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Bed Forms and Flow Mechanisms Associated with Dunes

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1. Introduction

This section will focus on the general features of flow in open channels with a brief analysis of rough open channel flow, shallow open channel flow and the latest developments. This section will serve as the background material to enable the reader to develop an appreciation of the important features that lead to the formation of dunes.

1.1 General description of flow in open channels

Open channel flow (OCF) occurs in canals, rivers and various types of waterways. Open channel flow is mainly driven by gravity unlike flows in closed conduits where the flow is mainly driven by a pressure gradient. An important feature of an open channel flow is the presence of the free surface (zero-shear state). The friction at the bed and the side walls acts as resistance to the flow which is mostly turbulent. The type of bottom and side walls are dependent on the material in which the flow is taking place. Lined canals and canals in rocky strata can be classified as fixed bed channels, and canals in erodible medium are termed as movable bed channels. The shear stress distribution and roughness characteristics of the boundary do not vary with time for a given flow rate in a fixed bed open channel. A movable bed generally accompanies the flow in an alluvium soil. The side slopes and bottom slope of erodible channels vary with time. The flow in open channels can be classified depending on the velocity changes in space and time. The flow is steady if $dU/dt = 0$ at any point in the flow field and it is unsteady if $dU/dt \neq 0$. Though the turbulent flow accompanied by the formation of ripples and dunes on the bed is strictly unsteady, in most practical situations, the time-averaged velocity acquired over long time intervals result in a quasi-steady flow. Flood flows in rivers and surges in power canals are examples of unsteady flows in open channels. Unsteady flows are more difficult to solve because the governing equations are hyperbolic (continuity and momentum). The flow is uniform if $dU/dx = 0$ and non-uniform if $dU/dx \neq 0$. Uniform flow can only occur in long prismatic channels or generated in laboratory flumes. Non-uniform flow can be classified into gradually varied flow (dy/dx is very small) and rapidly varied flow ($dy/dx >> 0$) depending on the amount of change in the velocity over space. Furthermore, most practical open channel flows are turbulent ($Re \geq 2000$) and accompanied by rapid changes in velocities and pressures, in space and time. Eddies and swirls are present in turbulent flow leading to lateral mixing. Figure 1 illustrates the presence of dunes in the Rhine River in The Netherlands.

1.2 Rough open channel flows

Turbulent wall-bounded flows on rough surfaces, including that in open channels, have been studied extensively. One should note that smooth open channel flows occur only in laboratory flumes. In rough open channel flows the non-dimensional equivalent sand roughness, $k_s^+ = ku_*/\nu$ is greater than 70, and the roughness elements completely penetrate the fully turbulent logarithmic layer. In fully developed open channel flow, the height of the turbulent boundary layer occupies the entire flow depth (d) and thus $\delta \approx d$. Recent particle image velocimetry (PIV) and planar light induced fluorescence measurements by Djenidi et al. (2008), Manes et al., (2007) and numerical results of Krogstad et al., (2005) document an increase in the Reynolds stresses in the outer layer which was different from that obtained on the smooth wall. Nikora et al. (2001) developed a comprehensive classification of rough open channel flows based on the value of the relative submergence (d/k). Krogstad et al. (2005) and Volino et al. (2009) speculated that in 3-D rough wall flow, the effect of the surface roughness on the outer layer may be dependent not only on the surface conditions but also on the type of flow: internal or external flow. Balachandar and Patel (2002) have shown that some types of 3-D roughness might produce very thin roughness sub-layers at low submergence, which will allow for development of the logarithmic layer. Roussinova and Balachandar (2011) investigated the effect of depth on turbulence characteristics in the fully rough regime of train of ribs and found that turbulence structures are affected by both roughness and depth.

1.3 Shallow open channel flow

Open channel flows can be classified as shallow when the vertical length scale of the flow (usually the depth, d) is significantly smaller than the width of the flow (Jirka and Uijttewaal, 2004). Fully turbulent shallow channel flow is highly chaotic with the presence of coherent motions. The key feature to understand shallow open channel flow may lie in analyzing the nature of the interactions of events occurring near the bed and near the free surface in greater detail. Ejection and sweep events, hairpin vortices of a length scale of the order of two to three wall units (Blackwelder and Kovasznay, 1972, Theodorsen 1955) and bursting phenomenon (Kline and Robinson 1989) have been observed in the shallow flows. Wu and Christensen (2006), Lin et al. (2003), and Roussinova et al. (2010) used PIV data to expose the signature of the horseshoe vortices, sweep and ejections for a typical shallow channel flow. Experimental evidence put forward by Balachandar and Patel (2005) shows that for a low turbulent intensity flow, a change in both the Cole's boundary layer wake parameter as well as in the rate of production of turbulent kinetic energy due to the presence of free surface disturbance is observed.

2. Bed forms

In alluvial streams, bed load and contact load movement results in the formation of bed forms, which vary geometrically in size and shape. Generally, all of them are grouped into "sand waves" because of the similarity of appearance to sea waves. The size and shape of bed forms depend on the flow velocity, flow depth, Froude number, stream power (defined as the product of mean bed shear stress and mean velocity of flow), sediment properties and fluid properties. In practice, a few principal types of bed forms are usually distinguished: ripples, dunes, plane bed, antidunes, standing waves and chutes and pools (Figure 2).

