegetation in nearshore ecosystems such as floodplains and marshes. Without sediment deposition, coastal zones can become eroded or non-existent. On the other hand, as sediment particles are mineral, therefore, sedimentologist and geologists always seek inverse solutions for sediment transport relationships to improve their understanding to interpret geologic history through observations of sedimentary rocks and sedimentary structures. Although the implications of sediment transport have been studied for more than two centuries, problems associated with understanding the exact transport mechanism of sediments are still far from being solved and constitute the basic issue for scientists dealing with environmental hydraulics, ecosystem of coastal zones, sedimentology and coastal engineering among many others.

In classical sediment transport theory, it is postulated that a critical mean velocity needs to be reached before sediment transport occurs: no transport will occur if the bed shear stress produced by mean current velocity is less than the critical mean shear stress value. However, in the laboratory and field conditions where this critical velocity is rarely exceeded, sediment resuspension and transport have been observed (Lavelle and Mofjeld, 1987; O'Callaghan et al., 2010). There have only been a few field studies that have been undertaken in shallow water environments that show that turbulence does have a role in...
resuspending and transporting sediments along boundary layers and this role becomes even more obvious when the magnitude of the flow is below the critical condition for sediment transport (Yang et al., 2016). In the viscous sub-layer that is close to the bed, the mean current velocity is generally too low to produce significant shear stress that could cause sediment movement, yet there have been recorded instances where transport occurs (O'Callaghan et al., 2010). This suggests that there are some factors other than the mean current velocity that may contribute to sediment movement under these conditions. Since movement of sediment has significant implications for the marine environment, it is therefore very important to understand the process of sediment movement and characteristics of turbulence which are responsible for this transport in different flow fields. Only a limited amount of work has been undertaken on sediment transport processes, particularly with respect to turbulence generation near the bed.

1.2 Objectives

The overall objective of this thesis was intended to develop a better understanding of the role of intermittent turbulence processes near the bed in resuspending and transporting sediments along the bottom boundary layer under contrasting flow conditions: laboratory (unidirectional flow); continental slope (unidirectional flow), tidal Inlet (unidirectional flow) and the nearshore (oscillatory flow). In particular, this study aimed at examining how the fluid turbulent characteristics contributed to sediment transport processes (i.e. resuspension events, turbulent flow structure and sediment diffusion) in different flow environments. To achieve these aims, the following research questions were addressed:

- What are the interactions of localized near-bed coherent turbulent events in event based sediment resuspension and transport in four-contrasting laboratory and marine environments that included:
unidirectional currents in an open channel laboratory environment where time-averaged measured and estimated critical velocity were below and above the mean flow velocity.

• along the continental slope region where the mean tidal currents were below the time-averaged critical velocity.

• tidal inlet where the unidirectional mean currents were well above the time-averaged critical velocity.

• Wave dominated nearshore flow region of a beach where combined wave and currents were well above the time-averaged estimated critical velocities but the currents changed significantly over a wave period.

1.3 Outline of the thesis

In agreement with the guidelines of The University of Western Australia, this thesis is presented as a compilation of papers published in, or in preparation for submission to peer-reviewed scientific journals. Each paper corresponds to a chapter with identical content to the published/prepared work.

This thesis is organised into six chapters. The outline of the thesis is as follows: Chapter 2 presents a literature review which provides an overview of present state of knowledge on sediment resuspension such as ‘bursting phenomenon’ in various laboratory and field environments. The main thrust of the original work includes Chapter 3-5 and is presented as a compilation of three journal papers published/prepared to submit in international journals. Chapter 3 presents the results of laboratory experiments in order to investigate the role of turbulent coherent structures both above and below the measured critical velocity conditions. Field investigation in the continental slope where mean velocity was below the calculated and measured critical velocity is presented in Chapter
4. Chapter 5 presents investigation in a tidal inlet and wave-dominated flow environment of a beach where mean current velocity is above the calculated critical velocity using a multipoint field measurements instrumental facility. Finally, Chapter 6 presents the overall conclusions of the work. Note that, as Chapter 3, 4 and 5 are self-contained papers, there is some repetition of introductory material, methodology, and literature which was unavoidable. Bibliographical references for all cited works are given together at the end of the thesis.
Chapter 2: Literature review

2.1 Introduction

An overview of the current knowledge on sediment transport especially the role of ‘turbulent bursting’ phenomena in different fluvial and marine flow environments, is presented in this chapter. Physical properties of fluid and sediment are first introduced in Section 2.2, Section 2.3 describes the role of turbulence on sediment transport. Finally concluding remarks are presented in Section 2.4.

2.2 Physical properties of fluid and sediment

Sediments are inorganic or organic particulate matter that can be transported through the action of fluid flow. Sediments can easily be classified on the basis of their size and composition. Broader categories of sediments include boulders, gravels, sand and mud. They can be of cohesive or non-cohesive nature based on their composition and the intermolecular forces between the particles. Sediments with different physical and chemical properties act differently when some external force is applied to them. However, this thesis is restricted to the study of non-cohesive sediments composed of inorganic material.

Different factors contribute to the sediment transport process including particle size, shape and composition, current speed, density of sediments, density of water, viscosity and the nature of flow (Wright et al., 1999). The fluid at the boundary layer experiences a resistance to flow due to the boundary. The lower portion of the fluid facing flow resistance due to its closeness to the surface is known as the boundary layer (Wright et al., 1999; Sleath, 1984). The mean velocity distribution near a smooth, flat boundary increases logarithmically from the no-slip condition till it reaches the velocity of the mean
stream flow at some height (Fig. 2.1a). This velocity profile conforms to the law-of-the-wall (Bradshaw and Huang, 1995) and is represented as:

\[ \bar{u} = \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right) \]  

(2.1)

where, \( \bar{u} \) is the mean velocity, \( u_* \) is the frictional velocity, \( k \) is the von Kármán constant, \( z \) is the height above bed and \( z_0 \) is the roughness length scale.

**Figure 2.1.** (a) Logarithmic mean velocity profile, (b) Classification of flow field in different layers (layer thickness not according to scale) adopted from Dey (2011).

The boundary layer can be further divided into two regions: the viscous sub-layer immediately above the bed with dominant viscous effects and the second layer at some distance from the surface where turbulence becomes more significant as shown in Fig. 2.1b (Sleath, 1984). This boundary layer is the major area of concern for the exchange of various materials (Grant and Madsen, 1986) as well as for sediment transport and turbulence studies (Cantwell, 1981). It is therefore essential to examine processes in this boundary layer. Fluid motion can be visualised in a form of thin layers, with every layer acted upon by the immediate overlying as well as underlying layer. The upper layer exerts a stress and tends to drag the middle layer along whereas the underlying one also applies a frictional force and inhibits the movement. Determination of net stress on the moving
fluid can help to estimate the likelihood of sediment movement. Wright et al. (1999) assumed that due to the stronger viscous effect of bottom surface, the fluid layer in direct contact with the surface is static and stationary. As the frictional forces become weaker with an increase in distance from the bed, the overlying layers move with a gradually increasing speed creating a velocity gradient. The flow speed becomes almost constant when the effect of surface closeness diminishes.

The amount of sediment transported from one point to another point in a particular time interval is called the sediment transport rate or sediment flux. Total sediment flux is the sum of bedload and suspended load fluxes. Sediment transport in flowing water has been explored in the last few decades but still found to be a difficult field to be clearly understood. It becomes even more complex in strong water flows (Dyer and Soulsby, 1988; Wright et al., 1999). Despite considerable effort invested by scientists and engineers to model the sediment transport in natural flow systems, predictions of mass transport are hampered by the difficulty of accurately describing the erosion and deposition processes in turbulent flows, and the complex feedback between moving suspended sediments, migrating bedforms, and the water flow (Trevethan et al., 2007; Dyer et al., 2004; Dyer and Soulsby, 1988). Currents, waves and their non-linear interaction are the main hydrodynamic forces controlling erosion of a bed deposit in riverine and coastal areas. Erosion and entrainment of bottom sediments begin when the mean shear stress acting on the bed exceeds a critical threshold, which depends on the sediment size, density, cohesiveness and presence of bedforms (bottom roughness) amongst others (Dyer, 1986; Amos et al., 1997; Houwing, 1999). Natural sediments with different grain size distribution, composition and cohesive properties act differently when external stress is exerted on them (Dyer and Soulsby, 1988). Thus, the determination of erosion rates in sediment transport models depends upon accurate specification of the
shear stress exerted by the water flow on the bed and of the critical resuspension threshold.

The term ‘incipient motion’ defines the initiation of bed-material after the threshold has just been exceeded. However, identification of the threshold point has always been difficult. Neill and Yalin (1969) suggested that to identify the threshold point, some subjectivity (e.g. area, duration of observation) could be eliminated that might have a fixed value from one experiment to the next. However, a major problem with the threshold is the ‘experimental definition’ because the initiation of motion is a probabilistic process. In smaller water bodies, stress on the near-bed can be determined by ‘slope of water surface’ but this approach is not applicable to large water bodies due to the multi-dimensional movement of water molecules (Dyer and Soulsby, 1988). The accuracy of sediment transport models is also likely to be much smaller in the deeper regions of the oceans where very little information is available.

Traditionally sediment transport studies have been based on the presence of a particular friction velocity and shear stress. According to the well-known ‘Shields criterion’ for sediment transport given by Shields (1936), a mean critical or threshold shear stress exists below which particles does not move (Fig. 2.2). At velocities lower than the threshold, shear stress represents the viscous drag imparted by the moving fluid to the bed particles whereas at velocities higher than the critical, it is related to the pressure differential between the upstream and downstream sides of the particle. Shields (1936) also defined the non-dimensional critical shear stress, \( \theta_{cr} \), as a function of the boundary Reynolds number, \( Re_p \), defined as:

\[
\theta_{cr} = \frac{\tau_o}{(\rho_s - \rho)gd_s} \quad (2.2)
\]

\[
Re_p = \frac{u_*d_s}{\nu} \quad (2.3)
\]
where, $\tau_c$ is the critical bottom shear velocity, $\rho_s$ and $\rho$ are the sediment and fluid densities, $g$ is the acceleration due to gravity, $d_s$ is the particle diameter, $u_* = \sqrt{\tau_c / \rho}$ is the critical shear velocity and $\nu$ is the kinematic viscosity of the fluid.

Figure 2.2. Shields diagram representing threshold Shields parameter $\Theta_c$ as a function of shear Reynolds number $Re_p$ (Shields 1936).

2.3 Role of turbulence on sediment transport

Turbulence is a characteristic feature of fluids. It is complex, arbitrary and disorganized with high temporal and spatial variability. Turbulent flows can be described as three dimensional, unsteady, unpredictable, dissipative, diffusive and have strong vorticity and with a broad spectrum (Kundu and Cohen, 2002). For these reasons, studying turbulence is very challenging. In the past, due to certain technological limitations, it has been very difficult to study boundary layer dynamics especially turbulence. More recently, the advent of high-spatial and high-temporal resolution instruments to measure both turbidity and flow velocity has facilitated a deeper understanding of the processes controlling
sediment fluxes within turbulent bottom boundary layers (Voulgaris and Trowbridge, 1998).

Turbulent stress production is intermittent and associated with a sequence of motions. Kline et al. (1967) found a cyclic process with turbulent flow near walls, in which the near-wall layer propagates slowly and then interacts strongly with the outer layer flow—an event known as ‘turbulent bursting’. At the beginning, the low-speed streak ejects away from the wall, and oscillations in both the spanwise and normal directions appears. As the oscillations increase in amplitude, a breakdown (burst) occurs in the form of a violent and chaotic upward eruption of the low-speed fluid in the near-wall layer into the outer layer, termed usually as ejection. The ejection is soon followed by a sweep, in which the chaotic motion is swept away. The wall-layer streaks reappear at different spanwise locations, and a new quiescent period begins. The development of a horseshoe vortex showing the lifts, stretches, ejection, and sweep associated with velocity profiles is shown in Fig. 2.3. The action of turbulent coherent flow structures related to such a sequence of turbulent bursting involving ejections and sweeps (Robinson, 1991) has been shown to play a central role in sediment entrainment (Cao et al., 1996).
Predictions of bed stress and sediment transport have traditionally made use of theory and results derived from steady flows, because of the difficulties in obtaining accurate in-situ measurements under turbulent flows (Dyer and Soulsby, 1988). In turbulent flows, the high energy downward motion of water causes a significant disturbance of the near-bed as it moves into the low lying water layers even the ones which are very close to the bed and exerts a strong shear stress resulting in upward movement of water along with sediment displacement (Wright et al., 1999). It has also been noticed that tides have a significant effect on turbulent structure and suspended sediment concentrations (Trevethan et al., 2007). Wright et al. (1999) state that the amount of sediments being transported increases if the current speed is higher close to the
bed. In return, it increases the current density which has a negative effect on turbulence because near-bed fluids offer more resistance to turbulence.

To examine the turbulence characteristics of the flow field, each current component can be split into a mean ($\bar{u}$, $\bar{v}$, $\bar{w}$) and a fluctuating part ($u'$, $v'$, $w'$). This decomposition is called Reynolds decomposition (Reynolds, 1895) as shown in Fig. 2.4. This can be displayed as:

$$u = \bar{u} + u', \quad v = \bar{v} + v', \quad w = \bar{w} + w'.$$

(2.4)

where, $u$, $v$ and $w$ are the measured velocity components in the x, y and z directions; $u'$, $v'$ and $w'$ are the turbulent components and $\bar{u}$, $\bar{v}$ and $\bar{w}$ are the mean velocity components. This decomposition is very useful for determining turbulence characteristics including turbulent energy, turbulent shear stress, inertial dissipation and bursting phenomenon.

Figure 2.4. Time variation of $u'$ and its decomposition.

Quadrant analysis classifies different turbulent events and examines their intermittent nature and contribution to Reynolds stress. Kline et al. (1967) suggested the division of different burst motion events into $u'$-$w'$ quadrants, as shown in Fig. 2.5, so that each event could be characterized and better understood based on their associated velocity fluctuations and their positions within the quadrant. It has become common to use
quadrant analysis for studying intermittent turbulent structures and their contribution to sediment transport (e.g. Kularatne and Pattiaratchi, 2008; Yuan et al., 2009).

Figure 2.5. Classification of bursting events in u'-w' space, showing ejection, sweep, up-acceleration and down-deceleration, adapted from Soulsby (1983).

Heathershaw (1974) studied turbulence characteristics close to the bed in the Irish Sea at depths of 10 to 60m. On the basis of current velocity fluctuations, he categorized the turbulence events into four groups including ejection (u'<0, w'>0, u'w'<0), sweep (u'>0, w'<0, u'w'<0), down-deceleration (u'<0, w'<0, u'w'>0) and up-acceleration (u'>0, w'>0, u'w'>0). Soulsby (1983); Heathershaw and Thorne (1985) found that these intermittent events also cause sediment movement.

The discovery of the turbulent bursting phenomenon led researchers to study the role of turbulence on particle entrainment and to re-define the criteria of sediment motion (Dey, 2011). Several laboratory studies have linked coherent motions in the turbulent boundary layer with resuspension (Grass, 1974; Sumer and Oguz, 1978; Sumer and Deigaard, 1981, Falco, 1991). Grass (1974) filmed the resuspension process due to turbulent flow over a flat sand bed, identified the coherent flow structures in the boundary layer, and calculated the velocities of the particles advected by such motions. This led
directly to the conclusive link between the observed ejection of fluid away from the boundary layer and the corresponding response of bed sediment. This work also showed that the sweep events above the channel bed were more responsible for momentum transfer into the boundary layer than the ejection events. Sumer and Oguz (1978) and Sumer and Deigaard (1981) photographed intermittent, sweep-type fluid motions pushing sediment particles into the low-speed wall streaks; those particles were then subjected to upward, ejection-type fluid motions. Falco (1991) formulated an overall picture of the structure of the turbulent boundary layer in terms of experimentally identifying inner-outer wall region multiscale turbulent eddies and constructed a coherent motion model. Considering a flat plate, zero pressure gradient, boundary layer, Falco (1991) showed that a specific set of coherent structures in the turbulent boundary layer were dynamically significant for the transport of sediments. Further studies (Kaftori et al., 1995; Nelson et al., 1995; Niño and Garcia, 1996; Cellino and Lemmin, 2004) confirmed the importance of bursting events in sediment resuspension and transport in fluvial environments. Previous studies suggested that the ejections were associated with entrainment of sediment particles into the water column, while sweeps were effective at transporting bedload (Cao, 1997; Dyer and Soulsby, 1988; Heathershaw, 1979; Soulsby, 1983; Keylock, 2007; Yuan et al., 2009). To distinguish between different processes, in this study the term ‘resuspension’ is used for particles initially laying on the bed and at some point lifted into the water column, in contrast to particles permanently in suspension (i.e. washload).

In a study of the relationship between near-bed boundary turbulence and sediment transport, Heathershaw and Thorne (1985) established a link between bursting phenomena and sediment movement. During studies to examine the incipient motion of seabed gravels on the South coast of England they used electromagnetic current meters
at 14m water depth and discovered that bursting phenomena can produce higher stress than of mean current. They also determined that sweeps cause maximum transport and outer flows produce considerable sediment movement over a specific stress range. On average, sweeps and up-acceleration events were responsible for nearly 50% of the total stress while occurring only one-fourth of the time. Observations by Drake et al. (1988) on the mobility of gravels in alluvial streams using motion-picture photography suggested that the majority of gravel entrainment was associated with the sweep events giving rise to the motion of particles. These events occurred during a small fraction of the time episodically at any particular location on the bed. Thorne et al. (1989) conducted measurements of the near-bed turbulent current flow and the bedload transport of marine gravel in the tidal environment using electromagnetic current meters, a passive acoustic system and an underwater TV camera. They noticed that only sweeps and outward interactions derived a critical role in the transportation of coarse sedimentary material. Overall the transport process continued due to the instantaneous increase in streamwise velocity fluctuations which generated excess boundary shear stresses. Measurements made by French and Clifford (1992) within a macrotidal marsh channel using a two-component electromagnetic current meter offered a fundamentally different perspective on the nature and range of fluid motions provided by conventional impellor-type sensors. They noticed that, on average, around 90% of the total stress was contributed in 50% of the total sampling time. These results differed from those of Gordon (1974) and Heathershaw (1974), both of whom reported approximately 60% of the total stress contributed in 100% of the total time. Soulsby et al. (1994) conducted simultaneous measurements of the high-frequency fluctuations of the concentration of sand, resuspended in a tidal current, above a sandy bed of an estuary and showed that large upward fluxes of sediment were associated with ejection events. Field experiments by Couturier et al. (2000) showed that the macroscale flow modules strengthened the ejection
events which favoured sediment transport. Furthermore, ejection events were exaggerated during episodes of decreasing horizontal velocity and increasing turbidity, while sweep events were magnified during modules of increasing horizontal velocity and decreasing sediment concentration. Yuan et al. (2009) also revealed a similar relationship between turbulent coherent structures and sediment resuspension. They used an acoustic Doppler velocimeter (ADV), acoustic Doppler current profiler (ADCP) and optical backscatter sensors (OBS) to look at turbulence-linked sediment motions in the tidal environment of the western Yellow Sea of China. Their results revealed that sweep was the longest time occupied turbulent event among all others and ejection played the most significant part in the transport process. Overall, 98% of the total sediment flux was by ejection and sweep and the role of other turbulent events (i.e. up-acceleration and down-deceleration events) was negligible.

In the wave-dominated nearshore region, Jackson (1976) examined the turbulent bursting phenomenon under wind-generated surface waves and found that the mean values of the flow parameters did not remain sensibly constant during turbulent bursts and the timescale of the largest turbulent eddies. Additionally, the upward momentum flux in the bursts provided the vertical anisotropy in the turbulence which was needed to suspend sediment. Conley and Inman (1992) conducted high frequency velocity measurements close to the seabed under near-breaking swell waves to study the development of the fluid–granular boundary layer over permeable beds of loose sand. They also suggested that there was a pronounced asymmetry in instantaneous sand transport and boundary layer bursting phenomena between the wave crest and trough. Moreover, laboratory waves with field scale periods and wave heights over thin sand beds did not exhibit this crest-trough boundary layer asymmetry, indicating that a critical element of similitude was absent in laboratory experiments. Hay and Bowen (1994)
suggested coherent structures in combined flow turbulence as possible causes of higher suspension events observed at wave group timescales. Clarke et al. (1982) also suggested bursts of intense turbulence associated with peak values of wave orbital velocity caused higher suspension events. Kularatne and Pattiaratchi (2008) examined the wave-group induced higher suspension events and suggested that turbulence and bursting phenomena also cause sediment transport in shallow waters. They used an ADV and OBS to study the relationship of turbulent kinetic energy with sediment transport along south west coast of Western Australia. Their results suggested that higher sediment movements were associated with ejections rather than sweeps, where turbulent shear stress was greater during ejections and sweeps as compared to that during up-acceleration and down-deceleration motions as per the results of Heathershaw and Thorne (1985).