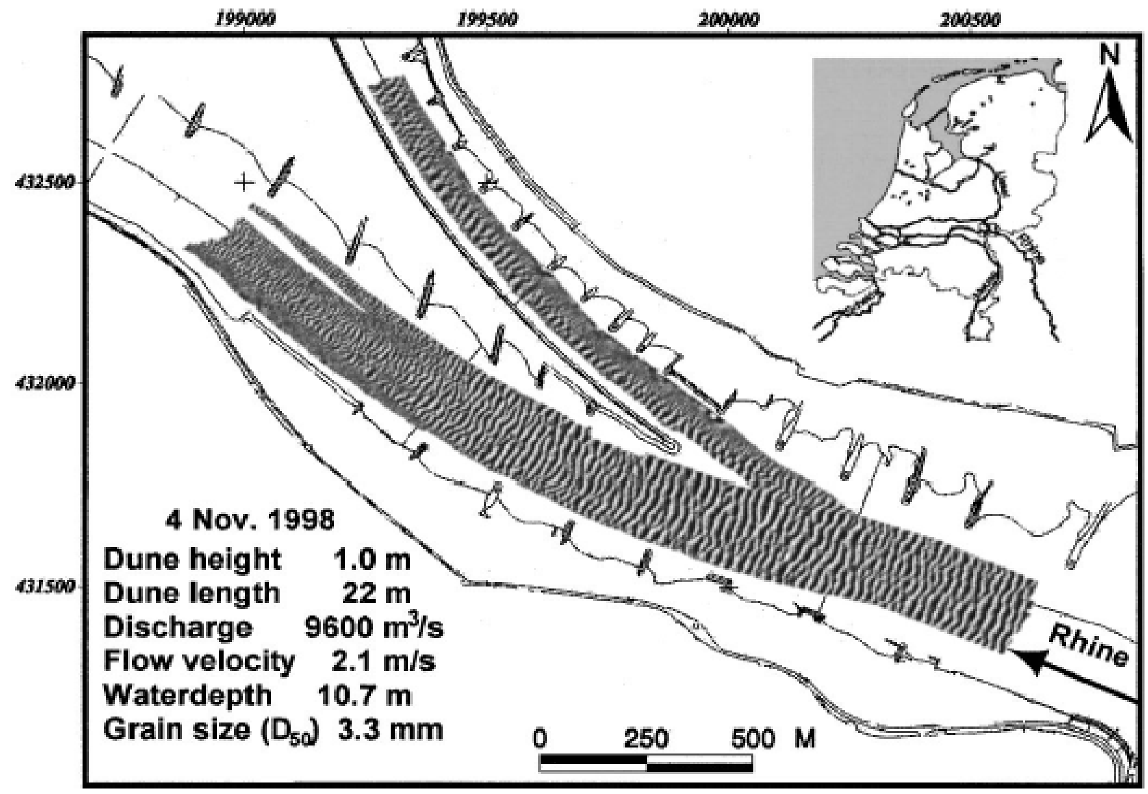


Fig. 1. Dunes around a bifurcation of the Rhine in The Netherlands at peak flood stage in 1998, mapped using data of a multibeam echosounder (from ASCE task committee 2002, copyright permission of ASCE)

Ripples are transverse bed forms, which normally have heights of less than 0.04 m and lengths below 0.6 m. Ripples are formed under hydraulically smooth flow conditions. If the flow velocity is great enough to move the individual sand grains but less than another limiting value, the bed is spontaneously deformed into irregular features called dunes. Dunes are formed under hydraulically rough conditions. Dunes have much larger dimensions and may have heights up to several meters and wavelength up to hundreds of meters. Observations and measurements suggest that lengths of dunes are about 3 to 8 times the water depth (Yalin 1977). When the velocity of flow is increased in beds composed of fine sediments (< 0.4 mm), a situation will be reached when dunes can no longer be sustained, and flat bed is formed in which the bed and free surface become flat. With increase in velocity and the Froude number, the water surface becomes unstable, and even small disturbances give rise to stationary surface waves thereby forming trains of long, sinusoidal-shaped waves of sand that are in phase with the surface waves and usually move slowly upstream. These features are called antidunes, and surface waves accompanying them are referred to as stationary waves. At higher velocities and stream powers, the bed reorients itself to create a series of hydraulic jumps for energy dissipation and these bed forms are called as chutes and pools. These high Froude number flows may occur when flash floods sweep down steep gullies of rocky areas. Large quantities of suspended sediment are carried by resulting breaking waves.

2.1 Dune geometry

The upstream side of a dune is commonly referred to as the stoss side (for example, see Figures 3 and 4). The downstream side is usually referred to as the lee face or slipface. Dune height h (Figure 4) is most often defined as the difference in elevation between the dune crest and corresponding downstream trough (Gabel 1993, Julien and Klaassen 1995): although sometimes dune height is measured from upstream trough to downstream crest (e.g., Nordin 1971). Dune length, λ is the longitudinal distance between subsequent crests or troughs. Dune steepness, $\delta = h/\lambda$, is the ratio of dune height to length and its value varies between 0.1 to 0.03 (Yalin, 1964). If the aspect ratio of the channel is small, dunes tend to be approximately triangular with straight crests and extend nearly across the width of the channel (Klaassen et al. 1986). On the other hand, when the aspect ratio is large, dunes will be three-dimensional with sinusoidal crests or several crests stretching across the flume.