Seminal work of Grass (1970) and Lavelle and Mofjeld (1987) due to the criticism on the critical velocity concept at the first instance, along with the above-mentioned laboratory and field investigations have stated the requirement for the revision of the critical velocity concept, proposing alternative statistical views of particle motion. Adrian (2007) investigated the structure of near bed organised motion in the canonical forms of wall turbulence and suggested that quadrant analysis permitted evaluation of the turbulent bursting events to the total mean values of kinetic energy and dissipation. Diplas et al. (2008) performed laboratory experiments to examine the role of turbulent fluctuations on particle movement under incipient flow conditions, and concluded that the duration of instantaneous turbulent events applied on a sediment grain was also significant in determining the sediment grain’s threshold of motion. In an attempt to propose a direct numerical simulation of bed load transport calculations, Schmeeckle and Nelson (2003) developed a model of bed load transport that captured the sources of fluid turbulence variability by directly integrating the equations of motion of each particle of a simulated
mixed grain-size sediment bed. However, they also mentioned that with the knowledge of the velocity structure within the bedload layer, a complete model of bedload transport could be built that includes the importance of turbulence fluctuations in entraining grains at low to moderate transport stages, and also includes the feedback that moving grains have on the fluid velocity in the whole bedload layer, which is important for moderate to high transport stages. The entrainment of coarse sediment particles under the action of fluctuating hydrodynamic forces was investigated from an energy perspective by Valyrakis et al. (2013). They found that the energy approach to grain dislodgement, although directly linked to the impulse criterion, demonstrated to be more versatile and intuitive, where the majority of the turbulent events performed sufficient mechanical work on the coarse grain for entrainment. Therefore, while research that moves beyond Reynolds stresses to incorporate quadrant analysis and ejection-sweep processes is an important advance (Dwivedi et al., 2011; Wu and Shih, 2012), further attempts can be taken to link two dimensional quadrants and three-dimensional octants into sequences that reveal flow-sediment structure (Keylock et al., 2014). It is noteworthy to mention that; the quadrant analysis considers the Reynolds stresses where octant analysis may be advantageous when one wishes to analyse turbulent structures with a strong three dimensionality. However, both traditional quadrant and octant analysis are insufficient to characterise flow structures, hence, the sequences in which such flow events arise relative to statistical null models should be taken into account. Further details in this regard is available in Madden (1997) and Keylock et al., (2014).

2.4 Concluding remarks

This chapter presented the current knowledge in sediment resuspension in various laboratory and field environments. It showed the complexity involved in the turbulent coherent structures in resuspending sediments and the need for further investigations.
Despite several attempts to develop a precise sediment entrainment theory merging turbulence features, previously few studies, however, have examined the role of turbulence on sediment resuspension as accessibility constraints for deployment of easily operated equipment (e.g. deployment of ADVs in deep water environments and ADCPs with near-bed multipoint measurement facilities in shallow water environments) has prevented further identification and understanding of such processes which may contribute to resuspension in the marine environment. These highlighted further investigations to observe the variation in turbulence near the bed in different flow environments. Recent advances in instrumentation for field and laboratory experimentation have made rapidly-obtained and spatially-resolved observations of turbulent flow fields. Collectively, these advances in instrumentation allow for multidimensional visualisation of turbulent coherent structures that was not previously possible. Therefore, in this study, firstly, laboratory experiments were performed where high-frequency acoustic data were recorded in fluvial conditions near the bottom boundary layer under unidirectional currents over a flat sandy bed (Chapter 3). This detailed laboratory investigation clarifies the turbulent characteristics and their effect on resuspension, both above and below the measured mean critical velocity test conditions. Secondly, in the deep ocean systems (i.e. continental slope and continental shelf regions), in-situ observations were performed which provided a unique perspective to further understand the interactions between sediment resuspension and turbulent characteristics where measured and calculated (considering widely used transport equations) mean critical velocity were rarely exceeded (Chapter 4). Finally, in order to validate the findings of the laboratory and numerical research in the field based on turbulent bursting phenomena, experiments were performed in the natural conditions of a unidirectional current flow environment of a tidal inlet and wave-dominated flow environment of the nearshore region where high frequency multipoint data were recorded near the bottom
boundary layer and traced the evidence of turbulent coherence structure in resuspending sediments (Chapter 5). Furthermore, the turbulent characteristics and their effect on the resuspension mechanism and the possible generation mechanisms of the observed patterns were discussed.
Chapter 3: The influence of turbulent bursting on sediment resuspension under unidirectional currents

Summary

Laboratory experiments were conducted in an open channel flume with a flat sandy bed to examine the role of turbulence on sediment resuspension. An acoustic Doppler velocimeter (ADV) was used to measure the instantaneous three-dimensional velocity components and acoustic backscatter as a proxy to suspended sediment concentration. Estimates of sediment transport assume that there is a mean critical velocity that needs to be exceeded before sediment transport is initiated. This approach does not consider the turbulent flow field that may initiate sediment resuspension through event-based processes such as the ‘bursting’ phenomenon. In this chapter, laboratory measurements were used to examine the sediment resuspension processes below and above the mean critical velocity. The results within a range above and below the measured mean critical velocity suggested that: (1) the contribution of turbulent bursting events remained identical in both experimental conditions; (2) ejection and sweep events contributed more to the total sediment flux than up-acceleration and down-deceleration events, and (3) wavelet transform revealed a correlation between the momentum and sediment flux in both test conditions. Such similarities in conditions above and below the measured mean critical velocity highlight the need to re-evaluate the accuracy of a single, time-averaged, mean critical velocity for the initiation of sediment entrainment.

3.1 Introduction

Understanding the physical processes that govern sediment resuspension has significant

implications for aquatic ecosystems and fish habitats as well as sustainable engineering applications such as beach nourishment, maintenance of hydraulic structures, dam breaching flows, sedimentation in reservoirs, defence schemes against erosion due to floods, and aggregate dredging (Buffington, 1999; Paphitis, 2001; van Rijn et al., 2007; Thompson et al., 2011; Aagaard and Jensen, 2013; van Rijn, 2013), all of which require improved predictive models of sediment transport. However, resuspension of sediment is a complex mechanism due to the difficulty in defining the fluctuating nature of turbulent flow. Shields (1936), the pioneer to investigate the entrainment of granular particles, concluded that a mean critical or threshold shear stress existed below which particles did not move. At velocities lower than the threshold, shear stress represented the viscous drag imparted by the moving fluid to the bed particles whereas at velocities higher than the critical, it was related to the pressure differential between the upstream and downstream sides of the particle. Shields (1936) also defined the non-dimensional critical shear stress, \( \theta_{cr} \), as a function of the boundary Reynolds number, \( Re_p \), defined as:

\[
\begin{align*}
\theta_{cr} &= \frac{\tau_o}{(\rho_s - \rho) g d_s} & (3.1) \\
Re_p &= \frac{u_* d_s}{\nu} & (3.2)
\end{align*}
\]

where \( \tau_o \) is the critical bottom shear velocity, \( \rho_s \) and \( \rho \) are the sediment and fluid densities, \( g \) is the acceleration due to gravity, \( d_s \) is the particle diameter, \( u_* = \sqrt{\tau_o/\rho} \) is the critical shear velocity and \( \nu \) is the kinematic viscosity of the fluid.

Such a criterion (commonly implemented via a Shields diagram, e.g. Kennedy, 1995; Buffington, 1999; Paphitis, 2001) states that sediment is entrained once bed shear stress exceeds the Shields mean critical value. The Shields diagram has been extensively applied and investigated by numerous researchers (Brownlie, 1981; van Rijn, 1984; Pattiaratchi and Collins, 1985; Soulsby and Whitehouse, 1997; Wu and Wang, 1999;
Paphitis, 2001). The impact of turbulence, however, was traditionally represented only by a mean quantity such as Reynolds shear stress (e.g. widely used bedload and suspended load formulations presented in van Rijn, 2013). Further attempts to characterize sediment entrainment advocated that it depended solely on fluid lifting force, with near-bed sediment being entrained due to instantaneous near-bed vertical velocity (Einstein, 1950; Velikanov, 1955; Yalin, 1963; Ling, 1995). In contrast, Bagnold (1956) hypothesized that particles remain in suspension as long as the turbulent eddies have dominant vertical velocity components, which would scale with the flow shear velocity, that exceed the particle settling velocity. This implies that to establish a dynamic equilibrium of sediment exchange, the flow must continuously pick up the sediment at the same rate with an upward velocity equalling (or exceeding) terminal fall velocity.

The critical bed shear stress concept asserts that bedload transport does not occur below the mean critical value of bed shear stress. However, Lavelle and Mofjeld (1987) studied historical data for incipient sediment motion and found that no true threshold value existed, and bedload transport could occur at any predicted threshold. This suggested that a single critical shear stress should not be included as an essential parameter when calculating bedload transport rates, agreeing with previous work from Paintal (1971) who observed that there was no distinct shear stress below which no single grain is entrained. Laursen et al. (1999) found that many values of the critical shear stress could be found for an equal-sized sediment particle, matching a similar number of sediment transport formulas available at the time. Since earlier developed diagrams showed a gap within the smooth and rough-flow regimes (Yalin and Karahan, 1979), further attempts conducting additional experiments and analysing the problem theoretically based on deterministic and probabilistic approaches, have been made to amend the Shields diagram to account for turbulent effects. Greater details on this
approaches can be found in the comprehensive surveys made by Miller et al. (1977), Buffington and Montgomery (1997), Paphitis (2001), and Dey and Papanicolaou (2008). Conclusions reached by these authors agree that a single mean value of shear stress is not an accurate estimate for sediment transport, and further consideration must be given to instantaneous turbulent parameters for a better characterization of flow-sediment interactions.

3.1.1 Turbulent bursting

Kline et al. (1967) found a cyclic process with turbulent flow near walls, in which the near-wall layer propagated slowly and then interacted strongly with the outer layer flow—an event known as ‘turbulent bursting’. At the beginning, the low-speed streak ejected away from the wall, and oscillations in both the spanwise and normal directions appeared. As the oscillations increased in amplitude, a breakdown (burst) occurred in the form of a violent and chaotic upward eruption of the low-speed fluid in the near-wall layer into the outer layer, termed usually as ejection. The ejection was soon followed by a sweep, in which the chaotic motion was swept away. The wall-layer streaks reappeared at different spanwise locations, and a new quiescent period began. The development of a horseshoe vortex showing the lifts, stretches, ejection, and sweep associated with velocity profiles (Please refer to Chapter 2, Fig. 2.3). The action of turbulent coherent flow structures related to such a sequence of turbulent bursting involving ejections and sweeps (Robinson, 1991) has been shown to play a central role in sediment entrainment (Cao et al., 1996).

This discovery of the turbulent bursting phenomenon led researchers to study the role of turbulence on particle entrainment and re-define criteria of sediment motion (Dey, 2011). Several laboratory studies have linked coherent motions in the turbulent boundary layer with resuspension (Grass, 1974; Sumer and Oguz, 1978; Sumer and Deigaard,
1981, Falco, 1991). Grass (1974) filmed the resuspension process due to turbulent flow over a flat sand bed, identified the coherent flow structures in the boundary layer, and calculated the velocities of the particles advected by such motions. This led directly to the conclusive link between the observed ejection of fluid away from the boundary layer and the corresponding response of bed sediment. This work also showed that the sweep events above the channel bed were more responsible for momentum transfer into the boundary layer than the ejection events. Sumer and Oguz (1978) and Sumer and Deigaard (1981) photographed intermittent, sweep-type fluid motions pushing sediment particles into the low-speed wall streaks; those particles were then subjected to upward, ejection-type fluid motions. Falco (1991) formulated an overall picture of the structure of the turbulent boundary layer in terms of experimentally identifying inner-outer wall region multiscale turbulent eddies and constructed a coherent motion model. Considering a flat-plate zero pressure gradient, boundary layer, Falco (1991) showed that a specific set of coherent structures in the turbulent boundary layer were dynamically significant for the transport of sediments. Further studies (Kaftori et al., 1995; Nelson et al., 1995; Niño and Garcia, 1996; Cellino and Lemmin, 2004) confirmed the importance of the bursting events in sediment resuspension and transport in fluvial environments. Previous studies suggested that the ejections were associated with entrainment of sediment particles into the water column, while sweeps were effective at transporting bedload (Cao, 1997; Dyer and Soulsby, 1988; Heathershaw, 1979; Soulsby, 1983; Keylock, 2007; Yuan et al., 2009). To distinguish between different processes, in this study the term ‘resuspension’ is used for particles initially laying on the bed and at some point lifted into the water column, in contrast to particles permanently in suspension (i.e., washload).

Heathershaw and Thorne (1985) conducted experiments in tidal channels flowing over sandy gravels in order to study the role of turbulent structures on sediment entrainment, and showed that entrainment was correlated with the near-wall
instantaneous streamwise velocity, and not with the instantaneous Reynolds shear stress. Drake et al. (1988) studied gravel mobility in alluvial streams and found that most of the gravel entrainment was associated with sweep events, which occurred during a small fraction of time at any particular location of the bed. The entrainment process was thus found to be episodic: short periods of high entrainment were interspersed with long periods of weak or no entrainment. Thorne et al. (1989) observed that turbulent coherent structures were the main transporters of coarse sedimentary material. Their experiment suggested that an instantaneous increase in streamwise velocity fluctuations generated excess boundary shear stresses, which drove the transport. Soulsby et al. (1994) made simultaneous measurements of the high-frequency fluctuations of concentration of sand suspended by a tidal current, and the horizontal and vertical components of the water velocity above the sandy bed of an estuary, and found that the large, upward sediment fluxes in the boundary layer were associated with ejection events. Kularatne and Pattiaratchi (2008) performed field experiments in the wave-induced flow environment of Floreat Beach, Perth, Western Australia, and concluded that higher sediment movements are associated with ejections rather than sweeps. In the tidal current environment of western Yellow Sea of China, Yuan et al. (2009) conducted experiments and noticed that ejection and sweep events caused most of the observed turbulent sediment flux.

Seminal work of Grass (1970) and Lavelle and Mofjeld (1987), along with the above-mentioned laboratory and field investigations have called for a revision of the critical velocity concept, proposing alternative statistical views of particle motion. Adrian (2007) investigated the structure of near-bed organized motion in the canonical forms of wall turbulence and suggested that quadrant analysis permitted evaluation of the turbulent bursting events to the total mean values of kinetic energy and dissipation. Diplas et al.
(2008) performed laboratory experiments to examine the role of turbulent fluctuations on particle movement under incipient flow conditions, and concluded that the duration of instantaneous turbulent events applied on a sediment grain was also significant in determining the sediment grain’s threshold of motion. In an attempt to propose a direct numerical simulation of bed load transport calculations, Schmeeckle and Nelson (2003) developed a model of bed load transport that captured the sources of fluid turbulence variability by directly integrating the equations of motion of each particle of a simulated mixed grain-size sediment bed. However, they also mentioned that with the knowledge of the velocity structure within the bedload layer, a complete model of bedload transport could be built that includes the importance of turbulence fluctuations in entraining grains at low to moderate transport stages, and also includes the feedback that moving grains have on the fluid velocity in the whole bedload layer, which is important for moderate to high transport stages. The entrainment of coarse sediment particles under the action of fluctuating hydrodynamic forces was investigated from an energy perspective by Valyrakis et al. (2013). They found that the energy approach to grain dislodgement, although directly linked to the impulse criterion, was demonstrated to be more versatile and intuitive, where the majority of the turbulent events performed sufficient mechanical work on the coarse grain for entrainment. Therefore, while research that moves beyond Reynolds stresses to incorporate quadrant analysis and ejection-sweep processes is an important advance (Dwivedi et al., 2011; Wu and Shih, 2012), further attempts can be taken to link two-dimensional quadrants and three-dimensional octants into sequences that reveal flow-sediment structure (Keylock et al., 2014).

Despite several attempts to develop a precise sediment entrainment theory merging turbulence features, it is widely recognized (e.g. Dey, 2011) that the effect of turbulent coherent structures on sediment motion and resuspension is yet to be fully
understood. The aim of this chapter, rather than developing a better transport equation, is to highlight the importance of instantaneous events on sediment resuspension, which were not considered when using the classical Shields diagram approach that uses a mean velocity concept. While the stochastic characteristic of turbulence discussed by Grass (1970) and posterior observations by Lavelle and Mofjeld (1987) demonstrated the need for using statistical tools to better conceptualize the process of sediment motion, the approach presented in this chapter takes a step further by (a) assessing the risk of overestimation of widely used sediment transport predictors (e.g. Shields, 1936; van Rijn, 1984; Soulsby, 1997; Soulsby and Whitehouse, 1997) following a mean critical velocity approach, and (b) verifying the relevance of such mean critical velocity concepts in terms of turbulent bursting phenomena. In this regard, laboratory experiments were performed where high-frequency acoustic data were recorded in fluvial conditions near the bottom boundary layer under unidirectional currents over a flat sandy bed. Data collected were post-processed using Reynolds decomposition, quadrant analysis, and wavelet transform methods, to clarify the turbulent characteristics and their effect on resuspension, both above and below the measured mean critical velocity test conditions.

3.2 Methodology

3.2.1 Laboratory set-up and experimental conditions

The experiments were conducted in a 54 m long, 2 m wide current flume located at the University of Cantabria, Santander, Spain. The flume contained an 18 m long, 0.20 m-deep, purpose-built sand bed (Fig. 3.2). The sediment was well-sorted silica sand with a grain size determined through sieve analysis as $d_{50} = 0.31 \text{ mm}$ with water depths of between $D = 0.16 \text{ m}$ and $0.42 \text{ m}$, sediment sorting coefficient, $S_o=1.72$, coefficient of gradation, $C_c=1.4$ and uniformity coefficient, $C_u=6$. 
Figure 3.2. Schematic diagram of the experimentation flume showing the key dimensions and ADV locations.

The three-dimensional, instantaneous flow velocities were measured using two Nortek Vectrino acoustic Doppler velocimeters (ADVs) with a sampling frequency of 50 Hz. The ADVs were located above the sand bed at distances of 5.5 m (ADV 1) and 8.5 m (ADV 2) from the beginning of the sand bed (Fig. 3.2 at an elevation, z=5 cm above the bed). Data from the near-bed ADV 1 is presented in this chapter where the mean flow speeds, $\bar{u}$, varied from 0.087 to 0.256 m/s, covering a range of boundary Reynolds number, $Re_p=\{342-1004\}$; flow Reynolds number, $Re_D=(\bar{u}D/\nu)=\{1.4\times10^4-4.1\times10^4\}$ and Rouse number, $P=w_s/ku_*=\{2.89-8.14\}$, where $u_*$ was calculated using the bed shear stress computed with Eq.4 at $z=5$ cm, $\bar{u}$ was mean velocity, $k_s$ was the von Kármán constant (assuming as 0.41) and $w_s$ was particle fall velocity calculated from Dietrich (1982).

The physical dimensions of the instruments determined the distance above the bed such that the sensor did not touch the flume bottom and would not be buried in the sand during the experiments. Since no bedforms developed during the experiments, the height of the sensors was constant for each test. The sand was flattened manually with a floor squeegee before each series (see Tinoco and Coco, 2014, 2016, for more details about the experimental set-up).
3.2.2 Data analysis techniques

Three experiments, each lasting 5 min, were conducted to study the effect of turbulent bursting on the resuspension of sediment in the range of above the measured critical velocity (AMCV) and below the measured critical velocity (BMCV) test runs. The critical resuspension velocity ($\bar{u}_{cr,\text{measured}} = 0.163$ m/s) was obtained through data from optical backscatter sensors (OBS) located at the same height of the ADVs. A threshold was considered when an OBS started recording a concentration higher than the background, meaning that the critical velocity was taken as the point of shifting the ‘mean’ concentration from one point to the higher point (Tinoco and Coco, 2014, 2016). The $\bar{u}/\bar{u}_{cr,\text{measured}}$ ratio for AMCV was between 1.04 and 1.57, and for BMCV was between 0.53 and 0.94. The results from two time series ($\bar{u}/\bar{u}_{cr,\text{measured}}= 1.23$ AMCV and $\bar{u}/\bar{u}_{cr,\text{measured}}= 0.59$ BMCV) were randomly chosen for detailed analysis in order to compare above and below the time-averaged measured critical velocity conditions. For both runs, data were used from the ADV 1 located 5 cm above the flat sand bed and 5.5 m from the upstream edge. The measured mean critical velocity was 0.163 m/s and the measured water depth was 0.16 m. Two time series (both from AMCV and BMCV runs) from three experiments at this depth were also used for comparison in the quadrant analysis results, and results from a 2 min segment of those two cases are shown for better clarity. The remaining three experiments with $D=0.42$ m and $z=5$ cm indicated similar trends, with bursting events occurring below and above the expected measured mean critical values.

Voulgaris and Trowbridge (1998) showed that ADVs can accurately measure mean flows, Reynolds stresses, and vertical turbulent components close to the bed within 1% of the estimated true values. Time series records of the ADVs’ high-frequency (50 Hz) velocity components (where $u =$ horizontal flow velocity, $v =$ transverse flow...
velocity, and \( w = \text{vertical flow velocity} \) were analysed using Reynolds decomposition (Fox et al., 2004), such that the flow was assumed to be composed of mean (overbar) and fluctuating (prime) parts:

\[
\begin{align*}
  u &= \bar{u} + u', \\
  v &= \bar{v} + v', \\
  w &= \bar{w} + w'.
\end{align*}
\] (3.3)

For easier visualization, a 1 s mean of the 50 Hz velocity time series was used. To comprehend the characteristics of the bursting events, the conditional statistics of the velocity fluctuations \((u' \text{ and } w')\) were plotted into the quadrants of a \(u'-w'\) plane (Lu and Willmarth, 1973), where \( u' \) is the turbulent velocity’s horizontal component and \( w' \) is the vertical component. Quadrants were named as ejection \((u'<0, w'>0)\), sweep \((u'>0, w'<0)\), up-acceleration \((u'>0, w'>0)\), and down-deceleration \((u'<0, w'<0)\) (Heathershaw and Thorne, 1985; Kularatne and Pattiaratchi, 2008; Thorne, 2014; Schmeeckle, 2015). Work from Keylock et al. (2014), has suggested the use of extending quadrant analysis into three dimensions (known as octant analysis) characterizing dominant flow structures, which can be linked to the entrainment of sediment from the bed and into suspension, and whose frequencies would dominate the velocity spectra and contribute the majority of the total shear stress. However, a widely used two-dimensional quadrant approach involving the \(u'-w'\) plane was chosen for this chapter due to the simplicity of its implementation and its efficacy in revealing aspects of turbulent flow physics that otherwise have remained unexplored.

Turbulent kinetic energy (TKE) shear stress was estimated using the three components of turbulent velocity \((u', v', \text{ and } w')\) near the bed (at \( z=5 \text{ cm} \)):

\[
\tau_{TKE} = 0.5 \rho C_1 (u'^2 + v'^2 + w'^2),
\] (3.4)
where $\tau_{TKE}$ is the TKE shear stress, $\rho$ is the fluid density, and $C_1$ is a coefficient which can be taken as 0.19 or 0.2 (Kim et al., 2000; Biron et al., 2004). In this analysis, $C_1=0.19$ was used to calculate the TKE shear stress.

The turbulent Reynolds stress was estimated near the bed as (Fox et al., 2004; Thorne, 2014)

$$\tau_{Re} = -\rho(u'w').$$  \hspace{1cm} (3.5)

ADV backscatter was used as a representation of suspended sediment concentration (SSC) based on the following equation (Fugate and Friedrichs, 2002; Voulgaris and Meyers, 2004):

$$EL = 0.43Amp + 20\log_{10}(R) + 2\alpha_w R + 20R \int \alpha_p dr,$$  \hspace{1cm} (3.6)

where $EL$ is the echo level in dB, $Amp$ is the amplitude in counts recorded by the ADV, $R=0.05$ is the range or distance between the transducer and focal point in metre, $\alpha_w=0.6$ (when salinity = 0 ppt for 1.5 MHz frequency, chosen from a list of values provided in Lohrmann, 2001) is the water absorption in dBm$^{-1}$, and $\alpha_p$ is the particle attenuation in dBm$^{-1}$ (Lohrmann, 2001). At low concentrations, the particle attenuation becomes very small (Lohrmann, 2001), therefore the fourth term (i.e. $20R \int \alpha_w dr$) was ignored in this study. Additionally, to better interpret the backscatter reading as a proxy of SSC, the signal processing digital ‘Butterworth’ filter was used as described in Thomson and Emery (2014). Since higher SSC produces higher backscatter amplitudes, EL is used to identify instantaneous increases of SSC resulting from sweeps and ejections. A concentration proxy ($c'$) was used as an indicator to identify variations in concentration of sediment in suspension which was also analysed using Reynolds decomposition (Fox et al., 2004), where the concentration proxy was assumed to be composed of mean (overbar) and fluctuating (prime) parts:
\[ c' = EL - \overline{EL} \]  

(3.7)

Wavelet analysis was used to identify localized variations of power within the time series (Torrence and Compo, 1998). The recorded time series were decomposed into timeframe space, and the dominant modes of variability and their variation in time were analysed as described in Grinsted et al. (2004). To limit the edge effects, the time series represented the region of spectrum where the effects might have been important (near large scales) by a ‘cone of influence’ (COI) following Torrence and Compo (1998). Farge (1992) suggested that continuous wavelet transform (CWT) unfolds the dynamics of coherent structures and measures their contribution to energy spectrum. Therefore, CWT was employed to derive the time evolution of momentum and sediment flux of turbulent coherent structures near the bottom boundary layer. Wavelet coherence (WTC) was also applied in order to expose regions with high common power showing phase relationships between the CWT of momentum and sediment flux.

### 3.2.3 Calculation of the threshold velocity

The mean velocity threshold for sediment movement was calculated using an average grain diameter \( d_{50} \) of 0.31 mm, a grain density \( \rho_s \) for wet sand of 2650 kgm\(^{-3}\), g gravity, and freshwater density at room temperature of 1000 kgm\(^{-3}\). Assuming the von Kármán constant as 0.41, and Nikuradse’s roughness \( z_0 \) was estimated using

\[
 z_0 = \frac{k_s}{30} \left( 1 - \exp \left( \frac{-u_*k_s}{27u} \right) \right) + \frac{u}{9u_*} , 
\]

(3.8)

with \( k_s = 2.5d_{50} \)

Several critical values can be thus calculated, ranging from 0.232 to 0.268 m/s, as shown in Table 3.1.
Table 3.1. Theoretical mean critical values for sediment entrainment at z=0.05 m compared in this study.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Equations</th>
<th>Calculated $\bar{u}_c$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shields (1936)</td>
<td>$\bar{u}_c = \frac{u}{k} \ln \left( \frac{z}{\delta} \right)$</td>
<td>0.268</td>
</tr>
<tr>
<td></td>
<td>$\bar{u}<em>c = \sqrt{\theta_c} (s - 1) g d</em>{50}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\theta_c$ from Shields diagram</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_p = \frac{u_\ast d_{50}}{n}$</td>
<td></td>
</tr>
<tr>
<td>van Rijn (1984)</td>
<td>$\bar{u}<em>c = 0.19 \ d</em>{50}^{0.1} \log_{10} \left( \frac{4D}{d_{50}} \right)$; $100 &lt; d_{50} &lt; 500 \mu m$</td>
<td>0.255</td>
</tr>
<tr>
<td></td>
<td>$\bar{u}<em>c = 8.5 \ d</em>{50}^{0.6} \log_{10} \left( \frac{4D}{d_{50}} \right)$; $500 &lt; d_{50} &lt; 2000 \mu m$</td>
<td></td>
</tr>
<tr>
<td>Soulsby (1997)</td>
<td>$\bar{u}<em>c = 7 \ \left( \frac{d</em>{50}}{d_{90}} \right)^{1/2} \left[ (\rho_s - 1) d_{50} \sqrt{D_s} \right]^{1/2}$</td>
<td>0.232</td>
</tr>
<tr>
<td></td>
<td>$s_p = \frac{\rho_s}{\rho} = \frac{\text{density of the sediment}}{\text{density of the fluid}}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D_s = \left[ \frac{g(\rho_s - 1) d_{50}}{\rho_s} \right]^{1/3}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$f(D_s) = 0.30 \left[ \frac{D_s}{1 + 1.2D_s} \right] + 0.055(1 - e^{-0.2D_s})$ for values of $D_s &gt; 0.1$.</td>
<td></td>
</tr>
<tr>
<td>Soulsby and Whitehouse (Soulsby, 1997)</td>
<td>$\bar{u}_c = \frac{u}{k} \ln \left( \frac{z}{\delta} \right)$</td>
<td>0.264</td>
</tr>
<tr>
<td></td>
<td>$\bar{u}_c = \left( \frac{u}{\rho} \right)^{1/2}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_c = \theta_c \left( \rho - \rho_s \right) d_{50}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\theta_c = \frac{0.30}{1 + 1.2D_s} + 0.055(1 - e^{-0.2D_s})$</td>
<td></td>
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</tbody>
</table>

3.3 Results

The scatterplots of the Reynolds and TKE bottom shear stresses for the AMCV and BMCV runs (Figs. 3.3a and 3.3b) showed that higher bed shear stress (i.e. values >5 N/m² of TKE and Re shear stress estimations of both AMCV and BMCV runs) was produced to generate sediment resuspension (as evidenced with backscatter intensity in Figs. 3.4c and 3.5c). Such comparison of the TKE and Re shear stress methods also suggested the presence of coherent flow structures in the turbulent flow which created highly localized and persistent variability near the bed, hence affecting the bed shear stress.
Figure 3.3. Comparison of the 1 s mean Reynolds and TKE shear stresses from (a) above the measured mean critical velocity ($\bar{u} > \bar{u}_{cr, measured}$) and (b) below the measured mean critical velocity ($\bar{u} < \bar{u}_{cr, measured}$) experiments with a 2 min period. The dashed red line defines the equality.

The velocity fluctuations ($u'$, $w'$), Reynolds shear stress ($u'w'$) and backscatter over a 2 min period (for better visualization of bursting events) from the AMCV and BMCV runs were compared identifying ejection and sweep events (Fig. 3.4, 3.5, respectively). This comparison offered considerable insight into the contribution of turbulence in terms of the events associated with sediment resuspension. Overall, in the time series significant variability and intermittency both in Reynolds stress ($u'w'$) and sediment resuspension (backscatter) was also revealed. Such intermittent nature of $u'w'$ was expected and observed previously in the laboratory (Grass, 1974; Sumer and Oguz, 1978; Sumer and Deigaard, 1981; Niño et al., 2003; Schmeeckle, 2015) and in the field (Heathershaw and Thorne, 1985; Drake et al., 1988; Soulsby et al., 1994; Kularatne and Pattiaratchi, 2008 and Yuan et al., 2009).
Figure 3.4. Time series records from above the measured mean critical velocity experiment ($\bar{u} > \bar{u}_{cr, measured}$): (a) turbulent velocity ($u'$, red in color; $w'$, blue in color); (b) turbulent Reynolds shear stress ($u'w'$), showing the ejection (red upward arrows) and sweep (blue downward arrows) events; (c) 1 s mean of the backscatter.

In more detail, the time series of the AMCV run showed 28 major resuspension events (Fig. 3.4) of which 18 of which demonstrated ejections (at 5, 9, 17, 24, 30, 38, 49, 54, 66, 77, 83, 86, 98, 99, 101, 107, 109 and 116 s) and 10 of these events revealed sweeps (at 21, 25, 32, 42, 46, 53, 58, 61, 75, and 90 s), which confirmed that high resuspension events were mostly associated with ejection and sweep type motions rather up-acceleration and down-deceleration events during the analysed record. The same pattern was observed for the 2 min period of BMCV run where 25 major resuspension events were observed (Fig. 3.5) of which 15 were identified as ejections (at 2, 7, 19, 26, 38, 47, 52, 72, 77, 87, 90, 93, 100, 113 and 116 s) and 10 of these events confirmed sweeps (at 1, 32, 41, 46, 54, 60, 67, 79, 107, and 112 s). Such resuspension events identified below the measured critical velocity support the theory of the non-existence of a unique time-averaged critical shear stress as suggested by Paintal (1971) and Lavelle and Mofjeld (1987). The plot of the BMCV run further indicated that though flow conditions were
below the critical velocity conditions; sediment resuspension was observed due to ejection and sweep events.

**Figure 3.5.** Time series records from below the measured mean critical velocity experiment (\(\bar{u} < \bar{u}_{cr, measured}\)): (a) turbulent velocity (\(u', w'\)); (b) turbulent Reynolds shear stress (\(u'w'\)), showing the ejection (red upward arrows) and sweep (blue downward arrows) events; (c) 1 s mean of the backscatter.

Contributions to \(u'w'\) were also observed in four quadrants of the \(u'-w'\) plane with a threshold value (backscatter above 10 dB) both for AMCV and BMCV runs (Fig. 3.6). The plots clearly showed that the large contribution of \(u'\) and \(w'\) were associated with ejections and sweeps rather than up-acceleration and down-deceleration events. AMCV results were similar with previous studies (Cellino and Lemmin, 2004; Yuan et al., 2009). The distribution of turbulent components for BMCV in the \(u'-w'\) plane reflected a similar pattern which established that resuspension events can occur even below a critical threshold value. BMCV conditions, where mean velocity was 59% of the critical velocity, showed a similar behaviour to AMCV conditions. Similarities were also found in the other data sets within the range of \(\bar{u}/\bar{u}_{cr, measured}\) ratio; for AMCV between 1.04 and 1.57, and for BMCV between 0.53 and 0.94.
Figure 3.6. Classification of bursting events in $u'-w'$ space identifying ejection, sweep, up-acceleration, and down-deceleration events both for above and below the measured mean critical velocity conditions.

We performed a quadrant analysis to determine the frequency of different bursting events and their contributions to the Reynolds stress (i.e. $u'w'$). The occurrence percentages of four types of bursting motions, as well as their contributions to the momentum flux ($u'w'$) and sediment flux ($c'w'$) for the AMCV and BMCV experiments, are shown in Figs. 3.7 and 3.8, respectively. The results for the $u'w'$ signals for the AMCV and BMCV experiments agreed with the results from earlier studies (Wallace et al., 1972; Willmarth and Lu, 1972). For both AMCV and BMCV experiments, ejection and sweep events were the dominant source of the Reynolds stress; however, although the time occupied by ejection was comparable with, or even less than, that of sweep, ejection contributed more to the net Reynolds stress (AMCV = 49%; BMCV = 43%) as shown in Figs. 3.7a,b and 3.8a,b. Ejection (AMCV = 38%; BMCV = 38%) and sweep (AMCV = 37%, BMCV = 30%) mainly generated the upward sediment flux (Figs. 3.7c and 3.8c), which suggested the intense upwelling of low-speed fluid parcels with high-sediment-entrainment events was the main source of the overall sediment flux. In contrast, up-
acceleration (AMCV = 12%; BMCV = 14%) and down-deceleration (AMCV = 13%; BMCV = 18%) events transported less sediment (Figs. 3.7c and 3.8c). Thus ejection and sweep contributed more to the total turbulent sediment flux (AMCV = 75%; BMCV = 68%) than up-acceleration and down-deceleration events (AMCV = 25%; BMCV = 32%). Such consistent results in both AMCV and BMCV confirm the need to develop transport rate formulas that consider instantaneous Reynolds stress concepts along time-averaged critical velocities.

**Figure 3.7.** Quadrant analysis of coherent structures in above the measured mean critical velocity ranges (\(\bar{u} > \bar{u}_{cr, measured}\)) showing the (a) time occupied, (b) momentum flux (\(u'w'\)), and (c) sediment flux (\(c'w'\)). The error bars represent the maximum and minimum values of the total data.

**Figure 3.8.** Quadrant analysis of coherent structures in below the measured mean critical velocity range (\(\bar{u} < \bar{u}_{cr, measured}\)) showing the (a) time occupied, (b) momentum flux (\(u'w'\)), and (c) sediment flux (\(c'w'\)). The error bar represents the maximum and minimum values of the total data.

CWT and WTC analysis (Grinsted et al., 2004) for AMCV and BMCV runs offered a more intuitive way to visualize the turbulence data in both time and space (Figs. 3.9 and 3.10, respectively). In the presented scalograms, at higher periods (i.e. low-
frequency events), the power felt within the range of COI (i.e. the shaded region in the scalograms) which limited the capability to investigate the temporal evolution of the specific peak frequencies as stated in Section 3.2.2. Hence, investigation was restricted to examine high-frequency events occurring at timescales up to 32s for both runs. Overall, the scalograms (Figs. 3.9 and 3.10) traced the dynamics of coherent structures and then measured contribution to the sediment flux. It also revealed that within the large-scale motions (considering period bands >0.5s as large-scale motions), there existed multi-scale [e.g. in AMCV time series of ~47-52s, period band ~2-8s (large scale) and ~0.0625-1s (small scale); in BMCV time series of ~82-85s, period band ~2-8s (large scale) and ~0.0625-2s (small scale)] and some embedding small fine-scale (e.g. in AMCV at ~22-25s, period band ~0.0625-0.5s; in BMCV at ~22-23s, period band ~0.0625-1s) features. This suggested that both for AMCV and BMCV runs, near the bed, most of the energy was concentrated within the high period (warmer colour >0.5s) associated with the mean flow properties for both momentum flux and sediment flux. Results also showed that highly energetic turbulent events (i.e. warmer colour >0.5s) occurred:

i) Sporadically throughout the time series (e.g. in AMCV at 5, 9, 17, 21, 24, etc; in BMCV at 1, 2, 7 19, etc), especially in gradually developing clusters (considering clusters developed taking >2s time) that sustained short periods (i.e. lasted <1s) in the dominant streamwise-vertical plane of the flow near the bed,

ii) For longer periods (up to several seconds from a turbulence perception, in our case ~2-10s), vertically in the water column.

iii) At lower frequencies for both runs. The larger clusters felt over ~1 and 8s period band for both AMCV and BMCV runs, while the fast evolving clusters (considering those lasting up to 2s) stretched between ~0.0625 and 0.5s period band before weakening.
Figure 3.9. Wavelet power spectra (Morlet wavelet) for above the measured mean critical velocity experiment ($\bar{u} > \bar{u}_{cr, measured}$) for a 2 min period showing the (a) momentum flux ($u'w'$), (b) sediment flux ($c'w'$), and (c) coherence between the momentum and sediment fluxes.

Table 3.2. Major ejection (shaded cells) and sweep (white cells) events in the presented AMCV and BMCV time series.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) AMCV</td>
<td>5 9 17 21 24 25 30 32 34 39 42 46 49 53 54 58 61 66 75 77 83 86 90 98 99 101 107 109 116</td>
</tr>
<tr>
<td>(b) BMCV</td>
<td>1 2 7 19 26 32 38 41 46 47 52 54 60 67 72 77 79 87 90 93 100 107 112 113 116 - - -</td>
</tr>
</tbody>
</table>
Figure 3.10. Wavelet power spectra (Morlet wavelet) for below the measured mean critical velocity experiment ($\bar{u} < \bar{u}_{cr,\text{measured}}$) for a 2 min period showing the (a) momentum flux ($u'w'$), (b) sediment flux ($c'w'$), and (c) coherence between the momentum and sediment fluxes.

This was evident in the colour coded contours (Fig. 3.9a) which were associated with ejection and sweep events for AMCV runs (Table 3.2a). Similarly, for BMCV runs; it was evident with ejection and sweep events (Table 3.2b). In addition to that, in AMCV runs; momentum flux corresponded to the contour in sediment flux within similar period bands both in ejection and sweep events as shown in Figs. 3.9a and 3.9b in relation to Table 3.2a. A similar pattern was also observed in BMCV runs in the ejection events, as well as in the sweep events where momentum and sediment flux coincide with each other showing similar period bands (Fig. 3.10a and 3.10b, in relation to Table 3.2b). The WTC was applied to the momentum and sediment flux for both runs where common features were noticed as shown in Figs. 3.9c and 3.10c in relation to Table 3.2a and 3.2b. Both for AMCV and BMCV runs, during the identified ejection and sweep events (as
mentioned in Table 3.2a, 3.2b) the coherence was found to be higher (i.e. warmer colour >0.5s), suggesting that the transport mechanism relies greatly on the production of momentum flux by coherent structures in order to contribute to the sediment flux. For instance, the ejection event identified at 9s in the AMCV run (Table 3.2a, Fig. 3.9c) shows higher correlation between momentum and sediment flux (i.e. warmer colour > 0.5s) with period band ranging between ~0.5s and 3s. A similar trend was observed throughout the time series of AMCV and BMCV runs.

### 3.4 Discussion
In this study, the well-known Shields criterion, estimated using mean velocities, along with some of the most commonly used empirical curves (i.e. van Rijn, 1984; Soulsby 1997; Soulsby and Whitehouse 1997, which are also derivatives of Shields diagram) were investigated in order to re-examine the prediction of sediment threshold performance (Fig. 3.11). In the figure, the grey shaded areas defined the range of the AMCV and BMCV mean velocities presented in this study. The calculated critical values using different approaches were shown in red dotted lines. Our measured critical velocity is clearly below the calculated Shields (1936); Soulsby (1997); van Rijn (1984); and Soulsby and Whitehouse (1997) critical velocity conditions [i.e. measured mean critical velocity, $\bar{u}_{cr, measured}=0.163$ m/s < 0.268 m/s (Fig. 3.11d), 0.232 m/s (Fig. 3.11e), 0.255 (Fig. 3.11f), and 0.264 (Fig. 3.11g) respectively]. This suggested that the widely used above-mentioned empirical methods which are believed to be significant for the design of movable-bed channels as well as for future experimental investigations, potentially overestimated the transport of sediment by 1.64, 1.56, 1.42 and 1.61 times considering Shields (1936); van Rijn (1984); Soulsby (1997), and Soulsby and Whitehouse (1997) (Fig. 3.11) approaches respectively. Both reported cases, with mean velocities of AMCV ($\bar{u}= 0.200$ m/s) and BMCV ($\bar{u}=0.096$ m/s), above and below our measured threshold ($\bar{u}_{cr}$,
measured = 0.163 m/s), showed evidence of sediment in suspension, further showing that the mean critical stress approach also underpredicts the transport of sediment. Although it is still common to conceptualize the mechanics of sediment transport as a time-averaged approach, this approach sustained due to the lack of enough experimental and/or field data to perform stochastic analyses. Availability of such data, as those we present, advances our understanding of the turbulence structure and their role in transport processes.

![Figure 3.11](image)  
**Figure 3.11.** Schematic diagram showing the measured and calculated mean critical velocities.

Comparison of test results, where mean velocity was 1.23 times higher as well as 0.59 times lower than the measured mean critical velocity, showed strong similarities without major exceptions (Figs. 3.4 and 3.5). Although near-bed velocity and average transport rate were greater in AMCV runs, the peak instantaneous Reynolds stress were close (i.e. $u'w' > 0.05 \text{ m}^2/\text{s}^2$) in the identified peak ejection and sweep events shown in the Figs. 3.4b, 3.5b) in both AMCV and BMCV runs. Both ejection and sweep events contributed to the forward momentum flux as well as sediment flux, showing that the concept of time-averaged critical velocity by itself cannot provide a full representation of the physical processes in action in the resuspension of sediment.
In both tests (AMCV and BMCV), ejection and sweep events were the largest contributors to momentum transfer. Up-acceleration and down-deceleration events led to marginal effect on transport of momentum and sediment flux compared to the other two events (Fig. 3.6). Previously, performance of quadrant analysis by Heathershaw and Thorne (1985) and Nelson et al., (1995) and performance of octant analysis by Keylock et al. (2014) advised that up-acceleration and down-deceleration events were the individually effective means of resuspending sediments. However less net sediment flux was accomplished by these events in AMCV and BMCV runs presented here. This could be related to the strength of the up-acceleration and down-deceleration events which were much weaker and could not carry sediment particles to a higher level where the sampling volume was placed (i.e., 5 cm above the bed). It is also noteworthy that up-acceleration and down-deceleration events contributed less significantly with a positive stress.