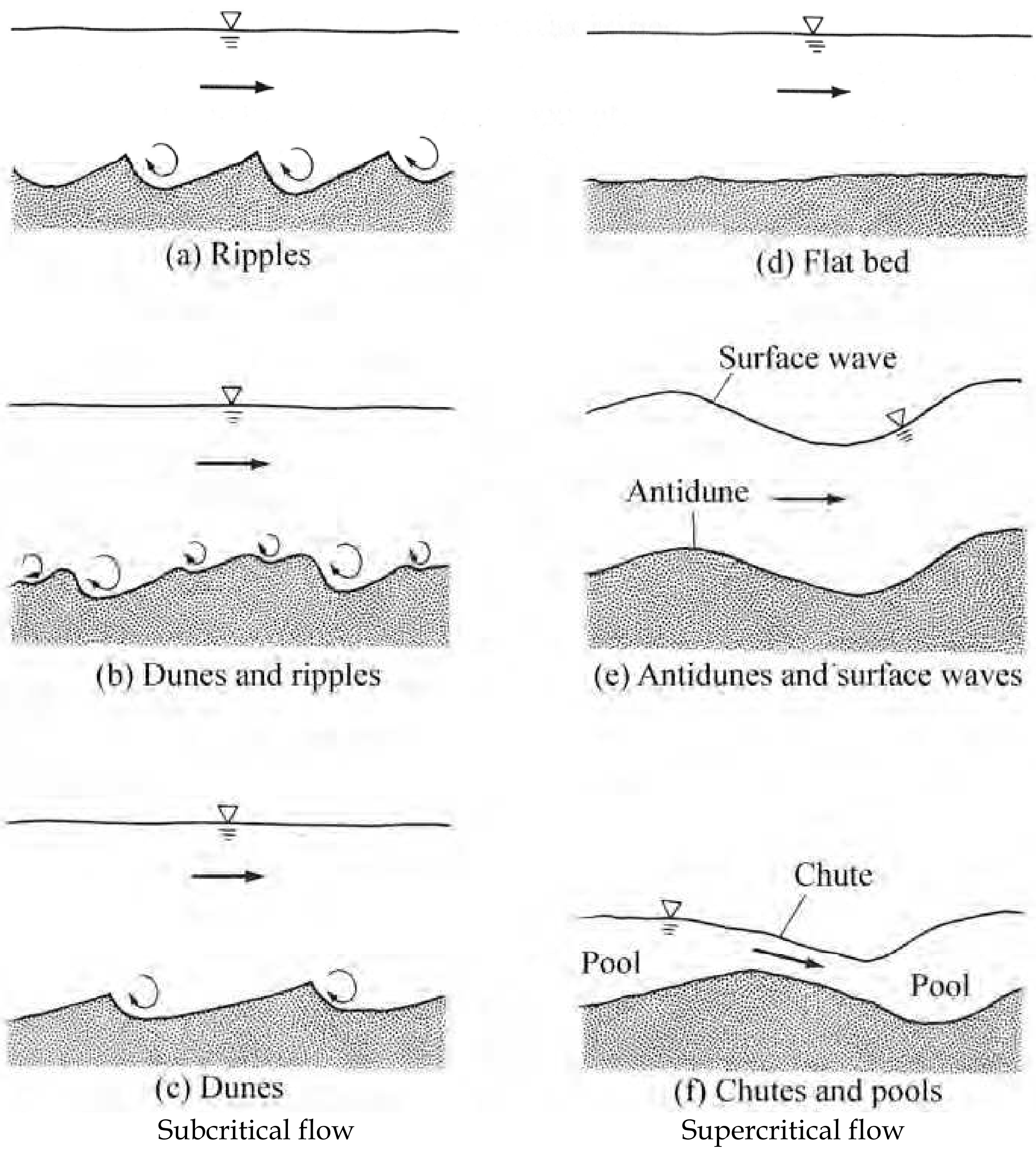


Fig. 2. Bed forms in alluvial channel (from Vanoni, 1975, copyright permission of ASCE)

2.2 Fully developed (equilibrium) bed forms

The simplification with equilibrium bed forms is that uniformly sized periodic dunes vary only in the streamwise direction and do not change with time. As a first step towards developing a comprehensive understanding of flow in natural channels, researchers have studied the flow field over a train of fixed, well developed dunes. Best et al. (2001) opined that a fixed dune approach doesn't capture the effect of sediment transport on velocity profiles and despite this limitation the simplification of dune morphology to a fixed two-dimensional profile does allow investigation of the major features of flow, as has been successfully demonstrated in previous studies of flow over two-dimensional bed forms (e.g. Bennett and Best, 1995; Lyn, 1993; Nelson et al., 1993; Raudkivi, 1966). Such studies also provide a basis for a better understanding of the effects of dune three-dimensionality. The laser-Doppler (LDV) technique has been used in several laboratory fixed sediment bed form investigations (e.g., Balachandar et al., 2007; Balachandar and Patel 2008; Bennett and Best 1995; Coleman et al. 2006; Kadota and Nezu 1999; Lyn 1993; McLean et al. 1994 and 1996; Nelson et al. 1993; Nelson et al. 1995; Van Mierlo and de Ruiter 1988; Venditti and Bennett 2000). These studies have suggested that near-bed turbulence over much of the stoss side of a dune deviates markedly from either classical boundary-layer or wake turbulence. Cellino and Graf (2000) carried out detailed study of sediment-transport flows over mobile bed forms using acoustic Doppler technique. Mendoza and Shen (1990), Johns et al. (1993), Yoon and Patel (1996), Yue et al. (2006), Stoesser et al. (2008) and Noguchi et al., (2009) performed numerical simulations of flow over fixed bed forms by applying sophisticated turbulence models. Detailed flow characteristics will be discussed in the upcoming sections.

2.3 Transient bed forms

The shape and size of bed forms and flow conditions are inter-related. Significant progress has been made to understand the role played by topography on flow characteristics, separated flow dynamics, internal boundary layer development, and turbulence structures (Smith 1996). Raudkivi (1997) studied the formation and development of ripples. Bennett and Best (1996) and Lopez et al. (2000) studied the ripple to dune transition. Recent experimental and theoretical studies carried out by Coleman and Melville (1996) and Coleman and Fenton (2000) have focused on the bed form initiation process. Coleman and Eling (2000) observed that turbulence may not be an essential feature of the initial instability of a sediment bed.

Robert and Uhlman (2001) carried out experiments on different bed stages across the ripple-dune transition and found that turbulence intensity and Reynolds stresses gradually increase throughout the transition. Coleman et al. (2006) studied developing dunes using an innovative experimental approach and double averaging methodology to advance our understanding of the structure of the rough flow near the bed region. They found that flow structure doesn't change as dunes develop in time for a steady flow, even though overall flow structure must change as dunes develop and traditional boundary layer type features can be potentially destroyed. Interesting findings of this work include: (a) friction factor was noted to increase with bed form growth; (b) the location of the separated shear layer reattachment point was determined as approximately 4h downstream of the crest for time averaged flow fields over the developing dunes as compared to 4.2h of previous flows over fixed dunes (Bennett and Best 1995; Kadota and Nezu 1999; Lyn 1993; McLean et al. 1999;); (c) negligible variation of the vertical velocity distribution, spatial fields of Reynolds stresses , form induced stress, skin friction, form drag, bed stress and overall momentum flux as dunes grow and the overall form of the velocity profiles display an approximately linear distribution below roughness tops and a potentially logarithmic distribution above roughness tops; (d) peak Reynolds stresses occur in the shear layer associated with the separation zone consistent with shear layer instabilities and vortex shedding off this layer.