Buffington and Montgomery (1997) put forward a survey suggesting that many attempts have so far been made to modify the Shields diagram, conducting additional experiments and analysing the problem theoretically based on deterministic and probabilistic approaches. Several researchers have presented laboratory or field evidence supporting the close correlation between the instantaneous sediment flux and instantaneous streamwise velocity (u), suggesting that only sweeps and up-accelerations play a significant role in the entrainment and transport of sediment, since these motions were associated with positive u’ and thus greater streamwise velocities (Thorne et al., 1989; Nelson et al., 1995; Weaver and Wiggs, 2008). However, investigation presented in this chapter under AMCV and BMCV conditions showed similarities with other research groups which documented that sweeps and ejections were the primary contributors to sediment entrainment (Grass, 1970, 1974; Sumer and Deigaard, 1981; Best, 1992; Niño and Garcia, 1996; Hurther and Lemmin, 2003). In contrast, direct
numerical simulation (DNS) provides a new tool for examining turbulent structure of the flow (e.g. Mathis et al. 2013). However, further development is required to apply the DNS approach to intermittent turbulent bursting events both in fluvial and geophysical flows (Venditti et al., 2013). For example, Mathis et al. (2014) estimated bed shear-stress using conventional methods and the DNS modelling approach and reported a large disparity between the two methods where an order of magnitude difference between the levels of energy spectra was observed. While DNS has the potential to develop methodologies for the prediction of bursting events and associated sediment resuspension mechanisms, its application on large-scale, complex flows still remains limited (e.g. Schmeeckle and Nelson, 2003). Experimental investigations such as the one developed herein, will allow the use of new and existing data from acoustic velocimetry sensors to further identify and characterize such turbulent events. Direct observations of bursting events will in turn better inform DNS methods to better account for flow interactions.

Quadrant analysis showed that, in BMCV runs, ejection (in which low-speed fluid moves away from the boundary towards the outer layer) entrained particles away from the bed in order to maintain them in suspension as it was in AMCV runs (Figs. 3.7 and 3.8). Sweeps, (in which high-speed fluid moves near the wall), with a negative contribution, impacted on the particles in resuspension by pushing them towards the bed. Moreover, the time occupied in both AMCV and BMCV runs was almost identical and contributed in similar percentage to instantaneous momentum and sediment flux as well. Diplas et al. (2008) demonstrated that in addition to the magnitude of the instantaneous turbulent forces applied on a sediment grain, the duration of these turbulent forces is also important in determining the sediment grain’s threshold of motion, and that their product, or impulse, is better suited for specifying such conditions. This was evident in the results presented here both in AMCV and BMCV conditions where the time occupied by the
ejection and sweep events (which were also evidenced to play the dominant role in the momentum flux and sediment flux) were significantly higher in comparison to the up-acceleration and down-deceleration events. The understanding of accounting temporal contribution of bursting events presented in this study as well as discussed in Diplas et al. (2008) and Diplas and Dancey (2013) calls for consideration of the hydrodynamic impulse (i.e. value of force multiplied by required time for the accomplishment of the event) as a comprehensive criterion in the development of future models to predict particle entrainment.

Wavelet analysis was useful to diagnose characteristics of turbulence in order to explain information about the spatial structure of the flow. Particularly, the frequency content and energy variation (Figs. 3.9 and 3.10) were in focus. Previously, experimental investigation by Shugar et al. (2010) showed that stacked series of wavelet plots indicated that clusters of low-frequency coherent flow structures initiated close to the bed, grew with height above the bed, and then broke up as they were advected downstream, with their decay possibly being linked to topographically induced flow acceleration. The frequency at which these structures were generated was suitably predicted by the models of Driver et al. (1987) and Simpson (1989) for variation in separation zone size and wake flapping, respectively. Measured data as presented in this chapter in BMCV runs were consistent with AMCV runs as well as with previous investigations. Therefore, it can be stated that the cross-wavelet transform method was effective at visualizing and detecting the coherent structures from the raw turbulent data, which enabled to study the correlation between wall turbulence structures and sediment resuspension.

3.5 Concluding remarks
This chapter reports on an investigation on the validity of using the mean critical shear velocity of sediment to define thresholds of sediment resuspension. Although Lavelle and
Mofjeld (1987) previously reviewed the concept of critical stress for the initial motion of non-cohesive sediment beds under turbulent flow conditions suggesting the non-existence of true threshold in the movement of sediment, their conclusions were based on photographic observations employed in conjunction with current measurements to infer sediment thresholds in the field. Likewise, the work from Niño and Garcia (1996) and Niño et al. (2003) identified such instantaneous events from high-speed videos, which limit the number of captured and analysed events. This chapter examined the influence of turbulent coherent structures on sediment resuspension for flows both above and below the measured mean critical resuspension velocity over a flat sandy bed using widely used acoustic instruments. The presented methodology can be used on existing data sets from researchers using ADVs or ADCPs in either laboratory or field settings to identify turbulent structures and their effect on suspended sediment concentration if synchronous records of acoustic backscatter exist. Such observations presented in this chapter are also necessary to clarify our view of turbulent coherent structures in resuspending sediments both in low and high Reynolds-number flows while leading to widespread application of DNS.

Our results showed that the measured mean critical velocity alone is not sufficient to predict episodic initiation of motion, as turbulent events can move sediment even at mean flow conditions below the thresholds defined by time-averaged stresses. Measured fluctuations of turbulent Reynolds stress evidenced to move sediments at lower turbulent stresses than expected. Instantaneous particle entrainment occurred earlier than the suggested measured time-averaged critical velocity due to the stochastic nature of turbulence. Although near-bed shear stress can be used to estimate bedload transport, significant special variations in the magnitudes and durations of the ejection, sweep, up-acceleration and down-deceleration play a significant role in sediment resuspension. The
implications of sediment motion at Reynolds shear stress below the expected critical conditions further suggested that instantaneous shear stress has an important contribution to entrain particles, which cannot be predicted with a time-averaged critical velocity.

To the best of found knowledge, there is no universal agreement on identifying a unique threshold for initiation of motion or resuspension of sediment (e.g. how many grains rolling, for how long, over what area coverage) in the literature. This study demonstrated that turbulent bursting events induce sediment resuspension events at mean velocities below typical mean critical values. Statistical assessment suggests that the existing definition of threshold can be improved by incorporating turbulent effects for an accurate description of the processes involved that will result in better predictions of sediment transport. The results of this study are instrumental in resolving an important research question: how can turbulent bursting events best be incorporated into a theoretical model describing the sediment entrainment process? The analysis detailed herein on identification of bursting events and their contribution toward the near-bed Reynolds shear stress production governing sediment motion provides new avenues to answer such a question, incorporating the use of wavelet analysis on time series of acoustic backscatter or signal intensity readily available from commonly used acoustic velocimetry instruments (ADVs and ADCPs) as a powerful tool for investigating such processes. The fact that a similar methodology can be applied to existing field and laboratory data sets that focused on velocity but collected an indicator of signal backscatter as part of the data record, further highlights its potential in future research to elucidate a more complete understanding of the interactions between flow and sediment transport over complex topography.
Chapter 4: Sediment resuspension due to near-bed turbulent coherent structures on the continental slope

Summary

Sediment transport equations often consider a mean velocity threshold for the initiation of sediment motion and resuspension, ignoring event-based turbulent ‘bursting’ processes. However, laboratory experiments have suggested that near-bed sediment resuspension is influenced by intermittent turbulent coherent structures (Chapter 3). In the field, accessibility constraints for deployment of easily operated equipment has largely prevented further identification and understanding of such processes which may contribute to resuspension in the marine environment. Field experiments were conducted on the Northwest Shelf, Australia, under conditions where the mean current velocities were below the estimated time-averaged critical velocity to investigate the relationship between near bed turbulent coherent structures and sediment resuspension. Results indicate that sediment resuspension occur even when velocities are below the mean critical values. The majority of turbulent sediment flux is due to ejection and sweep events, with lesser contributions from up-acceleration and down-deceleration (vertical flow) events. Spectral and quadrant analysis indicated the anisotropic and intermittent nature of Reynolds stresses, and wavelet transform revealed a group of turbulent bursting sequences associated with sediment resuspension. These observations were in flow conditions where resuspension was not expected to occur based on mean threshold calculations. The results show that intermittent turbulent events control to sediment resuspension rather than existence of a single time-averaged mean critical velocity. This highlights the need of considering turbulence as a significant factor in sediment resuspension and should be further investigated for inclusion into future sediment transport equations and modelling of sediment movement.
4.1 Introduction

Accurate knowledge of sediment transport mechanisms is crucial for a variety of problems ranging from river and coastal engineering to environmental science (Mei et al., 1997; Buffington, 1999; Wolanski et al., 2003; Robinson et al., 2005; Thompson et al., 2013; Kondolf et al., 2014). Despite extensive research in this field, including a large number of experimental studies (as detailed in Dey, 2011), the ability to estimate sediment transport is still hindered by a lack of understanding of all the physical processes contributing to sediment entrainment and resuspension (Dwivedi et al., 2012; Aagaard and Jensen, 2013).

Most previous engineering and sedimentological applications have related sediment resuspension to a time-averaged bed shear stress. This concept suggests that sediment erodes and become re-suspended when the bed shear stress exceeds a critical value (e.g. Shields, 1936). However, Kline et al. (1967) discovered a cyclical, non-periodic process in fluids, a ‘turbulent bursting’, where the wall layer spreads slowly over a large period of time and then interacts strongly with the outer layer flow in an event-like manner. Bursting events involve a horseshoe or hairpin vortex, which travels centrifugally and ejects low speed fluid away from the bed, experiencing a partial breakdown into turbulence (an event known as ‘ejection’). High-speed fluid can also move towards the bed (identified as ‘sweep’). The vortex has transverse dimensions similar to the associated boundary-layer streaks, and keeps these general dimensions all over its lifespan (Allen, 1985; Wu and Shih, 2012).

This discovery of the ‘bursting phenomenon’, provided a new perspective to explore resuspension processes in turbulent flows. For clarity, in this study the term ‘resuspension’ is used for particles initially on the seabed and at some point in time ‘lifted’ into the water column, in contrast to particles permanently in suspension (i.e., washload).
Several laboratory studies established relationships between coherent motions within the turbulent boundary layer and sediment resuspension (Sutherland, 1967; Grass, 1974; Sumer and Oguz, 1978; Sumer and Deigaard, 1981). In a laboratory alluvial stream bed, Sutherland (1967) noticed that the entrainment of sediment was a result of the impact of a near bed eddy onto the bed particles, producing a streamwise drag force able to role the sediments. Grass (1974) investigated the resuspension process due to turbulent flow in strictly flat sand bed conditions, associating the ejection of fluid away from the boundary with the resultant response of bed sediment. Ejections conveyed a greater upward momentum flux of the particles than the downward flux and so were capable to resuspend particles denser than the fluid. Further laboratory studies using photographic techniques were conducted by Sumer and Oguz (1978), and Sumer and Deigaard (1981). They detected that the sweep events intermittently pushed bed particles into the near-wall turbulence and then the particles were subjected to upward ejection events. Falco (1991) experimentally noticed the multiscale turbulent eddies in the inner-outer wall region and developed a coherent motion model. Focusing on a flat plate, zero pressure gradient boundary layer, this study revealed that a particular set of coherent structures in the turbulent boundary layer were dynamically important for the movement of sediment. More recent experiments (Kaftori et al., 1995; Nelson et al., 1995; Niño and Garcia, 1996; Mao, 2003; Cellino and Lemmin, 2004; see also Chapter 3) have supported previous results and highlighted the importance of turbulent bursting in laboratory conditions relating the ejections to sediment entrainment into the water column, and sweeps effectively transporting bedload (Cao, 1997; Dyer and Soulsby, 1988; Heathershaw, 1979; Soulsby, 1983; Keylock, 2007; Yuan et al., 2009).

Heathershaw and Thorne (1985) investigated the role of turbulent structures on sediment entrainment. Conducting experiments in tidal channels, they argued that
entrainment was not correlated with the instantaneous Reynolds shear stress but with the near-wall instantaneous streamwise velocity. Observations by Drake et al. (1988) on the mobility of gravels in alluvial streams suggested that the majority of gravel entrainment was associated with sweep events giving rise to the motion of particles. These events occurred episodically during a small fraction of the time at any particular location on the bed. Thorne et al. (1989) observed that only sweeps and outward interactions played a significant role in the transport of coarse sedimentary material. It was the instantaneous increase in streamwise velocity fluctuations that generated excess boundary shear stresses in order to drive the transport process. In a microtidal saltmarsh channel, French and Clifford (1992) noticed that on average around 90% of the total intermittent Reynolds shear stress contributed to resuspend sediments for 50% of the total sampling time. Soulsby et al. (1994) demonstrated a significant link between the bursting process and the suspension of sediment within boundary layers. They made simultaneous measurements of the high-frequency fluctuations of the concentration of sand, resuspended in a tidal current, and the horizontal and vertical components of the water velocity, above a sandy bed of an estuary. They showed that large upward fluxes of sediment were associated with ejection events. Field experiments by Couturier et al. (2000) showed that the macroscale flow modules intensified the ‘ejection-like’ turbulent events and sediment resuspension. ‘Ejection’ events were associated with decreasing horizontal velocity and increasing turbidity, whilst ‘sweep’ events were present during increasing horizontal velocity and decreasing sediment concentration. Yuan et al. (2009) conducted field experiments in the western Yellow Sea of China and suggested that the majority of turbulent sediment flux was the result of ejections and sweeps, whilst contributions from up-acceleration and down-deceleration events were significantly less.
The timed-averaged bed shear stress threshold concept for initiation of motion has long played a central role in sediment transport theory (e.g. since Shields, 1936). However, several investigations (e.g. Nelson et al., 1995; Niño and Garcia, 1996; Mao, 2003; Cellino and Lemmin, 2004; see also Chapter 3) reconsidered this concept and suggested that the turbulent bursting-based sediment entrainment has a major influence on sediment resuspension. For instance, Grass (1971) and Lavelle and Mofjeld (1987) concluded that based on empirical evidence, even at very low values of mean bed shear stress, turbulent fluctuations in instantaneous bottom shear stress as well as the random exposure of bed grains to the flow made it possible for particles to move. To our knowledge, limited field studies have been reported in this regard where mean flow speeds were below the time averaged critical velocity. In one such investigation, O'Callaghan et al. (2010) examined the physical mechanisms underpinning sediment resuspension in the Swan River estuary, Western Australia, where mean currents were lower than critical levels, but yet showed large turbidity events during intertidal oscillations. Similarly, experimental evidence conducted by Yang et al. (2016) in the shallow marine environment of southern Yellow Sea, China, suggested that the resuspension of sediment was related to intermittent turbulent events, where mean current velocity was lower than is predicted by existing threshold models.

Although field observations of turbulent coherent structures have been conducted regularly, field experiments with below-critical velocity conditions are relatively scarce [e.g. O'Callaghan et al. (2010); Yang et al., (2016) as mentioned above]. To the best of found knowledge, no in-situ observational study in deep water conditions of the continental slope region has been performed to investigate the impact of bursting on below-critical flow fields, due to the lack of accessibility to the sites and availability of robust, easily operated deep-water field equipment to measure turbulent velocity and
acoustic backscatter (as a surrogate measure of suspended sediment concentration) simultaneously close to the seabed to estimate sediment resuspension. In the deep ocean systems (i.e. continental slope and continental shelf regions), engineers need to incorporate the influence of seabed mobility into the design of large scale marine infrastructure [e.g. platforms (rigs), subsea pipelines, jackets, and associated constructions such as subsea-mattresses and well-heads etc]. However, consideration of the effect of nearbed turbulence coherence structures on sediment mobility (i.e. sediment entrainment, resuspension leading to erosion and scour) in the stability analysis of marine engineering structures are still elusive. This is a major omission because transport of sediment can increase the risk of instability of such structures. Furthermore, Leckie et al., (2016) suggested that in the deep water systems (similar locations as investigated in this chapter), transport of sediment related to subsea pipelines causes changes in benthic habitat conditions. Therefore, investigating turbulent bursting based sediment transport process has significance for the better understanding of deep sea aquatic life.

All these abovementioned issue are good reasons to explore the deep water systems of the continental slope and to investigate the influence of turbulent bursting on the transport of sediment. Therefore, the aim of this chapter is to describe the temporal and spatial relationships between the near-bed turbulent coherence structures and sediment resuspension in the continental slope region, in particular when mean velocities are below the estimated and measured critical velocities. In-situ observations presented herein at the southern end of the Northwest Shelf (NWS), provide a unique perspective to further understand the interactions between sediment resuspension and turbulent characteristics on deep water conditions where measured and calculated (considering widely used transport equations) mean critical velocity are rarely exceeded.
4.2 Study area and methodology

4.2.1 Site description, conditions and instrumentation

This study was an industry based project, in collaboration with Apache Energy, an oil and gas company, using their remotely operated vehicles (ROVs) to deploy acoustic instrumentation on the seafloor. Data were collected from the southern end of the NW Shelf along the continental slope in 375m water depth. The bathymetry at the site was observed to be only gently sloping as the continental slope was quite wide in this location and it was still in the transitions stage, with only a small degree of slope. The instrument was deployed from a drilling rig located in the Van Gogh oil field (Fig. 4.1) using a sub-sea ROV which had real-time cameras and multi-functional arms (Fig. 4.2).

A sediment core was taken during the deployment adjacent to the site location, revealing very fine sand, sieve analysis determined with a mean particle size diameter $d_{50} = 1 \times 10^{-4}$ m, sediment sorting coefficient, $S_o = 1.70$, coefficient of gradation, $C_c = 1.3$ and uniformity coefficient, $C_u = 6$ through sieve analysis. Near the Van Gogh site, sediment samples were dominated by calcium carbonate ($\text{CaCO}_3$) deposited along a consistently flat terrain (AE, 2008; BHPB, 2012). These sediment classifications were consistent with previous investigations by Harris and Baker (1988). The drawback of taking measurements around the drilling rig was the presence of drill spoils which came from drilling of the well, and the deployed instrument might have measured this drilling spoils as the sediment concentration. Therefore, the deployment location was carefully selected considering a more open area that had less spoils so that it did not affect the results of the typical sediment movement of the area.

The NW shelf region experiences strong semidiurnal tides (Holloway, 1983) with the tidal motion dominated by the principal lunar (M2) and principal solar (S2)
constituents (Holloway 1983; Pattiaratchi 2007). Spring tides can produce a range of over 6m (Holloway 1983), and these tides are the main forcing of currents in the bottom boundary layer on the continental shelf and slope (Katsumata 2006; Swain, 2008). This suggests that the currents change direction twice a day, consisting four slack tides per day. The bottom boundary layer currents were up to a speed of 0.2ms\(^{-1}\) (Holloway & Nye 1985). The global ocean currents were also observed along the shelf where the chief current ran counter to the anti-clockwise flowing Eastern Boundary Current, and flows strongest away from the equator down the west coast of Western Australia during February – June. This unusual current is known as the Leeuwin Current and has maximum speed of approximately 0.25ms\(^{-1}\) over the shelf break (Holloway & Nye 1985). This current is driven by a pressure gradient that overwhelms the opposing southeast dominant winds to flow from the north east parallel to the coast towards the North West Cape and swings south to continue to follow the edge of the Australian continent (Woo 2005, ). This current has been noted although its influence on the bottom velocity currents will probably be negligible compared to the tidal currents and internal currents. The other influence on the shelf currents is internal waves (Grant & Madsen 1986; Antenucci & Ivey 2006; Nikora, Goring & Ross 2002; Swain, 2008). Attenucci & Ivey (2006) found that large, local increases in energy levels gave peak speeds varying from 0.59ms\(^{-1}\) to 1.87ms\(^{-1}\) for events lasting between 8 and 24 hours on the North West Cape in 302m of water. These waves can cause the velocities to go beyond the threshold value for sediment resuspension, but also cause turbulence, which can encourage the bursting phenomenon. Boegman and Ivey (2009) have shown that resuspension of sediment from shoaling internal waves was directly attributed to the near-bed viscous stress and near bed patches of elevated positive Reynolds stress generated by the vertical structures. They also found that elevated near-bed viscous stresses were found throughout the domain at locations that were not correlated to the resuspension events, and that while these stresses were
required for the sediment motion, it was not necessarily a precursor for resuspension (Boegman & Ivey, 2009), much like the results found for bursting (Soulsby 1983, Robinson 1991; Swain, 2008).

Data were collected continuously for a 23-hour period starting at 15:00 on September 26th, 2008, for a semidiurnal tidal cycle using a Nortek AS Vector Current Meter with titanium housing, rated to a depth of 3000m and a flexible head with a 2m long cable. Time series of the velocity in ENU (East, North, Upwards) coordinates and backscatter were recorded at a sampling rate of 8Hz. The acoustic Doppler velocimeter (ADV) was mounted looking downward where the sampling volume was located at 0.303m above the seabed where the height was considered as consistent due to the low current speed which did not change the dynamics of the visually observed flat bed with no presence of sand waves. The supply of sediment from the local bed rather advected in since no cyclone was there and low current speed. In this study the spectral frequency analysis suggested that the frequencies that were important influences on the motions of turbulence. These are the forcing frequencies in the system that gave peaks in sediment suspension concentrations as well as corresponding peaks in the current velocities. Although their causes were not being determined from this study as this was outside of the scope of the project, they are noted for future comparison of the hydrodynamics of the area. The tidal prediction for the area was compared to the temperature measurements taken by the ADV. The temperature can be used as a rough indication of the movement of water bodies of the area and so should roughly match the tidal prediction. As the tide comes in it should bring with it colder water from further down the continental slope, which will register with a lag behind the predicted tidal changes, and after the tide changes, the ebb tide should bring with it warmer water from the coast. These general characteristics were seen to occur, although there were many fluctuations in the
temperature recorded which indicated the interaction between the tide and local currents and other present water bodies. The other indication that the temperature gave was the presence of gravity waves. A sudden drop in the temperature was identified as an indication of a bottom surge, and although internal waves are known to occur on the continental shelf, none were believed present in the data. The history of tropical cyclones passing in the vicinity of the deployment location was also reviewed and no storms of sufficient strength to create sediment mobility were noted. Tidal currents and solitons are, however, known to create strong water movements through this area.

**Figure 4.1.** Bathymetric map of the NWS showing the study site (red dot), located 53 km north-northwest of Exmouth in Van Gogh (-21° 23’ 51.63″N, 114° 04’ 04.89″E). Contour lines represent water depth in meters.
Figure 4.2. Real-time camera view showing the instrumental setup while ROV extracting the instrument from the sea-floor (For better interpretation of ‘ROV extracting the instrument’, interested readers can watch the video 4.1 attached with the digital version of this thesis).

4.2.2 Calculation of the threshold velocity

The velocity threshold for initiation of motion at the deployment location (Van Gogh) was calculated using mean grain diameter ($d_{50}$) of $1 \times 10^{-4}$ m, a grain density ($\rho_s$) for Calcite (CaCO$_3$) of 2710 kgm$^{-3}$ [Allen, 1985] and seawater density of 1025 kgm$^{-3}$. Using von Kármán constant as 0.41, and obtaining Nikuradse’s roughness $z_0$ with:

$$z_0 = \frac{k_s}{36} \left(1 - \exp\left[-\frac{u_*}{k_s}\right]\right) + \frac{v}{9u_*} \tag{4.1}$$

with $k_s = 2.5d_{50}$

Several approaches were used to estimate critical velocities for initiation of motion (Table 4.1) where relationships from Shields (1936), van Rijn (1997), Soulsby (1997) and
Soulsby and Whitehouse (1997) were used to obtain mean threshold values that ranged between 0.281 and 0.679 m/s.

Table 4.1. Theoretical mean critical values for sediment entrainment at z=0.303m compared in this study.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Equations</th>
<th>Calculated $\bar{u}_c$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shields (1936)</td>
<td>$\bar{u}<em>{cr} = \frac{u</em>*}{v} \ln \left( \frac{z}{z_0} \right)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\bar{u}<em>c = \sqrt{[\theta</em>{cr}(s-1)gd_{50}]}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\theta_{cr}$ from Shields diagram</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_p = \frac{u_*d_{50}}{v}$</td>
<td></td>
</tr>
<tr>
<td>van Rijn (1984)</td>
<td>$\bar{u}<em>{cr} = 0.19 d</em>{50}^{0.5} \log_{10} \left( \frac{d_{50}}{d_{50}} \right)$; $100 &lt; d_{50} &lt; 500 \mu m$</td>
<td>0.520</td>
</tr>
<tr>
<td></td>
<td>$\bar{u}<em>{cr} = 0.5 d</em>{50}^{0.6} \log_{10} \left( \frac{d_{50}}{d_{50}} \right)$; $500 &lt; d_{50} &lt; 2000 \mu m$</td>
<td></td>
</tr>
<tr>
<td>Soulsby (1997)</td>
<td>$\bar{u}<em>{cr} = \frac{7}{\sqrt[3]{d</em>{50}}} \left[ \theta_{cr}(s-1) \right]^{1/2} d_{50}$</td>
<td>0.679</td>
</tr>
<tr>
<td></td>
<td>$\bar{u}_c = \frac{\rho_s}{\rho}$ density of the sediment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\theta_{cr} = \frac{(s-1)gd_{50}}{u_{<em>}^2} f(D_</em>)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D_* = \left( \frac{\rho_s - \rho}{\rho} \right)^{1/3} d_{50}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$f(D_<em>) = 0.30 \left[ \frac{1}{1+1.2D_</em>} \right] + 0.055(1-e^{-0.020D_*})$</td>
<td></td>
</tr>
<tr>
<td>Soulsby and Whitehouse (Soulsby, 1997)</td>
<td>$\bar{u}<em>{cr} = \frac{u</em>*}{v} \ln \left( \frac{z}{z_0} \right)$</td>
<td>0.281</td>
</tr>
<tr>
<td></td>
<td>$\bar{u}<em>c = \sqrt{[\theta</em>{cr}(s-1)gd_{50}]}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\theta_{cr} = \frac{(s-1)gd_{50}}{u_{*}^2}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\bar{u}<em>c = \frac{7}{\sqrt[3]{d</em>{50}}} \left[ \theta_{cr}(s-1) \right]^{1/2} d_{50}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.30 \left[ \frac{1}{1+1.2D_<em>} \right] + 0.055(1-e^{-0.020D_</em>})$</td>
<td></td>
</tr>
</tbody>
</table>

4.2.3 Measurement of in-situ mean critical velocity

A mean critical velocity can be determined in the field by tracking the changes in suspended sediment concentration and hydrodynamic conditions (Andersen et al. 2007; Shi et al. 2015). We measured mean critical velocities by identifying the mean longitudinal ($u$) tidal velocity (i.e. main direction of the flow), turbulent kinetic energy (TKE) shear stress, and backscatter readings where sediment entrainment was just initiated (a detailed description of the methods for estimating TKE shear stress and backscatter reading can be found in section 4.2.4).

Earlier studies suggest that the near-bed backscatter readings are always above a specific value meaning that there is a background suspended sediment concentration within the water column (Van de Kreeke et al. 1997; Wang et al 2009). Such background is likely due to the prevailing hydrodynamic conditions and the near-bed suspended
sediment and organic matter which has insufficient time to settle (Wang et al 2009, Yang et al., 2016).

In this study, the measured critical value was identified at some specific moments during the observation periods where the backscatter records were plotted with tidally induced mean velocity in the u direction, where the near-bed backscatter responded significantly to mean velocities on several occasions (events: i, ii, iii, iv, v in Fig. 4.3). The data indicated that the backscatter intensity, TKE shear stress and mean velocity all had local maxima corresponding to time stamps: (i) 236 minutes, (ii) 270 minutes, (iii) 376 minutes, (iv) 457 minutes and (v) 628 minutes with the mean velocity reached approximately 0.15 m/s (Fig. 4.3). At the same time, field data indicated that background sediment concentration remained similar throughout the tidal cycle at the observation site.

![Figure 4.3](image_url)

**Figure 4.3.** Time series between 40-800 minutes identifying events at (i), (ii), (iii), (iv), (v): (a) 1 minute mean absolute u-directional velocity, (b) TKE bed shear stress and (c) backscatter reading near the bed. The horizontal dashed line (green in color) showed the threshold resuspension velocity and the vertical dashed lines (purple in color) showed the relevant seabed resuspension occurrence. Time Series-1 (TS-1) and Time Series-2 (TS-2) between 46 to 48 minutes and 128 to 130 minutes respectively are the segments (two-minute long each) presented in this chapter for detailed analysis.
4.2.4 Data analysis

A total of twenty data sections, each of two-minute duration, was analysed and was focused on data with a mean current velocity lower than the calculated and measured critical velocities. Prior to analysis, the data were split in 2-minute segments, as is often done in this type of study in order to simplify the trends to best represent the data for visualization without losing any pattern (Soulsby et al., 1994; Kularatne and Pattiaratchi, 2008; Yang et al., 2016). Here, analysis from two such two-minute time series (between 46 to 48 minutes TS-1 and 128 to 130 minutes TS-2. Fig. 4.3) are presented. These two segments reflect similar patterns found throughout the whole time series (i.e. throughout the 20, two-minute series). An axis rotation algorithm based on Principle Component Analysis (PCA) was used along horizontal coordinates to transform the East (u velocity) component as the main direction of the flow for each section of the data (Emery and Thomson, 2001; Westra et al., 2010).

Spectral analysis was conducted based on spectral energy cascade theory (Kolmogorov, 1941) for the three-dimensional inertial subrange spectrum. Reynolds decomposition was used to determine the turbulent characteristics (French and Clifford, 1992; Emery and Thomson, 2001; Kularatne and Pattiaratchi, 2008). Due to the difficulty in identifying clear trends with the time series sampled at 8Hz, a one-second mean was used, as reported in previous studies (Heathershaw and Thorne, 1985; Chanson et al., 2007; Kularatne and Pattiaratchi, 2008; Yuan et al., 2009; Yang et al., 2016) to facilitate analysis. Quadrant analysis identified the frequency of occurrence of each individual event within a bursting process as: ejection (u'<0, w'>0), sweep (u'>0, w'<0), up-acceleration (u'>0, w'>0), and down-deceleration (u'<0, w'<0) (Izadinia, et al., 2013; Kwoll et al., 2016). We considered single point measurements of turbulent velocity fluctuations using ADV to calculate Reynolds and turbulent kinetic (TKE) shear stress.
(McLelland and Nicholas, 2000) widely used in previous field investigations (Heathershaw, 1979; Soulsby, 1983; Couturier et al., 2000; Kularatne and Pattiaratchi, 2008; Yuan et al., 2009). Kim et al., (2000) compared four different methods of bed shear stress estimations in the field conditions measured at 0.440 m above the bed where they successfully obtained unbiased results of bottom stress. Their finding concluded that ADV sensors should be close enough to the bed within the constant stress layer but simultaneously sufficiently far to avoid problems associated with velocity shear within the sampling volume. Therefore, in line with other previous experiments in the field conditions (e.g. Yuan et al., 2009 and Yang et al., 2016 who measured bottom stress at 0.450 m and 0.500 m above the bed respectively), measurements were conducted at 0.303 m above the bed considered as the optimum sensor height. The ADV also recorded the reflection of the acoustic signal from particulate matter in water. This backscatter reading was adopted as a proxy of suspended sediment concentration (SSC) where ejection and sweep events were identified using echo level (EL), considering the higher backscatter amplitudes produced by higher SSC. A concentration proxy (c') was also used as an indicator to identify variations in concentration of sediment which was analysed using Reynolds decomposition (Fox et al., 2004). To reveal the dynamics of coherent structures and measure their contribution to the energy spectrum, continuous wavelet transform (CWT) and wavelet coherence (WTC) were employed to derive the time evolution of momentum and sediment flux of turbulent coherent structures near the bottom boundary layer as described by Grinsted et al. (2004). Greater details of the data analysis techniques were presented in section 3.2.2 of Chapter 3.

4.3 Results

Time series records of turbulent velocities were used to obtain the frequency (f) spectra and the f spectra were then converted to wave number (k) spectra following Taylor’s
hypothesis of “frozen turbulence” (Soulsby, 1983). The velocity spectra agreed with the 
-5/3 slope in the inertial subrange (Taylor, 1938), in the range \(0.4 < k < 3 \text{ m}^{-1}\) and \(0.3 < k < 3 \text{ m}^{-1}\) for the two time series TS-1 and TS-2, respectively (Fig. 4.3). In the case of TS-1, the inertial subrange spectral slope was 1.67 (~5/3) for \(u\), 1.67 (~5/3) for \(v\) and 1.25 (~5/4) for \(w\) (Fig. 4.4a). For TS-2 the inertial subrange spectral slope was 1.67 (~5/3) for \(u\), 2.5 (~5/2) for \(v\) and 1.25 (~5/4) for \(w\) (Fig. 4.4b). The presence of ‘inertial subrange’ in both the time series confirmed the existence of turbulent structures dominating the TKE transfer process at the deployment location where the motions were governed by the inertial effects with viscous effects negligible (Ferziger, 2005). The -5/3 spectral slope in measurements close to the seabed is not common (Hino et al., 1983; George et al., 1994; Smyth and Hay, 2003; Kularatne and Pattiaratchi, 2008) since the closer to the seabed, the less steep the slope of vertical velocity spectra in the inertial subrange (Smyth and Hay, 2003). The observed spectral results were consistently determined the existence of the inertial subrange in the rest of the dataset which provided confidence for further analysis of small eddy turbulent coherent structures.

**Figure 4.4.** Wavenumber spectra of the velocity components between (a) 46–48 minutes (TS-1) and (b) 128-130 minutes (TS-2), where blue is the East component (\(u\)), magenta is the North component (\(v\)) and green is the vertical component (\(w\)). The solid line shows the -5/3 gradient of the energy dissipation equation.
The scatterplot of bottom shear stress term between TKE and Reynolds methods for the observed two time series (TS-1, TS-2) indicates that intermittent higher shear stress (i.e. values $> 0.1 \times 10^{-4}$ $m^2/s^2$) of TKE- and Re-shear stress term estimations of both TS-1 and TS-2 runs, red dots in Fig. 4.5) result in sediment resuspension (backscatter intensity on Figs. 4.6 and 4.7 respectively where the horizontal solid red line in 4.6a, 4.7a indicated higher shear stress values i.e. negative values $>0.1 \times 10^{-4}$ $m^2/s^2$). Biron et al. (2004) conducted experiments using a circulating flume with a mobile sediment bed using uniform-sized sand ($d_{50} = 1\times 10^{-4}$ m), and suggested that in a simple turbulent boundary layer the TKE estimates were systematically lower than Reynolds estimates at high stress levels. Therefore, Reynolds shear stress was a better choice when turbulent measurements were available. In this study, there was a reasonable relationship (i.e. with slope 1:1) between the two shear stress calculations, but with slight deviation towards the Re shear stress which is in general quantitative agreement with Biron et al. (2004). In addition to that, for single point measurements, Heathershaw (1979) suggested that the near-bed value of Re shear stress provided a better estimation of the highly intermittent nature of turbulence. Hence, Reynolds shear stress was chosen for further investigation.
The trends in Reynolds shear stress and backscatter were examined. The mean current velocity was $\bar{u}=0.053$ m/s, 66.25% of the measured time-averaged critical velocity ($\bar{u}_{cr}=0.08$ m/s) for TS-1 (Fig. 4.6). Overall ejection and sweep events occurred marginally more often than the up-acceleration and down-deceleration events, resulting in a larger contribution to the momentum and sediment fluxes. In greater detail, twenty-eight major resuspension events were analysed in detail, identifying fifteen events during ejections and thirteen during sweeps as shown in Fig. 4.6 and Table 4.2a. Similarly, in TS-2 where the mean current velocity ($\bar{u}=0.07$ m/s) was 87.5% of the measured time-averaged critical velocity ($\bar{u}_{cr}=0.08$ m/s) twenty-nine major resuspension events were analysed in detail, identifying sixteen events during ejection and thirteen during sweep (Fig. 4.7 and Table 4.2b). Both time series showed that high resuspension events below the measured time-averaged critical velocity were associated with ejections and sweeps, which was consistent with all the 20 sections investigated in this study. In the deep water field conditions of the continental slope (as studied here), identification of such resuspension
events due to the turbulent bursting features particularly ejections and sweeps, supports the argument of the non-existence of a mean critical velocity. Additionally, results further indicate that, although flow conditions were below the measured mean critical velocity conditions, sediment resuspension was prominently observed to be due to ejection and sweep events.

**Figure 4.6.** Time series records of the selected two-minute period between 46-48 minutes (TS-1) where \( \bar{u} (0.053 \text{ m/s}) < \bar{u}_{cr, measured} (0.080 \text{ m/s}) \): (a) turbulent Re shear stress \( u'w' \), showing ejection (up arrows) and sweep (down arrows) events, and (b) one-second mean of the backscatter.
Figure 4.7. Time series records of the selected two-minute period between 128-130 minutes (TS-2) where $u (0.070 \text{ m/s}) < u_{\text{cr, measured}} (0.080 \text{ m/s})$: (a) turbulent Re shear stress $(u'w')$, showing ejection (up arrows) and sweep (down arrows) events, and (b) one-second mean of the backscatter.

Table 4.2. Major ejection (shaded cells) and sweep (white cells) events in the presented (a) TS-1 and (b) TS-2 time series.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) TS-1</td>
<td>3 6 12 15 19 22 25 30 33 40 45 48 50 53 57 62 67 71 74 79 87 90 95 98 105 110 114</td>
</tr>
<tr>
<td>(b) TS-2</td>
<td>6 9 15 21 23 28 30 37 41 45 47 52 55 59 63 69 70 71 75 79 86 89 94 97 103 105 108 113 118</td>
</tr>
</tbody>
</table>

The contributions of $u'w'$ from the selected two-minute periods were separated into the four quadrants of the $u'-w'$ plane considering a threshold value $|u'w'| > 5 \times 10^{-5}$ (Fig. 4.8a); $|u'w'| > 20 \times 10^{-5}$ (Fig. 4.8b). Both figures showed a clear lack of large contributions (i.e. red dots for values above the thresholds) in up-acceleration and down-deceleration, compared to the ejections and sweeps. The scattering of turbulent components in the $u'-w'$ plane below the time-averaged measured critical velocity was consistent in the whole dataset. Such a distribution of turbulent components in the $u'-w'$ plane established that ejection and sweep events can occur even below a measured critical threshold value in deep sea conditions.
Figure 4.8. Classification of bursting events in $u'-w'$ space mentioning ejection, sweep, up acceleration and down declaration of the selected time series between (a) 46-48 minutes (TS-1) and (b) 128-130 minutes (TS-2) where red and grey dots for values above and below the thresholds respectively.

Quadrant analysis was used to quantitatively evaluate the intermittency and determine the contributions of the four kinds of bursting events to the Reynolds stress for TS-2 as a representation of the twenty datasets (Fig. 4.9). Below the measured critical velocity, it was observed that ejections and sweeps were the dominant sources of Reynolds stress generation. Time of occurrence, net Reynolds shear stress, and sediment flux by ejections (29%, 37% and 35% respectively) were equivalent with sweeps (31%, 37% and 34% respectively) while the up-acceleration and down-deceleration events made significantly less contributions to all three cases. Furthermore, the histograms (Fig. 4.9) showed that the upward sediment flux was prominently accomplished by ejections (37%) and sweeps (37%) suggesting intense surge of low-speed fluid containing high sediment concentration and high speed fluid rushing towards the bed were the main provider of $c'w'$ (i.e. ejection = 35% and sweep = 34% in sediment flux). Up-acceleration (17%) and down-deceleration (15%) events transported significantly less sediment. Collectively,
turbulent sediment flux primarily occurred as a result of ejection and sweep events (69%), with a smaller contribution from up-acceleration and down-deceleration events (32%).

**Figure 4.9.** Quadrant analysis of coherent structures of the selected two-minute period between 128 to 130 minutes (TS-2, where $\bar{u} < \bar{u}_{cr, measured}$) showing the (a) time occupied, (b) momentum flux ($u'w'$), and (c) sediment flux ($c'w'$). The error bars represent the maximum and minimum values of the analysed total dataset (twenty 2-minute long sections).

In order to examine the relationship between momentum ($u'w'$) and sediment fluxes ($c'w'$), CWT and WTC were performed with 8 Hz sampling rate over the selected two time series of TS-1 and TS-2 (Figs. 4.10 and 4.11). In the scalograms, the white-shaded region represents the ‘cone of influence’ (COI) where the image might be distorted due to edge effects limiting the capability to investigate the lower frequencies (see Section 4.2.4). Hence, we limited the investigation to examine high frequency events occurring over duration of up to 32s. In general, the two scalograms (Figs. 4.10 and 4.11) clearly showed the existence of multi-scale turbulent structures.
Figure 4.10. Squared wavelet coherence of the TS-1 between 46-48 minutes (where $\bar{u} < \bar{u}_c$) showing the (a) momentum flux ($u'w'$), (b) sediment flux ($c'w'$), and (c) coherence between the momentum and sediment fluxes.

Figure 4.11. As Figure 4.10 but for TS-2 between 128-130 minutes.
Results of the two time series (TS-1 and TS-2) also showed that high energy turbulent events (i.e. warmer colour >0.5s) occurred intermittently throughout the records (e.g. in TS-1 at 3, 6, 12, 15 etc; in TS-2 at 6, 9, 15, 21 etc), in slowly evolving groups (considering clusters developed taking >3s time). Such events continued over short times (i.e. lasted <2s) in the dominant streamwise-vertical plane near the bed, and for longer times in turbulence perspective (e.g. up to several seconds, in our case ~2-10s), vertically up in the water column as well as at lower frequencies. In TS-1, the larger groups fell over short bands of frequency scales (periods of predominantly 8 and 32s); while the rapidly evolving bands (considering those lasting up to 2s) were spread over a larger range of frequency scales (primarily between 0.5 and 2s) before fading. This was evident in the color coded contours (Fig. 4.10 with corresponding ejection events in Table 4.2a) where momentum flux corresponded to the contour in sediment flux within similar period bands. A similar trend was found during sweeps (Fig. 4.10 with corresponding sweep events in Table 4.2b). The Wavelet Coherence (WTC) was applied to the turbulent fluctuations of the momentum and sediment flux where such shared features were observed (Fig. 4.10c, 4.11c in relation to the Table 4.2). Resuspension events and turbulent stresses at a range of scales exhibited high common power (i.e. warmer colour >0.5s). For instance, the ejection event identified at 6s in the TS-1 (Table 4.2a, Fig. 4.10c) revealed a higher correlation between momentum and sediment flux (i.e. warmer colour > 0.5s) with the period band ranging between ~0.5s and 1s. At smaller frequencies, these regions of significant common power occurred near the bed for a majority of the time. Consistently, in TS-2, the larger groups fell over short bands of frequency scales (periods of predominantly 8 and 32s); while the rapidly evolving bands (considering those lasting up to 2s) spread over a larger range of frequency scales (primarily between 0.5 and 8s) before fading. This was evident in the colour coded contours (Fig. 4.11 with corresponding ejection events in Fig. 4.7 and Table 4.2b) where momentum flux corresponds to the
contour in sediment flux within similar period bands. A similar trend was found during sweeps, (Fig. 4.11 with corresponding sweep events in Fig. 4.7 and Table 4.2b). Similar to TS-1, the WTC was applied to the turbulent fluctuations of the momentum and sediment flux where such shared features were observed (Fig. 4.11c, Table 4.2b). Resuspension events and turbulent stresses at a range of scales exhibited high common power. At lower frequencies, these regions of significant common power occurred near the bed for majority of the time. Such results were also observed in the remaining dataset.