3. Temporal and spatial flow over dunes

This section presents a discussion of results related to temporal and spatial velocity characteristics and flow resistance of open channels with bed forms

3.1 Temporal and spatial flow over dunes

Compared to flow over a hydrodynamically smooth channel boundary, the interactions of flow with the bed formation are considerably harder to predict. Dunes disrupt the boundary layer type flow and generate turbulence. Extensive research regarding fluid flow over dunes has been undertaken in the past forty years (Engelund and Fredsøe 1982; Lyn 1993; McLean et al. 1994; Nelson et al. 1993; Raudkivi 1966). To summarize, five zones (Figure 3) have been recognized within the dune-flow interaction region (Balachandar et al., 2007; Balachandar et al. 2008; Bennett and Best, 1995; Best 2003).

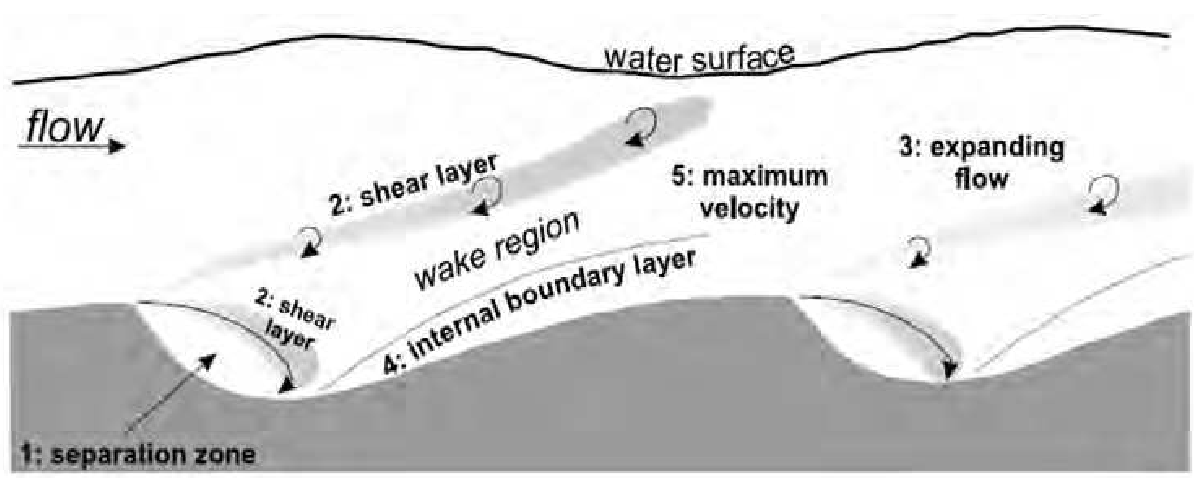


Fig. 3. Schematic diagram of the principal regions of flow over asymmetrical angle-of-repose dunes (from Best 2005, Reproduced by permission of AGU)

A typical dune and the flow over the dune are indicated in Figure 4 (Balachandar et al., 2007). The flow ahead of the crest (indicated by C in Figure 4) resembles a typical near-wall, boundary-layer like flow. Following separation at C, a typical recirculation pattern is formed. Above this separation zone lies a decelerating flow with wake-like characteristics that extends downstream beyond the reattachment point (denoted as R in Figure 4). Experimental and field investigations have documented the formation of kolks or boils, which are tilting vortices emanating from the reattachment region and rising to the free surface. Near the bottom, following reattachment, an internal boundary layer develops and interacts with the overlying wake zone. Close to the free surface and over the dune wavelength, there is an outer zone that is generally modeled as a quasi-inviscid region. Along the separating shear layer, regions of high Reynolds stresses have been observed. Many previous studies have suggested that the macroturbulence associated with dunes is important in controlling the stability of the bed forms and the entrainment and transport of the sediments. It has been suggested that this macroturbulence has its origin in Kelvin-Helmoltz instabilities in the separating shear layer (Best 2003; Kostaschuk and Church 1993; Muller and Gyr 1987). In particular, Best (2003) and Hyun et al. (2003) provide whole field quantification using particle image velocimetry. As an important step towards better understanding the flow-dune interaction, researchers have analyzed the flow field for the case of a fixed dune.

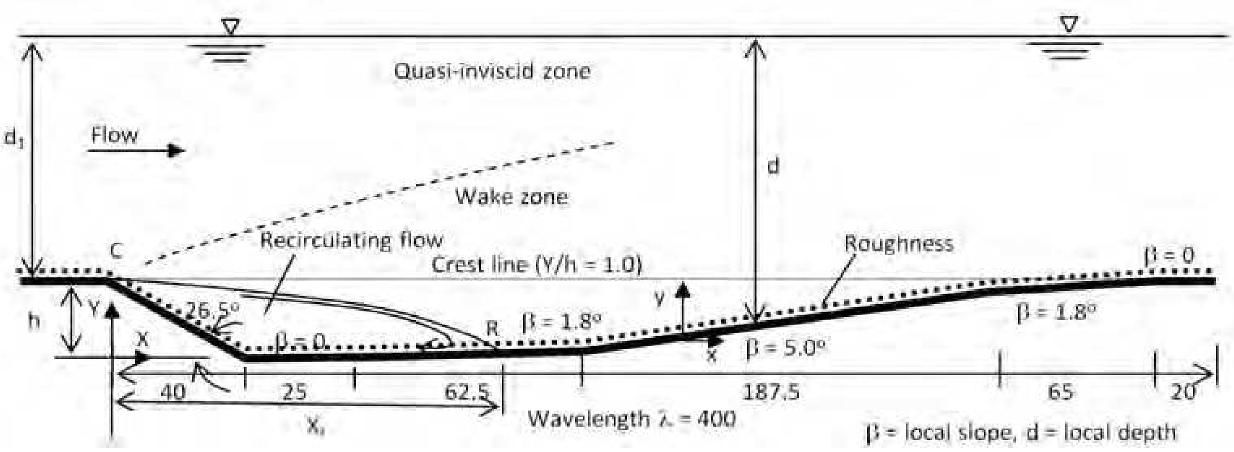


Fig. 4. Schematic of the flow field. Not to scale, all dimensions in millimeters (from Balachandar et al., 2007, copyright permission of NRC Research Press).