An inter comparison between widely used sediment motion criteria (Shields 1936, van Rijn, 1984; Soulsby 1997; Soulsby and Whitehouse 1997, primarily derived from Shields diagram) and measured mean critical velocity was undertaken to examine the validity of threshold predictors in the deeper ocean (water depths ~375m). The measured mean critical velocity was clearly below the calculated Shields (1936); van Rijn (1984); Soulsby (1997) and, Soulsby and Whitehouse (1997) threshold values (Fig. 4.12). This indicated that the well-known empirical methods, which are well established for the practical engineering design of movable-bed channels, potentially underestimate the transport of sediment by 3.5, 3.8, 6.5 and 8.5 times considering Soulsby and Whitehouse (1997), Shields (1936); van Rijn, (1984) and Soulsby (1997) (Fig. 4.12) approaches, respectively. In both cases with mean velocities of TS-1 (\( \bar{u} = 0.053 \) m/s) and TS-2 (\( \bar{u} = 0.070 \) m/s), below our measured threshold (\( \bar{u}_{cr}, \) measured=0.080 m/s), provided evidence of sediment in suspension.
Figure 4.12. Schematic diagram showing the measured (red solid line) and calculated mean critical velocities (blue dotted lines) where the grey shaded area defined the range of the mean velocities below the time averaged measured critical velocity analysed in this study.

4.4 Discussion

Previous studies (Lavelle and Mofjeld, 1987; Niño and Garcia, 1996; Niño et al., 2003) revised the concept of critical stress for the initial motion of non-cohesive sediment beds under turbulent flow conditions suggesting the non-existence of true threshold in the movement of sediment. Their conclusions were based on photographic observations employed in conjunction with current measurements limiting the number of captured and analysed events. This issue was explored in Chapter 3 through the analysis of high resolution (50 Hz) acoustic data in laboratory conditions and provided evidence for resuspension of sediments below the time-averaged, mean measured and calculated critical velocities. However, such conditions in deep water systems were not investigated
but are an important avenue to explore for several reasons. Firstly, the deep seabed resuspension process has a great impact on the local marine ecology, therefore, such investigation in continental slope regions will create opportunities for marine biologists to investigate further the role of sediment resuspension on aquatic life which were previously assumed to occupy regions of no sediment transport regions. Secondly, existing design guidelines for subsea infrastructures do not provide guidance on how the effects of sediment mobility can be taken into account in the stability analysis of deep water marine structures with respect to turbulence induced sediment entrainment. This necessitates improved predictions of pipeline burial resulting from scour and/or sedimentation caused by resuspension in the deep water systems, especially in locations where mean current velocities are below both the measured and calculated mean critical velocities.

Previously, turbulence data in the laboratory conditions as detailed in Chapter 3 provided evidence for resuspension of sediments below the time-averaged mean measured and calculated critical velocities. However, such conditions in the deep water systems were not investigated. It can now be established that both ejection and sweep events contributed to momentum flux as well as sediment flux in a deep-water environment. This demonstrate that the concept of time-averaged critical velocity, by itself, cannot provide a full representation of the physical processes in action in the resuspension of sediment in the unidirectional laboratory flow conditions.

The observed dependence of sediment resuspension on turbulent bursting events (in particular, ejections and sweeps) below time-averaged critical velocity conditions raises fundamental questions concerning the way in which sediment is transported in such flows is theorized. Our results call for the development of a new generation of turbulence incorporated transport models.
Researchers have presented laboratory and field evidence supporting the close correlation between the instantaneous sediment flux and instantaneous streamwise velocity (u), suggesting that only sweeps and up-accelerations play a significant role in the entrainment and transport of sediment, since these motions were associated with positive u′ and thus greater streamwise velocities (Thorne et al., 1989; Nelson et al., 1995; Weaver and Wiggs, 2008). However, with respect to the impact on transport of momentum and sediment flux, our study observed that ejection and sweep events strongly dominated over up-acceleration and down-deceleration events (Figure 4.8a, 4.8b). While previous investigations (e.g. Heathershaw and Thorne, 1985; Thorne et al., 1989; Nelson et al., 1995) found that up-acceleration and down-deceleration events considerably contributed to sediment resuspension, our investigation showed lower net sediment fluxes accomplished by such events. Our results, below measured time averaged critical velocity conditions, agree with other research which have documented that sweeps and ejections were the primary contributors to sediment entrainment (Grass, 1970, 1974; Sumer and Deigaard, 1981; Best, 1992; Niño and Garcia, 1996; Hurther and Lemmin, 2003). It must be noticed that our sampling volume was placed at a higher level above the bed (i.e., 0.303m), and weaker up-acceleration and down-deceleration events might not have carried sediment particles to such an elevation. Still, in our measurements, up-acceleration and down-deceleration events contributed less effectively.

Wavelet analysis provided a complementary approach to the traditional Fourier spectrum analysis diagnosing characteristics of turbulence in order to explain information about the spatial structure of the flow. Particularly, we were interested in its frequency content and energy variation (Figs. 4.10 and 4.11). The time series TS-1 and TS-2 through wavelet analysis indicated clusters of low-frequency coherent flow structures were initiated close to the bed. In agreement with the laboratory work of Driver et al. (1987) and Simpson (1989) that indicated the frequency at which coherent structures were
generated, our study revealed that at higher frequencies the intermittent and relatively large momentum regions exhibited a direct role in resuspension of sediment. Therefore, it can be stated that the cross wavelet transform method was effective at visualizing and detecting the coherent structures from the raw turbulent data, which enabled us to study the correlation between wall turbulence structures and sediment resuspension.

4.5 Concluding remarks

A full understanding of sediment transport can contribute greatly in the design specification of marine infrastructures in terms of reducing the risk factor of underestimating the transport rate of sediments. Therefore, the uniqueness of this study is that particle micromechanics were examined in terms of turbulent bursting features under deep water conditions where the mean current velocity was low. In particular, it was demonstrated that each turbulent event, relative to the time frame of measurement contributed to the suspension process below the mean critical velocity conditions. Our results showed consistency with laboratory studies (Chapter 3) where the mean current flow was below the measured mean critical velocity conditions. Quadrant analysis suggested that, in agreement with previous laboratory and field experiments, sediment flux was largely controlled by ejections and sweeps. Instantaneous particle entrainment occurred earlier than the suggested measured time-averaged critical velocity due to the stochastic nature of turbulence. Wavelet analysis revealed signatures of correlation between wall turbulent structures and sediment resuspension. Over time, turbulence occurred in slowly evolving clusters, that were closely followed by periods of high resuspension events near the bed, evolving from the primary leading scales towards low frequencies, and decaying in time after the termination of the turbulent event. Whilst sediment resuspension is related to a single time-averaged value of critical shear stress, our measurements demonstrated the importance of the instantaneous Reynolds shear
stress effects which in our observations appear to be a significant source of resuspension, resulting in the occurrence of resuspension well below the mean critical threshold.
Chapter 5: Sediment resuspension due to near-bed turbulent coherent structures in the nearshore

Summary

Previous laboratory and field experiments suggest that near-bed sediment resuspension is influenced by intermittent turbulent coherent structures (Chapters 3 and 4). In this chapter, the role of turbulent coherent structures in two contrasting nearshore environments (strong unidirectional currents in a tidal inlet and a swell dominated beach) were examined using an acoustic High Resolution Doppler current profiler. Here, the single point measurements in Chapters 3 and 4 were extended to include multiple point measurements in the boundary layer. These observations were analysed to examine the turbulent coherent structures resuspending sediment. The temporal and spatial turbulent characteristics of the measured data suggested that at three sampling heights above the bed: (1) the contribution of turbulent bursting events; (2) the dominating role of ejection and sweep events to the total sediment flux; and, (3) the correlation of turbulent bursting sequences with intense sediment resuspension in the wavelet analysis were identical. The field results also confirmed the findings in Chapters 3 and 4 suggesting the necessity of considering turbulence as an essential parameter to be considered into future modelling of sediment movement.

5.1 Introduction

An understanding of sediment resuspension in the bottom boundary layer of coastal waters is important for developing solutions to engineering problems such as coastal protection, beach nourishment, erosion due to coastal floods etc. In this regard, much research has been pursued proposing various sediment transport equations and models (e.g. Brownlie, 1981; van Rijn, 1984; Pattiaratchi and Collins, 1985; Soulsby and Whitehouse, 1997; Wu and Wang, 1999; Paphitis, 2001). However, our ability to predict
sediment transport is still limited because of the insufficient knowledge on relevant hydrodynamic and physical processes contributing to mobilization and suspension of sediment into the water column (Aagaard, 2013).

In existing sediment transport equations, the fluid turbulence was introduced as a mean Reynolds shear stress usually calculated using a drag coefficient. However, Kline et al. (1967) discovered a repetitive collective process in the fluid flow which involves sequence of events known as turbulent ‘bursting’ phenomenon. At the beginning, low-momentum streamwise fluid leading to outward eruption of the fluid at the boundary leading to the development of hairpin-like (horseshoe) vortices that are stretched and deformed to create tilted three-dimensional structures (an event known as ejection). Later these vortices become unstable and after disintegrating, high-speed fluid is brought to the boundary forming a high-speed streak (an event known as a ‘sweep’). These features of ‘bursting’ phenomenon attracted a great deal of attention to investigate the role of turbulence on sediment entrainment in order to improve the criterion of existing transport equations (Dey, 2011). In the laboratory several studies have been found establishing a substantial link between coherent motions in the turbulent boundary layer with resuspension (Grass, 1974; Sumer and Oguz, 1978; Sumer and Deigaard, 1981; Kaftori et al., 1995; Nelson et al., 1995; Mao, 2003; Cellino and Lemmin, 2004, Kassem et al., 2015). On the other hand, due to the inherent difficulties of conducting large-scale experiments in the field which are both labour and equipment intensive, only a small number of studies have been conducted in highly variable unidirectional and oscillating natural flow environments.

In a tidal channel of the South coast of England, Heathershaw and Thorne, (1985) investigated the role of turbulent structures on sediment entrainment deploying electromagnetic current meters. They established a link between bursting phenomena and sediment movement arguing that the sediment entrainment was correlated with the
intermittent turbulent events rather instantaneous Reynolds shear stress. With the poor instrumental facility they captured and analysed limited events and determined that sweeps cause maximum transport and outer flows produce considerable sediment movement over a specific stress range. Observations by Drake et al. (1988) on the mobility of gravels in alluvial streams using motion-picture photography suggested that the majority of gravel entrainment was associated with sweep events giving rise to the motion of particles. These events occurred episodically during a small fraction of the time at any particular location on the bed. Thorne et al. (1989) conducted measurements of the near-bed turbulent current flow and the bedload transport of marine gravel in the tidal environment using electromagnetic current meters, passive acoustic system and an underwater TV camera. They noticed that only sweeps and outward interactions derived a critical role in the transportation of coarse sedimentary material. Overall the transport process continued due to the instantaneous increase in streamwise velocity fluctuations which generated excess boundary shear stresses. Measurements made by French and Clifford (1992) within a macrotidal marsh channel using a two-component electromagnetic current meter, offered a fundamentally different perspective on the nature and range of fluid motions to that provided by conventional impellor-type sensors. They noticed that on average ~90% of the total stress was contributed in 50% of the total sampling time. These results differed from those of Gordon (1974) and Heathershaw (1974), both of whom reported approximately 60% of the total stress contributed in 100% of the total time. Soulsby et al. (1994) conducted simultaneous measurements of the high-frequency fluctuations of the concentration of sand, resuspended in a tidal current, above a sandy bed of an estuary and showed that large upward fluxes of sediment were associated with ejection events. In recent times, field experiments by Couturier et al. (2000) demonstrated that macroscale flow modules strengthened the ejection events which favoured sediment transport. Furthermore, ejection events were exaggerated
during modules of decreasing horizontal velocity and increasing turbidity, while sweep events were magnified during modules of increasing horizontal velocity and decreasing sediment concentration. Yuan et al. (2009) also revealed a similar relationship between turbulent coherent structures and sediment resuspension. They used an acoustic Doppler velocimeter (ADV), acoustic Doppler current profiler (ADCP) and optical backscatter sensors (OBS) to examine turbulence-induced sediment motions in the tidal environment of the western Yellow Sea, China. Their results revealed that sweep events occupied the turbulent events when compared to others and ejection events were the most significant component in the transport process. Overall, 98% of the total sediment flux was by ejection and sweep events, and the role of other turbulent events (i.e. up-acceleration and down-deceleration events, explained in section 2.3) were negligible.

In the wave-dominated nearshore region, Jackson (1976) examined the turbulent bursting phenomenon under wind-generated surface waves and found that the mean values of the flow parameters did not remain sensibly constant during turbulent bursts and the timescale of the largest turbulent eddies. Additionally, the upward momentum flux in the bursts provided the vertical anisotropy in the turbulence which was needed to suspend sediment. Conley and Inman (1992) conducted high frequency velocity measurements close to the seabed under near-breaking swell waves to study the development of the fluid–granular boundary layer over permeable beds of loose sand. They also suggested that there was a pronounced asymmetry in instantaneous sand transport and boundary layer bursting phenomena between the wave crest and trough. Moreover, laboratory waves with field scale periods and wave heights over thin sand beds did not exhibit this crest-trough boundary layer asymmetry, indicating that a critical element of similitude was absent in laboratory experiments. Hay and Bowen (1994) suggested coherent structures in combined flow turbulence as possible causes for higher suspension events observed at wave group timescales. Clarke et al. (1982) also suggested bursts of intense
turbulence associated with peak values of wave orbital velocity caused higher suspension events. Kularatne and Pattiaratchi (2008) examined the wave-group induced higher suspension events and suggested that turbulence and bursting phenomena also cause sediment transport in shallow waters. They used a combination of ADV and OBS instruments to study the relationship of turbulent kinetic energy with sediment transport along south west coast of Western Australia. Their results suggested that higher sediment movements were associated with ejections rather than sweeps where turbulent shear stress was greater during ejections and sweeps as compared to that during upward and downward motions which corroborates the ideas of Heathershaw and Thorne (1985).

Although the laboratory and numerical models cited above provided many valuable insights into the mechanics of turbulent coherent structures resuspending sediments, they generally involved substantial simplification of the natural environment such as actual scale effects, seabed dynamics, boundary roughness, tidal effects among many others. In addition to that, due to the limited in situ experiments, our modern understanding of turbulent bursting based sediment entrainment relies largely on laboratory experiments (e.g. Mao, 2003) and numerical models (e.g. Cao et al., 1996). Therefore, in order to legitimise and accurately parameterize the laboratory and numerical research, further quantitative experiments in the natural environment are urgently required. The aim of this study is to validate the findings of the laboratory and numerical research in the field based on turbulent bursting phenomena employing modern multipoint acoustic measurements. We performed experiments in the natural conditions of a unidirectional current flow environment of a tidal inlet and wave-dominated flow environment of the nearshore region where high frequency multipoint data were recorded near the bottom boundary layer and traced the evidence of turbulent coherence structure in resuspending sediments. Furthermore, data were post-processed using Reynolds decomposition, quadrant analysis, and wavelet transform methods to clarify the turbulent
characteristics and their effect on the resuspension mechanism. Finally, the possible generation mechanisms of the observed patterns were discussed.

5.2 Study area and methodology

5.2.1 Site description, conditions and instrumentation

Majority of the measurements described in this chapter were made at two hydrodynamically contrasting locations. The characteristics of the two sites and a description of the instrumentation are provided below.

Wilson Inlet

The first experiment (‘inlet’) was conducted in Wilson Inlet, located on the south-western coast of Australia. The inlet is seasonally closed but the measurements were made during a period where it was open to the ocean (Ranasinghe and Pattiaratchi, 1999). This region experiences a diurnal tide with an oceanic spring tidal range of ~0.8m whilst inside the estuary it is lower (~5cm) due to severe attenuation along the inlet channel (Ranasinghe and Pattiaratchi, 1999). In order to prevent flooding of low-lying farm land, the inlet is artificially opened in winter when the estuarine water level rises to 1m above mean sea level (Hodgkin and Clark, 1988 in: Ranasinghe and Pattiaratchi, 1999). The typical rapid initial discharge of water during the breaching of the bar, scours a channel through the sand bar which was visualized in the form of cluster of sediment clouds where sediments were transported towards the sea (see Video 5.1 and 5.2). This location was selected for deployment considering a cluster of sediment clouds as ideal conditions with continuous resuspension under strong unidirectional currents.

Hydrodynamic and sediment resuspension measurements included a bottom-mounted Nortek Aquadopp HR profiler located at 35°01'33.3"S 117°19'47.6"E (Fig. 5.1). The instrument recorded the turbulent velocities and echo intensity simultaneously at
three sampling volumes located 0.113m, 0.083m and 0.053m height above bed (hab), where the deployment location was visually observed as flat bed with no presence of sand waves. During the deployment, the mean water depth was 0.63m. Data were collected for 60 minutes with a burst interval of 2 minutes starting at 0900 h on 28th November, 2015. Time series of velocity in XYZ coordinates (u was the main direction of flow) and backscatter were recorded at a sampling rate of 8Hz. For quality control purposes, a GoPro video camera was also mounted in the frame in order to visualize the resuspension events during data collection which was also analysed to retrieve qualitative data avoiding any debris (see Video 5.3).

Figure 5.1. (a, b) Map of the study area showing deployment locations (red dots) of Wilson Inlet (Site 1) and Point Peron beach (Site 2). (c) Photograph of the instrument setup deployed at the observation sites during field measurements.

Calculation of the threshold velocity at Wilson Inlet

The velocity threshold for sediment movement at the site location 1 (Wilson Inlet) was calculated using an average grain diameter ($d_{50}$) of 0.25 mm (calculated from the sieve analysis of the collected sediment sample from the deployment location), a grain density
\( \rho_w \) for wet quartz sand of 2650 kgm\(^{-3}\), sediment sorting coefficient, \( S_o=1.55 \), coefficient of gradation, \( C_c=1.1 \) and uniformity coefficient, \( C_u=5.3 \) through sieve analysis. The seawater density \( (\rho_w) \) at 22.06°C of 1025 kgm\(^{-3}\) and \( g \) is the gravity. Assuming the von Kármán constant as 0.41 and Nikuradse’s roughness \( z_o \) was estimated using:

\[
z_o = \frac{k_s}{30} \left( 1 - \exp \left[ \frac{-u_c k_s}{27v} \right] \right) + \frac{v}{9u_c} \tag{5.1}
\]

with \( k_s = 2.5d_{50} \)

Several critical values can be thus calculated, ranging from 0.256-0.306 m/s (Table 5.1).

**Table 5.1.** Theoretical mean critical values for sediment entrainment at \( z=0.053 \) m compared in this study.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Equations</th>
<th>Calculated ( u_c ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shields (1936)</td>
<td>( u_c = \frac{u_c}{k} \ln \left( \frac{z}{z_o} \right) ) ( \theta_c ) from Shields diagram</td>
<td>0.261</td>
</tr>
<tr>
<td></td>
<td>( u_c = \sqrt{B + (S - 1)gd_{50}} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( R_p = \frac{u_c d_{50}}{v} )</td>
<td></td>
</tr>
<tr>
<td>van Rijn (1984)</td>
<td>( u_c = 0.19 d_{50}^{0.3} \log_{10} \left( \frac{d_{50}}{d_{50}^{0.3}} \right) ); ( 100 &lt; d_{50} &lt; 500 ) μm</td>
<td>0.306</td>
</tr>
<tr>
<td></td>
<td>( u_c = 8.5 d_{50}^{0.6} \log_{10} \left( \frac{d_{50}}{d_{50}^{0.3}} \right) ); 500 &lt; ( d_{50} &lt; 2000 ) μm</td>
<td></td>
</tr>
<tr>
<td>Soulsby (1997)</td>
<td>( u_c = \left( \frac{D}{d_{50}} \right)^{1/7} \left[ g(s_c - 1)d_{50}f(D) \right]^{1/2} )</td>
<td>0.274</td>
</tr>
<tr>
<td></td>
<td>( s_c = \frac{\rho_s}{\rho} ) density of the sediment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( f(D) = \frac{1}{1 + 0.42D} ) ( D = \frac{[g(s_c - 1)]^{1/3}}{d_{50}} ) ( \rho_s = \frac{\rho}{D} ) density of the fluid</td>
<td></td>
</tr>
<tr>
<td>Soulsby and Whitehouse (Soulsby, 1997)</td>
<td>( u_c = \frac{u_c}{k} \ln \left( \frac{z}{z_o} \right) )</td>
<td>0.256</td>
</tr>
<tr>
<td></td>
<td>( u_c = \left( \frac{\rho}{\rho_s} \right)^{1/2} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \tau_c = \theta_c s_c (\rho_s - \rho) d_{50} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \theta_c = \theta_c s_c (\rho_s - \rho) d_{50} )</td>
<td></td>
</tr>
</tbody>
</table>

**Point Peron Beach**

The second experiment (‘beach’) was conducted at Point Peron beach located southwestern coast of Australia that experiences diurnal, microtidal conditions. Point Peron is situated within the Perth metropolitan coastline which experiences large seasonal wind variations. It is a semi-sheltered and steep beach where the swell waves break on the beach face with a narrow surf zone. During winter, this region is exposed to strong
westerly and north-westerly winds. In winter, westerly and north westerly winds are dominant although the occurrence of low wind speeds tends to be evenly spread through all directions. Westerly and north westerly winds are dominant during winter because of storm systems arriving from the north west. This location was chosen in this study as a convenient place to deploy the instruments as well as conducting experiment in a swell dominated system. Further details about the study site wave climate and sediment properties can be found in Department of Transport Report (2009).

Field observations included similar instrumental setup as for experiment 1 (see above) located at 32°16'08.0"S 115°41'34.0"E. During the deployment the mean water depth was 0.36 m. The deployment location was visually observed as flat bed with no presence of sand waves. Data were collected for 60 minutes with a burst interval of 2 minutes starting at 1602 h on 11th October, 2015. Time series of velocity in XYZ coordinates (u was the main direction of flow) and backscatter were recorded at a sampling rate of 8Hz where recorded video footage was analysed for quality control purposes of the data (see Video 5.4). The significant wave height was 0.4 m with a RMS wave height of 0.3 m. The boundary layer thickness estimated using Nielsen (1992) method was 0.03 m, suggesting turbulent velocity and sediment concentration were measured close to or within the wave boundary layer.

**Calculation of the threshold velocity at Point Peron beach**

The velocity threshold for sediment movement at the site location 2 (Point Peron beach) was calculated using an average grain diameter (d50) of 0.27mm (calculated from the sieve analysis of the collected sediment sample from the deployment location), a grain density (ρs) for well sorted quartz, unconsolidated sand of 2650 kg m⁻³, sediment sorting coefficient, S₀=1.65, coefficient of gradation, Cc=1.2 and uniformity coefficient, Cu=5.6
through sieve analysis. The seawater density \( \rho_w \) at 22.06°C was 1025 kgm\(^{-3}\). The estimated critical velocities ranged between 0.186 and 0.239 m/s (Table 5.2).

**Table 5.2.** Theoretical mean critical values for sediment entrainment at \( z = 0.053 \) m compared in this study.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Equations</th>
<th>Calculated ( \bar{u}_{cr,w} ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shields (1936)</td>
<td>( \bar{u}_{cr} = \frac{u_s}{k} \ln \left( \frac{z}{z_0} \right) )</td>
<td>0.238</td>
</tr>
<tr>
<td></td>
<td>( \bar{u}<em>s = \sqrt{\frac{\theta</em>{cr}(s - 1)g d_{50}}{\frac{d_{50}}{v}}} )</td>
<td>0.238</td>
</tr>
<tr>
<td></td>
<td>( \theta_{cr} ) from Shields diagram</td>
<td>0.238</td>
</tr>
<tr>
<td></td>
<td>( R_p = \frac{u_s d_{50}}{v} )</td>
<td>0.238</td>
</tr>
<tr>
<td>Soulsby and Whitehouse (1997)</td>
<td>( f_w = 0.00251 \exp \left[ 5.21 \left( \frac{\bar{u}<em>{cr,T}}{4 d</em>{50}} \right)^{-0.19} (D_s) \right] )</td>
<td>0.186</td>
</tr>
<tr>
<td></td>
<td>( \tau_w = \frac{1}{2} \rho_w f_w \bar{u}_w^2 )</td>
<td>0.186</td>
</tr>
<tr>
<td></td>
<td>( \theta_{cr,w} = \frac{\tau_{w,cr}}{g(\rho_s - \rho)d_{50}} )</td>
<td>0.186</td>
</tr>
<tr>
<td></td>
<td>( D_s = d_{50} \left( \frac{d_{50}}{u_s^2} \right)^{0.17} )</td>
<td>0.186</td>
</tr>
<tr>
<td>van Rijn (2007)</td>
<td>( \bar{u}<em>{cr,w} = 0.24 \left[ (s - 1)g \right]^{0.66} d</em>{50}^{0.33} (T_p)^{0.33} )</td>
<td>0.239</td>
</tr>
<tr>
<td></td>
<td>0.0001 &lt; ( d_{50} &lt; 0.0005 ) m</td>
<td>0.239</td>
</tr>
</tbody>
</table>

### 5.2.2 Data analysis

In the inlet experiment, a set of 30 bursts were analysed. Results from a two-minute period (burst 15) was randomly chosen for detailed analysis where the mean current velocity (\( \bar{u} \)) was 0.335 m/s above the mean critical velocity (Table 5.1)

Similarly, for the beach experiment 30 individual two minute sections were analysed. A single burst (no. 11) was randomly chosen for detailed analysis with the mean current velocity (\( \bar{u} \)) of 0.241 m/s. In order to analyse the turbulence, the velocity signals were high pass-filtered with a cut-off frequency of 0.3 Hz and low pass-filtered with a cut-off frequency of 4 Hz (Kularatne and Pattiaratchi, 2008). Therefore, the filtering process removed most of the incident wave band energy from the original data record.

To determine the turbulent characteristics, the fluctuating part of the measured velocity was separated from its mean using Reynolds decomposition. In order to identify clear trends of the time series with 8Hz, a one-second mean was used as found in the previous studies conducted by Heathershaw and Thorne (1985); Chanson et al. (2007);
Kularatne and Pattiaratchi (2008); Yuan et al. (2009); and Yang et al. (2016). It is noteworthy that ADCP has a spreading of beams from the source, therefore, the beams might not have sampled the same volume of water (especially turbulent events below 8Hz) which indicates that the turbulence may vary between the beams. Quadrant analysis was employed to determine the frequency of occurrence of each individual event within a bursting process where the quadrants were named as ejection (u'<0, w'>0), sweep (u'>0, w'<0), up-acceleration (u'>0, w'>0), and down-deceleration (u'<0, w'<0) (Anwar, 1981; Izadinia, et al., 2013). The measurements of turbulent velocity fluctuations were used to calculate Reynolds shear stress (McLelland and Nicholas, 2000). We also considered the backscatter reading of ADCP as a proxy of suspended sediment concentration (SSC) where a concentration proxy (c') was also used as an indicator to identify variations in concentration of sediment which was analysed using Reynolds decomposition (Fox et al., 2004). Continuous wavelet transform (CWT) was employed to derive the time evolution of momentum and sediment flux of turbulent coherent structures near the bottom boundary layer with 8 Hz sampling rate over the selected data of a two-minute period. Greater details of the data analysis techniques were presented in Chapters 3 and 4.

5.3 Results

5.3.1 Wilson Inlet

Different threshold criteria (i.e. Shields 1936; van Rijn, 1984; Soulsby 1997 and Soulsby and Whitehouse 1997) were used to estimate the time-averaged critical velocity (Table 5.1). The results indicated that the mean current velocity during the field experiment was above the estimated critical velocities, i.e. measured mean velocity, \( \bar{u}_{\text{measured (inlet)}} = 0.335 \) m/s was higher than the different estimates (Table 5.1).

The intermittent nature of turbulent Reynolds shear stress in three sampling heights above the bed (at 0.113m, 0.083m and 0.053m, height above bed respectively)
and backscatter reading (at 0.053m hab) for the selected burst were examined (Fig. 5.2). Overall, ejection and sweep events occurred marginally more often than the up-acceleration and down-deceleration events at all three heights above the bed, ensuing both in a larger contribution to the momentum and sediment fluxes vertically in the water column (Fig. 5.2, Table 5.3). This pattern was present in all 30 bursts collected during the experiment.

The Reynolds shear stress at three different heights above the bed along with backscatter reading between 20s to 70s were expanded and observed in greater detail (Fig. 5.3). It was found that consecutive ejection events lifted the sediments (evidenced with high resuspension backscatter reading) and entrained the particles from 0.053m up to the height of 0.083m and 0.113m above the bed in 1/8th and 2/8th second time (up arrows in Figs. 5.3d to 5.3a respectively). These ejection events assisted the sediment to maintain resuspension in the water column resulting series of sediment clouds as observed in the video clips 5.1 and 5.2. Similarly sweep events were seen to transport the suspended particles towards the bed with the negative contribution to the Reynolds shear stress (down arrows in Figs. 5.3a to 5.3d respectively).
Figure 5.2. A burst time series records showing one-second mean of the turbulent Reynolds shear stress \((u'w')\), identifying the ejection, (up arrows) and sweep (down arrows) events at (a) 0.113m; (b) 0.083m; (c) 0.053m; hab and, (d) one-second mean of the backscatter at 0.053 m above bed.

Table 5.3. Major ejection (shaded cells) and sweep (white cells) events in the time series in Fig. 5.2.

<table>
<thead>
<tr>
<th>hab (m)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 0.113</td>
<td>2/8 7/8 9/8 12/8 14/8 17/8 20/8 22/8 25/8 28/8 31/8 34/8 37/8 40/8 43/8 46/8 49/8 52/8 55/8 58/8 61/8 64/8 67/8 70/8 73/8 76/8 79/8 82/8 85/8 88/8 91/8</td>
</tr>
<tr>
<td>(b) 0.083</td>
<td>2/8 7/8 12/8 15/8 18/8 21/8 24/8 27/8 30/8 33/8 36/8 39/8 42/8 45/8 48/8 51/8 54/8 57/8 60/8 63/8 66/8 69/8 72/8 75/8 78/8 81/8 84/8 87/8 90/8 93/8 96/8</td>
</tr>
<tr>
<td>(c) 0.053</td>
<td>2/8 7/8 12/8 15/8 18/8 21/8 24/8 27/8 30/8 33/8 36/8 39/8 42/8 45/8 48/8 51/8 54/8 57/8 60/8 63/8 66/8 69/8 72/8 75/8 78/8 81/8 84/8 87/8 90/8 93/8 96/8</td>
</tr>
</tbody>
</table>

In order to visualize the change in turbulent coherent structure, the streamwise one second mean \((\bar{u})\) and fluctuating part \((u')\) of the velocity traced the coherent structure showing (Fig. 5.4) its ejection from the bed.
Figure 5.3. As Fig. 5.2 but showing time series records between 20 to 70 seconds showing the ejections of the coherent structure ejected up to 0.113m hab and the sweep events consecutively pushed the coherent structure down from 0.113m hab towards the bed where backscatter reading indicated the change in sediment resuspension.

Figure 5.4. Visualization of the coherent structure in velocity profile considering the section A in Fig. 5.3 where black dotted line denotes the 1 second mean ($\bar{u}$) and red solid line denoted the fluctuating part in the direction of the flow ($u'$).

The contribution of $u'w'$ from the selected burst into the four quadrants of the $u'$-$w'$ plane in all three-sampling heights above the bed indicated that the larger contributions
(above a threshold value $|u'w'| > 0.06 \text{ m}^2/\text{s}^2$ shown in red dots in Fig. 5.5) were from ejections and sweeps rather up-acceleration and down-deceleration events. Thus, ejections and sweeps collectively played a dominating role to the total Reynolds stress at three sampling heights above the bed in the water column. The scatter plots of turbulent components in the $u'-w'$ plane at all three measured heights above the bed (i.e. 0.113m, 0.083, 0.053 m hab) were consistent throughout the whole dataset (i.e. set of thirty burst sections).

![Figure 5.5](image_url)

**Figure 5.5.** Classification of bursting events in $u'-w'$ space mentioning ejection, sweep, up-acceleration and down-deceleration events at (a) 0.113m; (b) 0.083m; (c) 0.053m measured sampling heights above the bed respectively.

In order to quantitatively evaluate the intermittency and determine the contributions of four bursting events to the Reynolds stress (i.e. $u'w'$), quadrant analysis was performed for the burst time series as a representation of the analysed total thirty sections of the dataset (Fig. 5.6). It is observed that, ejections and sweeps are the dominant sources of the Reynolds stress generation at all sampling heights above the bed (i.e. at 0.113m, 0.083m, and 0.053m hab). In more detail, the time occupied, net Reynolds shear stress and sediment flux by ejections (e.g. at $Z=0.113m$, 34.9%) were equivalent with sweeps (e.g. at $Z=0.113m$, 31.3%) where the up-acceleration and down-deceleration events made significantly less contributions at all three sampling heights above the bed. Furthermore, histograms showed that the upward sediment flux was prominently
accomplished by ejections and sweeps (e.g. at Z=0.113m, ejection was 33.3% and sweep was 42.4% in momentum flux) suggesting intense surge of low-speed fluid containing high sediment concentration and high speed fluid rushing towards the bed were the main provider of $c'w'$ at all three sampling heights (e.g. at $Z=0.113m$, ejection= 38.0%, sweep=32.8%; in sediment flux). By comparison, up-acceleration (e.g. at $Z=0.113m$, 12.8%) and down-deceleration (e.g. at $Z=0.113m$, 16.4%) events transported sediment significantly less. Therefore, turbulent sediment flux was accomplished collectively by ejection and sweep events for most of the time (i.e. at $Z=0.113m$, 70.8%, at $Z=0.083m$ 59.3% and $Z=0.113m$, 70.8%), while the contributions coming from the up-acceleration and down-deceleration events were less (i.e. at $Z=0.113m$, 29.2%, at $Z=0.083m$ 40.7% and $Z=0.053m$, 38.2%).

**Figure 5.6.** Quadrant analysis of coherent structures of the selected two-minute period showing the (a) time occupied, (b) momentum flux ($u'w'$), and (c) sediment flux ($c'w'$). The error bars represent the maximum and minimum values of the total data.

In order to examine the relationship of momentum flux ($u'w'$) variability with sediment flux ($c'w'$) conditions, CWT were performed (Fig. 5.7). In these scalograms, the white-shaded region represents the COI where the image might be distorted due to the
edge effects. It is noteworthy to mention that, at higher periods (low frequency events),
the power fell within the range of COI which limited the capability to investigate the
temporal evolution of the specific peak frequencies as stated in Section 5.2.3. Hence, the
investigation was limited to examine high frequency events occurring at time scales up
to 32s. In general, the four scalograms (see Fig. 5.7) clearly showed the existence of multi-
scale turbulent structures [e.g. between ~37-39s, period band ranging ~2-8s (large scale)
and ~0.25-1s (small scale)] where some overlap between small fine-scale structures (e.g.
at ~9-11s, period band ranging ~0.25-1s) with the large-scale motions (considering period
bands >2s as large-scale motions) showing similarities with Yuan et al., (2009) and those
in Chapter 3. This suggests that, at three sampling heights, most of the near-bed energy
was in the lower frequency range, in conjunction with the mean flow properties for both
momentum flux and sediment flux.

Results also showed that high energy turbulent events (i.e. warmer colour >0.5s)
occurred intermittently throughout the records, in slowly evolving groups (considering
clusters developed taking >3s time), that continued over short times (i.e. lasted <2s) in
the dominant streamwise-vertical plane near the bed, and for longer times in turbulence
viewpoint (e.g. up to several seconds, in this case ~2-10s), vertically up in the
watercolumn (i.e. at 0.053m, 0.083m and 0.113m hab) as well as at lower frequencies.
The larger groups fell over short bands of frequency scales (periods, predominantly 8 and
16s), while the rapidly evolving bands (considering those lasting up to 2s) spread over a
larger range of frequency scales (primarily between 1 and 4s) before fading. This was
evident in the colour coded contours during ejection events where momentum flux
corresponds to the contour in sediment flux within similar period bands (comparing Fig.
5.2 and 5.7 respectively with corresponding ejection events in Table 5.3). Similarities
were also found in the sweep events (comparing Figs. 5.2 and 5.7 respectively with
corresponding sweep events in Table 5.3). Such patterns were also observed in the remaining dataset.

![Wavelet power spectra](image)

**Figure 5.7.** Wavelet power spectra (Morlet wavelet) for a two-minute period showing the momentum flux \((u'w')\) at (a) 0.113m, (b) 0.083m, (c) 0.053m and (d) sediment flux \((c'w')\) at 0.053m above the bed.

### 5.3.2 Point Peron beach

Similar to the previous experiments, we also used widely known threshold curves (i.e. Shields 1936; van Rijn, 1984; Soulsby 1997 and Soulsby and Whitehouse 1997) to estimate the time-averaged critical velocity in the oscillatory flows (Table 5.2). Intercomparison of the beach experiments also showed that the mean current velocity was well above the estimated critical velocities [i.e. measured mean velocity, \(\bar{u}_{\text{measured (wave)}}\) = 0.241 m/s > 0.238 m/s (Shields, 1936), 0.186 (Soulsby and Whitehouse, 1997), 0.239
m/s (van Rijn 2007), respectively]. However, it should be noted that in the wave dominated flow system the currents change rapidly over a wave period.

The intermittent nature of turbulent Reynolds shear stress in three sampling heights above the bed (at 0.113m, 0.083m and 0.053m respectively) and backscatter reading (at 0.053 hab) for the selected two-minute period were examined (Fig. 5.8). Overall, ejection and sweep events occurred marginally more often than the up-acceleration and down-deceleration events at all three heights above the bed, ensuing both in a larger contribution to the momentum and sediment fluxes vertically in the water column (Fig. 5.8) which also represented all the analysed 30 sections investigated in this study.

![Figure 5.8](image.jpg)

**Figure 5.8.** Time series records of (a) the mean cross-shore velocity ($u$), (solid line), and (b-e) as Figure 5.2 but for beach experiment.
Table 5.4. Major ejection (shaded cells) and sweep (white cells) events in the presented time series of Fig. 5.8.

<table>
<thead>
<tr>
<th>hab (m)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 0.113</td>
<td>2/8 8/8 14/8 21/8 28/8 32/8 45/8 48/8 50/8 58/8 66/8 79/8 91/8 97/8 109/8 113/8</td>
</tr>
<tr>
<td>(b) 0.083</td>
<td>2/8 7/8 8/8 14/8 21/8 28/8 32/8 45/8 48/8 51/8 58/8 66/8 79/8 91/8 97/8 109/8 113/8</td>
</tr>
<tr>
<td>(c) 0.053</td>
<td>2/8 7/8 7/8 14/8 21/8 28/8 32/8 45/8 48/8 51/8 58/8 66/8 79/8 91/8 97/8 109/8 113/8</td>
</tr>
</tbody>
</table>

The Reynolds shear stress at three different heights above the bed along with backscatter between 20s to 70s were magnified and observed in greater detail (Fig. 5.9). It was found that the consecutive ejection events suspended the sediments (evidenced with high backscatter reading) and entrained particles from 0.053m up to the height of 0.083m and 0.113m above the bed in 1/8th and 2/8th second (up arrows in Fig. 5.9). Such a contribution of ejection events assisted the sediments to remain in suspension in the water column resulting series of sediment clouds as observed in the video clip 5.3.

Figure 5.9. As Fig. 5.8 but time series records between 20 to 70 seconds showing the ejections of the coherent structure ejected up to 0.113m hab and the sweep events consecutively pushed the coherent structure down from 0.113m hab towards the bed where backscatter reading indicated the change in sediment resuspension.
Similarly, sweep events were traced to rush the resuspend particles towards the bed with the negative contribution in the Reynolds shear stress (down arrows in Fig. 5.9 respectively).

In order to visualize the change in turbulent coherent structure, the streamwise one second mean (\( \bar{u} \)) and fluctuating part (\( u' \)) of the velocity was plotted (Fig. 5.10). Results clearly traced the coherent structure showing how it ejected from the bed transporting sediments (i.e. dB value as mentioned in Fig. 5.9 section A in relation to Fig. 5.10f, 5.10g, 5.10h respectively).

![Velocity profile identifying the turbulent coherent structure](image)

**Figure 5.10.** Velocity profile identifying the turbulent coherent structure in relation to the Fig. 5.9 (section A) where black dotted line denotes the 1 second mean (\( \bar{u} \)) and red solid line denoted the fluctuating part in the direction of flow (\( u' \)).

The contribution of \( u'w' \) from the selected burst into the four quadrants of the \( u'-w' \) plane in all three-sampling heights above the bed indicated that the larger contributions (above a threshold value \( |u'w'| > 2 \times 10^{-3} \text{ m}^2/\text{s}^2 \) shown in red dots in Fig. 5.11) were from ejections and sweeps rather up-acceleration and down-deceleration events. The scatter plots of turbulent components in the \( u'-w' \) plane at all three measured heights above the bed (i.e. 0.11 m, 0.083, 0.053 m hab) were consistent in all the analysed dataset (i.e. set of thirty burst sections).
Figure 5.11. Classification of bursting events in \( u'-w' \) space mentioning ejection, sweep, up-acceleration and down-deceleration events at (a) 0.113m; (b) 0.083m; (c) 0.053m measured sampling heights above the bed respectively.