3.2 Time averaged flow along the dune

Using laser-Doppler measurements, Balachandar et al., (2007) analyzed the velocity data at various axial stations between two dune crests and is shown in Figure 5. In the figure, d_1 = flow depth ahead of the crest at X/h = -2 or 18; X = horizontal distance from the dune crest; h = dune height. It was observed that the flow over the dune train was periodic in space insofar as the flow pattern was the same over successive dunes, but there was a significant variation in flow properties along the wavelength of the dune. The velocity profile at X/h = -2, just ahead of the crest, indicates a log-region, although of a much reduced extent compared with a plane channel flow (see Figure 5a). A region of reverse flow can be seen at X/h = 4 and the mean reattachment point is located around X/h = 4.5. It was also observed that the flow in the outer region was not influenced by the local bed geometry, which is shown in Figure 5b. The average vertical velocity is zero at the dune crest, yet flow expansion and separation cause bed wise movement and thus negative velocities over much of the dune. This indicates downward deflection of streamlines (Figure 5c). The positive vertical velocities at X/h = 12 suggest streamlines following the upward slope of the surface. The profiles of streamwise turbulence intensity show that the turbulence reaches a high peak just below the crest line, which is also the location of maximum value of mean shear, shown in Figure 5d. A second peak at all the stations in the vicinity of y/d = 0.2, leads to the conclusion that there is a distance from the bed beyond which the turbulence is little affected by the dune shape. The peak exists at X/h = 12 and -2, and suggests the presence of remnant of the turbulence generated in the shear layer of the upstream dune. Figure 5e indicates that large values of vertical components of the turbulent intensities occur in recirculation zone and in the shear layer above it. Quite large values of shear stress (Figure

5f) can be seen measured in the separation zone. Shear stresses decrease to upstream values with increasing distance from the reattachment.

3.3 Effect of flow depth

In studying ripple-dune transition, Bennett and Best (1996) noted important changes in macroturbulence structure due to effect of depth on flow past bed forms. Wiberg and Nelson (1992) studied two flow depths over a train of ripples closely resembling the bed form shape of Nelson and Smith (1989) and noticed a higher value of bed friction at the smaller depth. Figure 6 (Balachandar et al., 2007) shows streamwise mean velocities profiles at six locations along the dune for four depth ratios (y/h), ranging from 3 to 8. At X/h = -2, in inner scaling, U^+ versus y^+ (inset of Figure 6a) collapses at all depths but the outer region is different from a simple open channel with a smooth bed. Velocity profiles at X/h = 2 to 12 show similarity in the near wall region and independent of depth in the outer region (y/d > 0.35). It is important to note that at X/h =5, the mean velocity in the near-wall region is positive for $d_1/h \geq 4$ and is negative at d_1/h = 3. This indicates the depth of flow influences the near-bed region and the length of the separation region is longer at the shallower depth. The profiles of the vertical component of turbulence reveal a systematic dependence on flow depth near the crestline and at the larger depths indicate lower values of turbulent intensity. In the recirculation region, the shear stresses are very high and increase with decreasing flow depth.

3.4 Effect of bed roughness on the flow over dunes

Balachandar and Patel (2008) studied the effect of bed roughness superimposed on a train of well-formed dunes by conducting laser-Doppler measurements at several stations between two dune crests. In these studies, rough surfaces were generated using (a) stainless steel wire mesh made of 0.72 mm wires with 6.35 mm centerline spacing and (ii) sand grain roughness created from sand grains of 1.8 mm nominal mean diameter carefully glued onto a double-sided tape to ensure a uniform distribution. Their results showed that the wire mesh provided for a higher degree of roughness as compared to sand grain roughness. It was found that with increasing streamwise distance from the crest, the dependence of the near-bed part of the profiles on the roughness becomes apparent. In the outer region (y/d > 0.2), the profiles are independent of the bed roughness (Figure 7). It is also found that outer region was clearly different from that in the simple open channel flow over a smooth surface, indicating that the entire depth of flow has been affected by the dune geometry. The effect of the near-bed roughness is more dominant in the recirculation zone. The peak value of turbulence at any station is influenced by the bed roughness and the location of the peak is farther extended into the flow away from the wall with increasing roughness. It is found that the length of the separation region is longer for the flow with larger bed roughness. The results indicate that the shape of the dunes have a major influence on the flow features, where as the effect of dune roughness is limited to the near wall region extending to a distance of about 80% of the dune height about the crest.

3.5 Relation between suspended sediment and dune characteristics

Bennett and Best, (1996), Best (2005 a, b), Lopez et al., (2000), Robert and Uhlman (2001) and Schindler and Robert (2004) have shown that suspended sediment concentration increases with increase in scale and magnitude of turbulent structures. Schindler and Robert (2005)