A quadrant analysis (Fig. 5.12) shows that, ejections and sweeps are the dominant sources of the Reynolds stress generation at all sampling heights above the bed. In more detail, the time occupied, net Reynolds shear stress and sediment flux by ejections (e.g. at \( Z=0.113 \), 28.1\%) were equivalent with sweeps (e.g. at \( Z=0.113 \), 27.5\%) where the up-acceleration and down-deceleration events made significantly less contributions to at all three sampling heights above the bed. Furthermore, the histograms show that the upward sediment flux was prominently accomplished by ejections (e.g. at \( Z=0.113 \), 32.8\% in momentum flux) and sweeps (e.g. at \( Z=0.113 \) was 35.7\% in momentum flux) suggesting surge of low-speed fluid containing high sediment concentration and high speed fluid rushing towards the bed were the main provider of \( c'w' \) at all three sampling heights (e.g. at \( Z=0.113 \), ejection= 29.1\%, sweep=32.4\% in sediment flux). In comparison to that, up-acceleration (e.g. at \( Z=0.113 \), 22.5\%) and down-deceleration (e.g. at \( Z=0.113 \), 16.1\%) events transported sediment significantly less sediment. Therefore, collectively turbulent sediment flux was accomplished by ejection and sweep events (i.e. at \( Z=0.113 \), 61.5\%, at \( Z=0.083 \) 56.3\% and \( Z=0.113 \), 62.2\%), whilst contributions from the outward and inward interactions were less (i.e. at \( Z=0.113 \), 38.6\%, at \( Z=0.083 \) 43.0\% and \( Z=0.053 \), 37.8\%).
Figure 5.12. Quadrant analysis of coherent structures of the selected two-minute period showing the (a) time occupied, (b) momentum flux ($u'w'$), and (c) sediment flux ($c'w'$). The error bars represent the maximum and minimum values of the total data.

In order to examine the relationship of momentum flux ($u'w'$) variability with sediment flux ($c'w'$) conditions, CWT were performed with 8 Hz sampling rate over the selected data of two-minute period (Fig. 5.13). In these scalograms, the white-shaded region represents the COI where the image might be distorted due to the edge effects. It is noteworthy to mention that, at higher periods (low frequency events), the power fell within the range of COI which limited the capability to investigate the temporal evolution of the specific peak frequencies as stated in Section 5.2.3. Hence, we limited the investigation to examine high frequency events occurring at time scales up to 32s. In general, the four scalograms (see Fig. 5.13) clearly show the existence of multi-scale turbulent structures [e.g. between ~31-33s, period band ranging ~2-8s (large scale) and ~0.25-1s (small scale)] where some implanting of small fine-scale structures (e.g. at ~11-12s, period band ranging ~0.25-1s) presented within the large-scale motions (considering period bands >2s as large-scale motions) showing similarities with Yuan et al., (2009)
and see also Chapter 3. Such agreements at three sampling heights indicated that most of the near-bed energy concentrates within the lower frequency range, in conjunction with the mean flow properties for both momentum flux and sediment flux. Results also showed that high energy turbulent events (i.e. warmer colour >0.5s) occurred during the rapid change in velocity from the crest to the trough (‘backwash’) throughout the records, in slowly evolving groups (considering clusters developed taking >3s time), that continued over short times (i.e. lasted <2s) in the dominant streamwise-vertical plane near the bed, and for longer times in turbulence viewpoint (e.g. up to several seconds, in our case ~2-10s), higher up in the waterbody (i.e. at 0.053m, 0.083m and 0.113m hab) as well as at lower frequencies. The larger groups fell over short bands of frequency scales (periods, predominantly 8 and 16s), while the rapidly evolving bands (considering those lasting up to 2s) spread over a larger range of frequency scales (primarily between 0.5 and 4s) before fading. This is evident in the colour coded contours during ejection events where momentum flux corresponds to the contour in sediment flux within similar period bands (comparing Figs. 5.8 and 5.13 with corresponding ejection events in Table 5.4). Similarities were also found in the sweep events. Such results were also observed in the remaining dataset (not shown). Also, the wavelet plot based on oscillatory flow data was different from the unidirectional current mentioned above and in previous studies (Yuan et al., 2009 and Chapter 3). In the scalograms, there were also periods where significantly less energy was observed (where hatch regions in Fig. 5.13a in relation to the Figs. 5.13b-e revealed the energetic regions). As mentioned the velocity (u), varied with the rapid change in velocity (‘backwash’) as happened at those periods [e.g. at 95s in Fig. 5.13, high energy in the wave resuspended sediments].
Figure 5.13. Time series records of (a) the mean cross-shore velocity (u), (solid line), Wavelet power spectra (Morlet wavelet) for a two-minute period showing the momentum flux \((u'w')\) at (b) 0.113m, (c) 0.083m, (d) 0.053 m and (e) sediment flux \((c'w')\) at 0.053m above the bed.

5.4 Discussion

Several studies have reported the link between the turbulent ‘bursting’ process and sediment resuspension in the laboratory (e.g. Niño et al., 2003, see also Chapter 3) and in the field (Heathershaw and Thorne, 1985; Drake et al., 1988; Soulsby et al., 1994; Kularatne and Pattiaratchi, 2008 and Yuan et al., 2009), where the mean current velocity was well above the lower limit of the time-averaged critical velocity. These suggest that, partly due to the lack of relative novelty of the instrumentation simultaneously measuring multipoint turbulent data along with backscatter reading near the bed, previous research on natural flows has largely been restricted to investigate the role of turbulent coherent structures in the river, estuarine, nearshore coastal regions considering single point acoustic measurements. Therefore, results presented in this chapter, advance
understanding of the turbulence structure and their role both in laboratory and field transport processes. In this study, comparison of test results simultaneously at three sampling heights above the bed, in both unidirectional tidal current and wave-dominated flow environments showed strong similarities (Figs. 5.2 and 5.8) with previous studies in particular the work of Yuan et al., (2009) and Yang et al., (2016, see also Chapter 3) and extends them using three sampling heights above the bed. These results indicate that the concept of a time-averaged critical velocity requires consideration of the intermittent nature of turbulence (i.e. inclusion of turbulent bursting effects) for a complete representation of sediment resuspension processes.

It was further observed that ejection and sweep events strongly dominated over up-acceleration and down-deceleration events regarding their impact on transport of momentum and sediment flux at all three heights above the bed (Figs. 5.2 and 5.8). While previous investigations (e.g. Heathershaw and Thorne, 1985; Thorne et al., 1989; Nelson et al., 1995) found that up-acceleration and down-deceleration events considerably contributed to sediment resuspension, our investigation showed lower net sediment fluxes accomplished by such events. This study focus in both unidirectional current of a tidal inlet and wave-dominated nearshore conditions, similarities with other studies that documented that sweeps and ejections are the primary contributors to sediment entrainment (Grass, 1970, 1974; Sumer and Deigaard, 1981; Best, 1992; Niño and Garcia, 1996; Hurter and Lemmin, 2003, see also Chapter 3). Since our sampling volume was placed at three different heights above the bed (i.e., at 0.113m, 0.083m and 0.053m respectively), weaker up-acceleration and down-deceleration events might not have carried sediment particles to such heights. Up-acceleration and down-deceleration events contributed less effectively with a positive stress. Still, overall, in this measurements, up-acceleration and down-deceleration events contributed less effectively (e.g. in the beach
experiment, sum of ejection and sweep events were higher ranging between 56.3% - 62.2% in compare to the sum of outward and inward interactions ranging between 38.6% - 43.0%, as mentioned in the results section).

Earlier experimental evidence by researchers supported the theory that only sweeps and up-accelerations play a significant role in the entrainment and transport of sediment, since these motions were associated with positive $u'$ and thus greater streamwise velocities (Thorne et al., 1989; Nelson et al., 1995; Weaver and Wiggs, 2008). However, results presented in this thesis in two contrasting environments showed similarities with other research that documented that sweeps and ejections were the primary contributors to sediment entrainment (Grass, 1970, 1974; Sumer and Deigaard, 1981; Best, 1992; Niño and Garcia, 1996; Hurter and Lemmin, 2003). In greater detail, quadrant analysis revealed that in both unidirectional and wave-dominated flows and at different sampling heights above the bed (i.e. at 0.053m, 0.083m and 0.113m hab), ejection was largely dominated in moving sediment particles away from the bed and maintaining them in suspension (Figs. 5.6 and 5.12), as shown in other studies (e.g. Yuan et al., 2009, see also Chapter 3). In contrast, sweep events, transporting suspended particles towards the sea bed, contributed largely to maintain the resuspension process. Moreover, the contribution of time occupied in both coastal environments by all four events were almost identical (i.e. ejection, sweep > up-acceleration and down-deceleration events), with similar percentage of momentum and sediment flux as in similar studies with velocities above critical conditions in natural flow environments. The results of quadrant analysis presented in this study were consistent with the findings of Diplas et al. (2008) who suggested that besides force magnitude, duration in terms of impulse (which accounts for both aspects of force application) should also be considered in identifying the threshold of motion conditions. This was evident in results of this study in both experimental conditions as well as at three different heights above the bed where
the time occupied by the ejection and sweep events (which were also evidenced to play the dominant role in the momentum flux and sediment flux) were significantly higher in comparison to the up-acceleration and down-deceleration events. The understanding of accounting temporal contribution of bursting events presented in this study as well as discussed in Diplas et al. (2008) and Diplas and Dancey (2013) calls for consideration of the hydrodynamic impulse (i.e. value of force multiplied by required time for the accomplishment of the event) as a comprehensive criterion in the development of future models to predict particle entrainment.

Wavelet analysis provided a complementary approach to the traditional Fourier spectrum analysis diagnosing characteristics of turbulence in order to explain information about the spatial structure of the flow (Figs. 5.7 and 5.13). Our measured data in two different coastal boundary flows as well as three different heights above bed revealed that at higher frequencies the intermittent and relatively large momentum regions exhibited a direct role in resuspension of sediment where within a given array of turbulence, both stresses and resuspensions extended over a certain range of frequencies which were supported by the previous investigation by Shugar et al., (2010). In line with their work, results of this study further demonstrated that the set of wavelet plots based on the multipoint measurements in the field specified collections of low-frequency coherent flow structures originated close to the bed. With time these low frequency coherent structures raised vertically up in the water column and then disintegrated as they were advected downstream, with probable interruption being linked to topographically-induced acceleration of the flow. The frequency at which these structures were generated was appropriately projected by the models of Driver et al. (1987) and Simpson (1989) for variation in separation zone size and wake flapping, respectively. Therefore, it can be stated that the cross wavelet transform method was effective at visualizing and detecting
the coherent structures from the raw turbulent data, which enabled us to study the correlation between wall turbulence structures and sediment resuspension.

The quadrant and wavelet analysis as well as observed velocity profiles in both tidal inlet and oscillatory flow systems consistently exhibited the role of turbulence coherent structures in resuspending sediments. To explain the bursting process a schematic diagram was developed, based on the field observations as an attempt to unify the existing observation of complex coherent motion into a single ‘cyclic’ process (Figs. 5.14, 5.15). The diagram shows the succession of flow structures within the cycle, and also the changing pattern of the instantaneous velocity profile in the axial plane of the flow structure as compared to the profile of mean velocity. Initially, it is assumed that a suspended particle was at height 0.053m above the bed (Stage 1 in Fig. 5.14 and 5.15). As the coherent structure travels downstream, it begins to bend the vortex forwards and move upwards above the streak, which decelerates the $u'$ and accelerates the $w'$ commencing to rise. This is the stage called up-acceleration, where the instantaneous velocity profile does not differ from the mean profile (Stage 2 in Figs. 5.14 and 5.15). The continuous bending and upward movement of the vortex creates a horseshoe- or hairpin-shaped structure and cause the sediment particles to ‘eject’ (Stage 3 in Figs. 5.14 and 5.15). With time (in our case 1/8th second) the coherent structure transporting the resuspended sediment becomes unstable (Stage 4 in Figs. 5.14 and 5.15) and disintegration of the coherent structure occurs (Stage 5 in Figs. 5.14 and 5.15). Finally, in Stage 5, high-speed fluid (i.e. sweep event) rushes the particles towards the bed carrying the sediments.
5.5 Concluding remarks

This chapter presented observations of sediment resuspension events obtained from a tidal inlet and a wave-dominated nearshore region in order to examine the effects of turbulent bursting events. In agreement with previous laboratory and field experiments of single point turbulent data as stated in Chapter 3 and 4, our quadrant analysis suggested that sediment flux was mainly controlled by ejections and sweeps at all three measured heights above the bed. Observations in the unidirectional current and wave dominated flow environment of Western Australia also suggest that sediment transport is an event based system. Wavelet analysis confirmed that over time, high variability strong
turbulence occurred in slowly evolving clusters, which were closely followed by periods of strong resuspension near the bed, evolving from the primary leading scales at low frequencies, and decaying in time after the termination of the turbulent agitation. All these above-mentioned results necessitate the requirement of considering the instantaneous Reynolds shear stress effects in the existing sediment transport equations which are developed based on a single time-averaged and bulk critical value of critical shear stress concept.
Chapter 6: Conclusions

6.1 Introduction

In engineering and sedimentological applications, it is usual to relate sediment movement to a time-averaged bed shear stress (van Rijn, 1984; Pattiaratchi and Collins, 1985; Soulsby and Whitehouse, 1997). In addition, a mean critical threshold bed shear stress (based on the Shields (1936) criterion) has to be exceeded before sediment transport occurs. Many field and laboratory studies have indicated that the shear stress exerted on the sea bed is intermittent in nature due to the turbulent bursting phenomenon (Heathershaw, 1974; Heathershaw and Thorne, 1985; Chapter 2). In addition, there have been suggestions that sediment movement at the sea bed could also occur in bursts. Attempts to link these two processes in the past have not been very successful due to the limitations of three-dimensional velocity and sediment transport measurement techniques.

The existence of a critical bed shear stress above which sediment transport occurs has been the subject of conjecture. For example, Lavelle and Mofjeld (1987) examining historical data for critical shear stress concluded that no ‘true’ threshold value existed and that sediment transport could occur at any time. In developing an equation to predict sediment transport in rivers Einstein (1950) assumed that sediment transport is a stochastic process where there is a probability that a sediment grain will move at any given time with that probability increasing with higher shear stress. Recent field observations (e.g. O’Callaghan et al., 2010; Yang et al., 2016) have also indicated that sediment transport can occur below the threshold. These results imply that high bed shear stress values are a necessary, but not limiting condition for sediment transport.
In this thesis, an attempt was made to link fluid turbulence and sediment movement using high resolution velocity measurements and acoustic backscatter as a proxy for sediment concentration. The measurements were undertaken in four contrasting flow regimes that included unidirectional currents (open channel flow in the laboratory, continental slope region, tidal inlet) and oscillatory flow (nearshore beach). The flow conditions in relation to the Shields diagram indicated (Fig. 6.1) that the measurements were made close to the threshold values (mainly due to the absence of high currents in the local study region). However, the laboratory and deep sea conditions were below the threshold whilst the inlet and beach experiments were conducted under flow conditions that were above the threshold value (Fig. 6.1). Overall, finding of this study will contribute to select well understood parameters while researching on future sediment transport models as existing transport equations still does not account the uncertainty of turbulent coherent structures. Therefore, in broad perspective, the application of this finding better lead to improved various sediment transport communal issue (e.g. reducing the risk factor of hydraulic structural failure, well maintaining water health, influencing biological production among many others).

The main findings of the study and conclusions are summarised in this Chapter.

6.2 Summary of the main findings

- The laboratory and field observations, in all four contrasting flow regimes, revealed that sediment transport is event based with resuspension events related to turbulent velocity fluctuations. This was true irrespective of whether the flow conditions were either above or below the threshold criterion for sediment transport based on the mean flow (Figure 6.1 and Chapters 3, 4 and 5). Wavelet transforms of momentum and sediment flux were a very good indicator of this
event based transport (Fig. 6.2) indicating also that the shear stress exerted on the sea bed was intermittent and reflected in sediment flux.

- Measurements of nearbed turbulence and associated sediment concentrations indicate that the measured mean critical velocity alone was not an accurate predictor of the episodic initiation of sediment motion. Turbulent events were able to transport sediment even at mean flow conditions below the predicted threshold defined by time-averaged stress (Fig. 6.1). In the inlet experiment, there was more frequent sediment transport events as the mean velocities ($\bar{u} = 0.34$ m/s) were higher, compared to the other three flow regimes (Fig. 6.2d).

![Shields diagram](image)

**Figure 6.1.** Shields diagram adopted from van Rijn (1984) contrasting laboratory (error bar indicating measured critical velocity), deep water, inlet and beach (error bar indicating maximum velocity) experiments.

- Laboratory, continental slope and inlet experiments were all conducted under unidirectional flow conditions. The beach experiment was dominated by
incoming swell waves (with periods ~15s) that allowed for the changes in the current velocity over a wave cycle (Fig. 6.2e). The current pattern was asymmetric as expected for incident waves on a beach. Here, there was a gradual increase in the velocity from the trough to the crest (‘onrush’) followed by a more rapid change in velocity from the crest to the trough (‘backwash’). The results indicated that the majority of the turbulent events (both momentum and sediment concentration) occurred on the backwash (hatched region in Fig. 6.2e).

**Figure 6.2.** Wavelet power spectra plots for Panel A (momentum flux): (a) above critical condition in the laboratory; (b) below critical condition in the laboratory; (c) deep water condition; (d) inlet flow; (e) mean cross-shore velocity (u) the crest-to-trough phase is hatched; and, (f) oscillatory flow conditions. Panel B: as Panel A but for sediment flux.

- Measurements of turbulent velocities at three sampling heights above the sea bed (inlet and beach experiments) indicated that the turbulent coherent structures contributing to resuspending sediments were present throughout the lower water column (i.e. the turbulent structures were identical at the 3 different levels of
measurements). This indicated that an exact location above the bed was not necessary to undertake the turbulent measurements.

- Although some studies have presented laboratory or field evidence suggesting that only sweeps and up-accelerations play a significant role in the entrainment and transport of sediment, the results of this study indicate that sweeps and ejections were the primary contributors to sediment entrainment in agreement with others (Grass, 1970, 1974; Sumer and Deigaard, 1981; Best, 1992; Niño and Garcia, 1996; Hurter and Lemmin, 2003).

- Time series presented in this study consistently demonstrated the role of turbulence coherent structures in resuspending sediments and allowed for the development of a schematic diagram to visualise the bursting process linking fluid turbulence and sediment movement (Figs. 6.3, 6.4). The diagram shows the succession of flow structures within the single ‘bursting’ cycle together with the instantaneous velocity profile compared to the profile of mean velocity. Note that a turbulent eddy may rotate either clockwise or anti-clockwise and both these conditions are presented (Figs. 6.3, 6.4).

**Figure 6.3.** Schematic diagram of velocity profile summarising turbulent bursting process as captured in the field condition (considering vortex travelling anti-clockwise)
Figure 6.4. Schematic diagram of velocity profile summarising turbulent bursting process as captured in the field condition (considering vortex travelling clockwise).

6.3 Future work

There are several avenues of research that may be undertaken as an extension of this study. Some of them are as follows:

- In this study measurements were conducted in idealised conditions (both in laboratory and field conditions). Therefore, a full deployment in a wave-current environment should be undertaken in order to generalize the turbulent bursting process in resuspending sediments.

- Methodology similar to that used here could be applied to existing field and laboratory datasets that focus on velocity but also as signal backscatter is part of the data record. They could be combined. This will allow for a more complete understanding of the interactions between flow and sediment transport over complex near bed topography (e.g. over ripples) to reveal the role of turbulent coherent structures in resuspending sediments.

- Direct Numerical Simulation (DNS) has the potential to develop methodologies for the prediction of bursting events and associated sediment resuspension
mechanisms, its application on large-scale, complex flows still remains limited. Further development on such avenues is required to apply the DNS approach to intermittent turbulent bursting events both in fluvial and marine flows.

- The knowledge of how the bursting events contribute toward the near-bed Reynolds shear stress production governing the sediment motion would be an essential prerequisite for Large Eddy Simulation and Direct Numerical Simulations. Therefore, in the near-bed flow regions, a gain in turbulence production due to negative pressure energy diffusion rate is another aspect that can be given adequate importance for developing a theoretical model.

- Development of universal database of fluid velocities, sediment concentrations and sand transport rates along sandy beaches in the field and in laboratories which prominently can lead to improve the practical sand transport models using data from various laboratory and field experiments (databases) and new insights from sand transport process research.

- The comparison of turbulent eddy time-scale and their effect on sediment resuspension is another avenue that can be investigated in detail in future research.

- Despite decades of work on fluid flow, the linkage between coherent flow and sediment transport remains unclear. The majority of nearbed turbulent flow studies have investigated the flow with the underlying assumption that what happens in the flow must control the morphodynamics of the boundary and sediment transport. Yet, most studies end with conceptual models of how nearbed fluid turbulent flow and the boundary interact. Therefore, more work is needed to link coherent flow structures of nearbed fluid flow formally with the boundary in
a predictive manner if the paradigm is to significantly improve our understanding of Earth surface dynamics.

- At bridge sites, localized scour in the vicinity of piers, over which the bridge superstructure rests, poses a challenging problem to the hydraulic engineers. Engineers often need to consider various aspects such as mechanism of scour and design formulas for the prediction of scour depth in order to protect hydraulic structures from failures. It is however pertinent to mention that despite large number of investigations, hydraulics of local scour is as yet not well established, because most of the studies came from the laboratory and only a few from the fields. As such, the scour prediction formulas can only provide a general guideline for the designers or engineers where the resuspension of sediments due to turbulent bursting phenomena is not considered.

- It is well known that most of the practical problems on fluvial system are highly intricate in nature so that a desirable solution of the hydrodynamic equations is rather hoping against hope. Even in many occasions, the equations are not at all applicable. The obvious benefit of using a laboratory model, if it is carefully fabricated representing a simulated miniature prototype, could lead to a much accurate prediction being applicable to the field.

- Future research should be directed to examination of flow past isolated patches of vegetation, which occurs often in practical applications, rather than fully developed vegetated flows in which the mean properties of the vegetation canopy are inde-pendent of the location. Of fundamental interest is the study of the spatial changes in the flow and turbulence structure in the transition layer forming upstream and downstream of the vegetation patch. Configurations in which the
extent of the vegetation patch is limited in the lateral direction should also be considered.
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