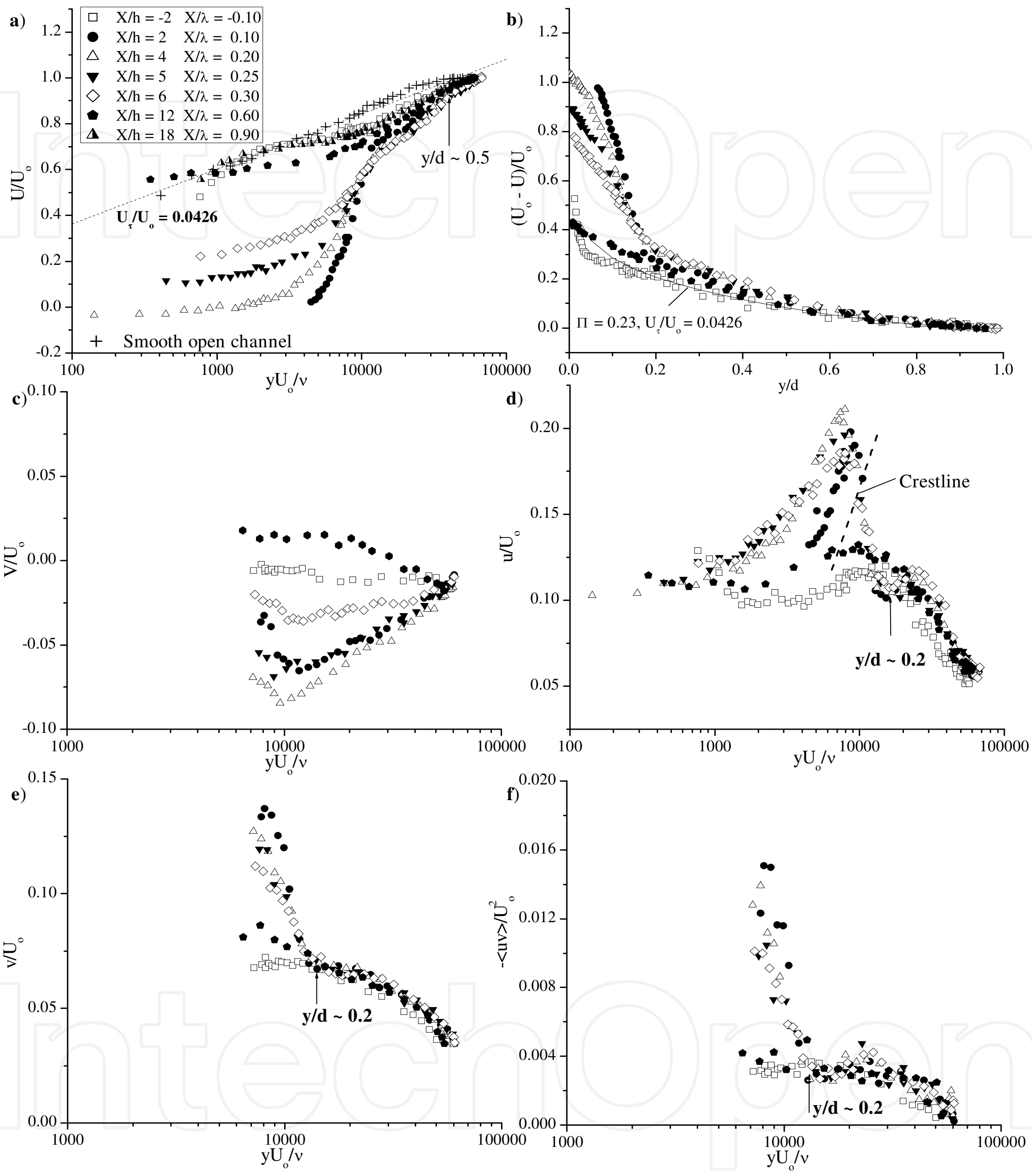


Fig. 5. Mean velocity and turbulence profiles (d_1/h = 6): (a) streamwise mean velocity profiles; (b) mean velocity profiles plotted in the velocity-defect format; (c) vertical component, V, of the mean velocity; (d) profiles of the streamwise root mean squared (rms) turbulence intensity (u/U_o); (e) vertical component of the rms turbulence intensity (v/U_o); (f) Reynolds shear stress profiles (from Balachandar et al., 2007, copyright permission of NRC Research Press).

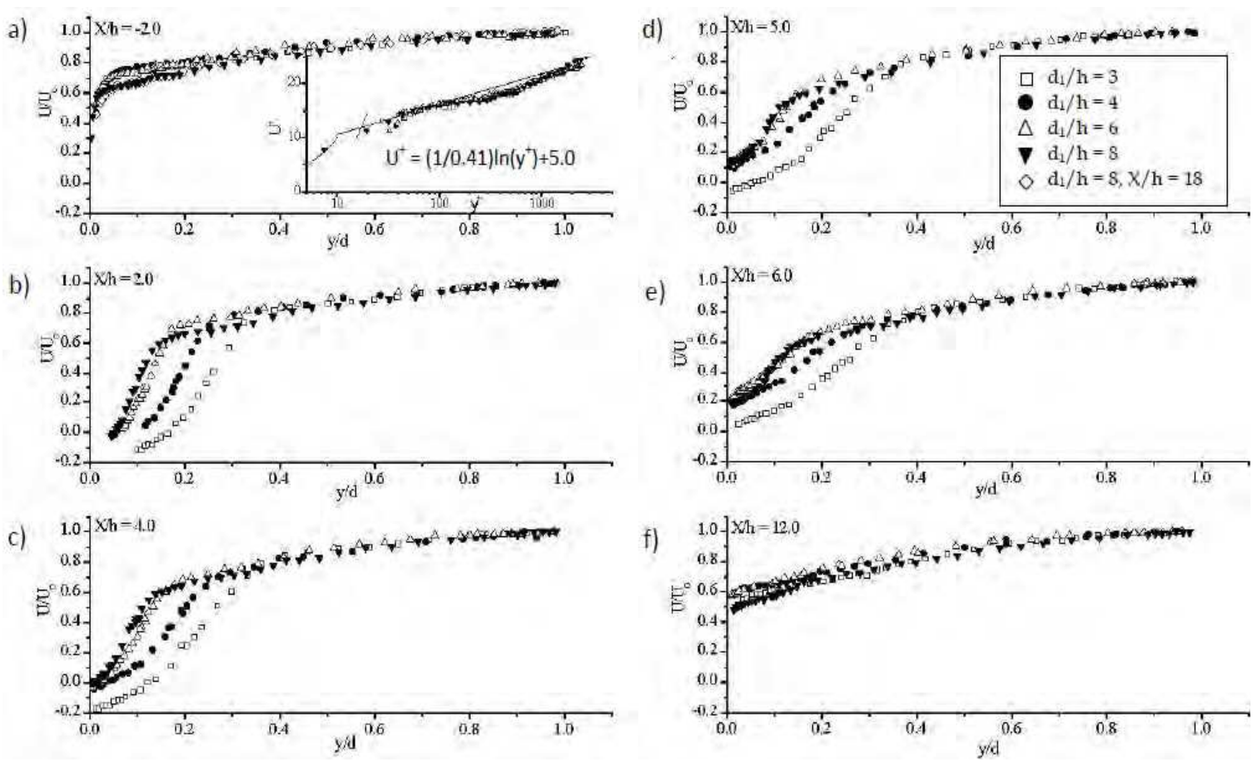


Fig. 6. Effect of depth on mean velocity profiles at various axial stations (-2≤X/h≤12) using the depth of flow, d, as the normalizing length scale (from Balachandar et al., 2007, copyright permission of NRC Research Press).

have concluded that the transition from 2-D to 3-D bed forms, result in increased sediment transport, increased turbulence and increased bed form migration rate. Venditti and Bennett (2000) found that suspended sediment concentration is highest over the dune crest and at flow reattachment. Further research is needed to spatially analyze both the fluid dynamics and the sediment transport processes over mobile bed forms.

Tevez et al. (1999) reported that spatially averaged mean velocity profiles over dunes consist of upper and lower semi log-linear segments. The upper segment reflects the total shear stress of the flow. The lower segment on symmetric dunes reflects the skin friction from sand particles, but for asymmetric dunes it is the skin friction plus the effect of form roughness from the superimposed dunes. Villard and Kostaschuk (1998) found that predictions of the Rouse equation indicated that sediment suspension is controlled by total stress for symmetric dunes, whereas for asymmetric dunes sediment suspension is related to stress associated with skin friction plus form roughness. It is reported that dunes in bed load-dominated environments are often asymmetric having low-sloping upstream side (stoss) and steep lee faces (Guy et al. 1966; Kostaschuk et al. 2004), while those in suspended load dominated environments are often more symmetric with relatively low angle lee faces (Best and Kostaschuk 2002; Kostaschuk and Villard 1996).

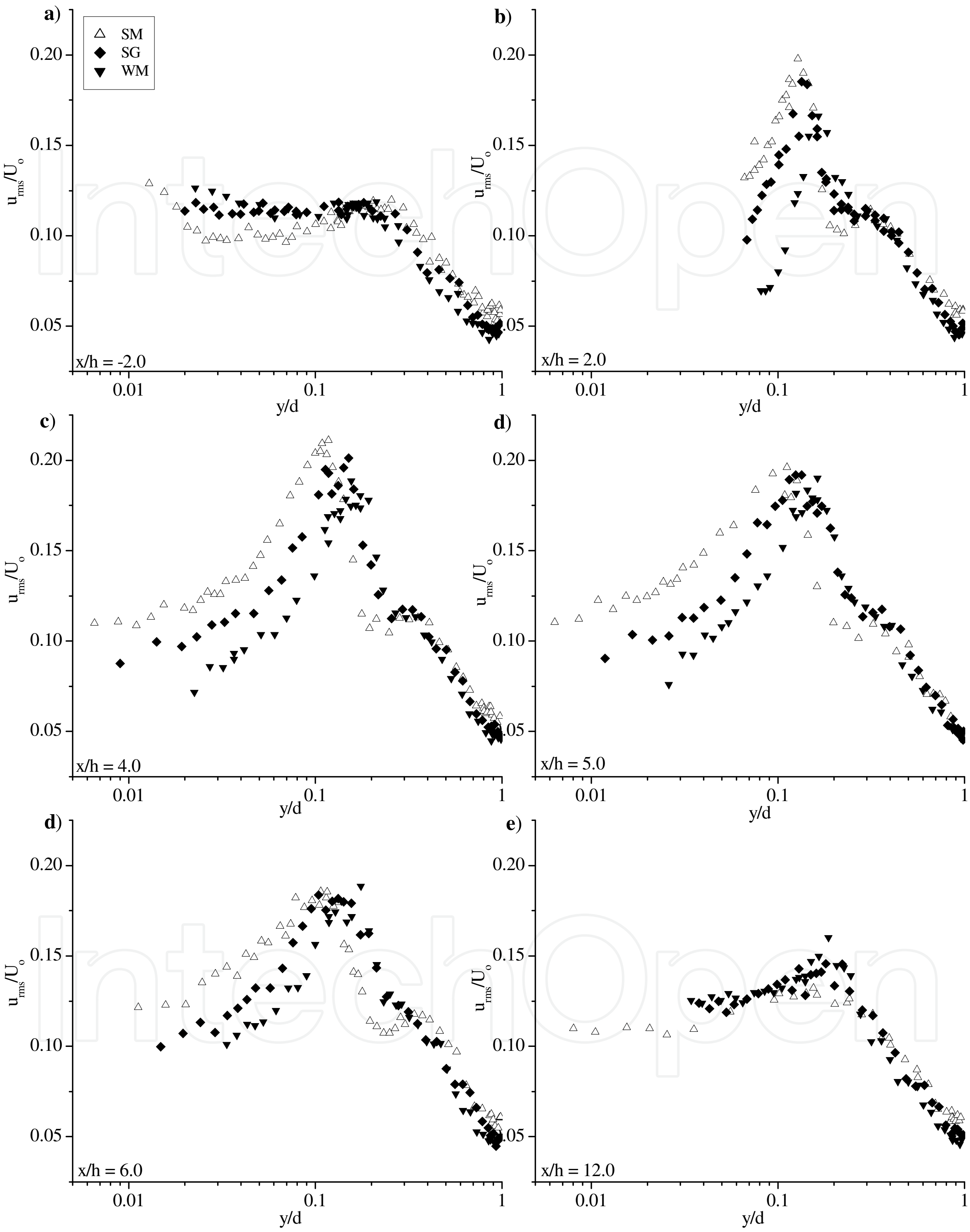


Fig. 7. Variation of streamwise turbulence intensity. SM - experiments conducted with a train of smooth bed dunes manufactured from Plexiglas, SG sand grain pasted on smooth dune; WM, wire mesh glued to dune. (from Balachandar et al., 2007, copyright permission of NRC Research Press)

3.6 Sediment heterogeneity

Existing literature mostly points to studies that focus on the case of uniform sediment while dealing with laboratory dune studies. However, sediment heterogeneity may be of practical interest because formation and development of bed forms in natural rivers happens distinctively with non-uniform sediment. It is quite challenging to study flow over dunes with sediment mixtures in a laboratory. A few studies have been conducted in this area (Parker et al., 1982, Wilcock and Southard, 1988 and Wilcock, 1992). Wilcock and Southard (1989), Klaassen et al., (1987), Ribberink, (1987) and Klaassen (1990) investigated the mutual influence of sediment gradation on ripples and dunes, on fractional transport rates and on vertical sorting. ASCE Task Committee on Flow and Transport over Dunes (2002) reported that fully developed dunes composed of highly heterogeneous sediment exhibit different geometric, flow, and transport characteristics than the more intensively studied homogenous-sediment counterparts. Klaassen (1991), Blom and Kleinhans (1999), Kleinhans (2002) and Blom and Ribberink (1999) have reported that, in the vertically sorted bimodal gravel bed streams the coarser material tends to accumulate at the base of the dunes, creating a partial barrier between the coarser substrate below and finer material in the migrating dunes above (see Figure 8). A clear armour layer was also observed at the level of the dune troughs.

Lanzoni (2000), Lanzoni and Tubino (1999), Lanzoni et al., (1994) and Lisle et al., (1991) studied the sand bar formation with bimodal mixtures of fine and coarse sediment and suggested that grain sorting associated with selective transport of graded sediment may induce a overall stabilizing effect on bottom development with appreciable reduction of bar amplitude and a shortening of bar wave lengths (see Figure 9). In the caption of Figure 9, the term FC70 is a sediment mixture of poorly sorted with strongly bimodal character, i_s is the water surface slope and MUNI is near uniform sand. In addition, these studies are designed to get a better insight on longitudinal and vertical sorting. Lanzoni (2000) opined that a suitable model for vertical sorting is required to study the presence of heterogeneous sediments.

4. Experimental studies, limitations of some of the studies, recent PIV studies

Turbulence studies in water flows over dunes were commenced with the development of hot-film anemometers and flow visualization techniques. Muller and Gyr (1982) used fluorescent dye, a light sheet and video to visualize the flow. Nezu et al. (1994) used both dye and hydrogen bubbles in conjunction with video to study turbulent structures over dunes, and Bennett and Best (1995) took long exposure photographs of small neutrally buoyant particles to view the paths of fluid particles. These studies provide valuable information about features such as point of separation, point of reattachment, shear layer development, and generation and shedding of transverse vortices. Since three decades, much more accurate measurements of water flows became feasible with the increased use of laser-Doppler anemometer or laser Doppler velocimeter (LDA or LDV).

In the last decade, quantitative flow visualization techniques such as particle tracking velocimetry (PTV) and particle image velocimetry (PIV) have become popular to study coherent eddies in space and time. The ability of PIV to yield flow-field information ensures its usage to extend further. Hyun et al. (2003) provide a discussion of the factors that determine the accuracy of PIV data, and a discussion of the physics of the flow over a dune is given in Balachandar et al., (2003).

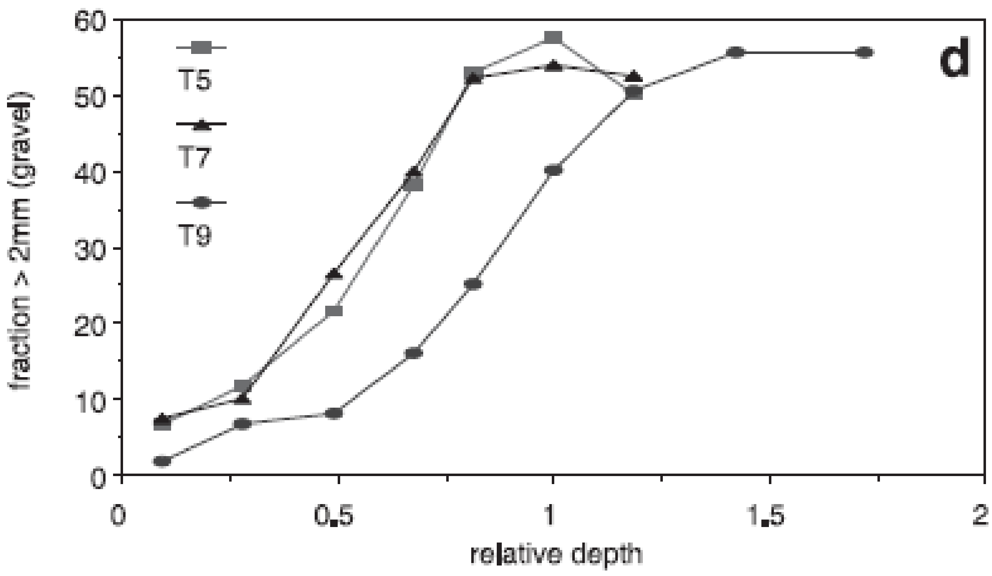


Fig. 8. Vertical sorting measured in experiments. The dune or bar top is on the left-hand side of the graphs, and the base is on the right-hand side. Vertical sorting in the dunes in Kleinhans (2002), Blom and Kleinhans (1999), experiments T5, T7 and T9. The sediment here is divided into two grain size fractions (sand and gravel), coarser and finer than 2.0 mm. The level of the dune troughs agrees with the level of the armour layer in T5 and T7, whereas in T9 the armour layer of T7 can still be observed. (From Kleinhans, 2004, copyright permission of Science Direct)

Schmeeckle et al., (1999) presented a method for the 3-D simulation of turbulence over 2-D dunes and compared the accuracy of PIV measurements and numerical simulations using a dense grid of two-dimensional laser Doppler velocimetry measurements. Balachandar et al. (2002) carried out LDV and PIV measurements and complementary LES simulation over a fixed dune. LDV and PIV provide complementary data on time-averaged and instantaneous flow structure over the dune. The time-averaged results reveal, in considerable detail, flow features such as separation and reattachment, and associated large variations in velocity and turbulence profiles. The instantaneous PIV results reveal a complex pattern of near-random but well-defined vortices. Vortices form downstream of flow separation and grow in size as they are convected along the dune. Balachandar and Patel (2008) studied the turbulent flow over a long train of fixed two-dimensional dunes, identical in size and shape by combining the complementary capabilities of LDV and PIV over a range of flow depths in a fully developed region. In this study, the points of interest were the instantaneous and mean velocity fields, the Reynolds stresses, triple-correlations, vorticity maps and analysis of events in the four quadrants.

4.1 Combined use of PIV and LDV to measure turbulence and flow over a dune

Hyun et al. (2003) assessed the relative merits of LDV and PIV to measure mean velocity and turbulence in water flow over a train of fixed two-dimensional dunes. Figure 10 shows the LDV measurement stations and PIV field-of-views. The flow field over the dune was divided into five different fields-of-view with a 20 mm overlap between the images. Though PIV is limited in the field-of-view normal to the bed, it provides instantaneous flow-field information that reveals the true complexity of the flow over dunes.

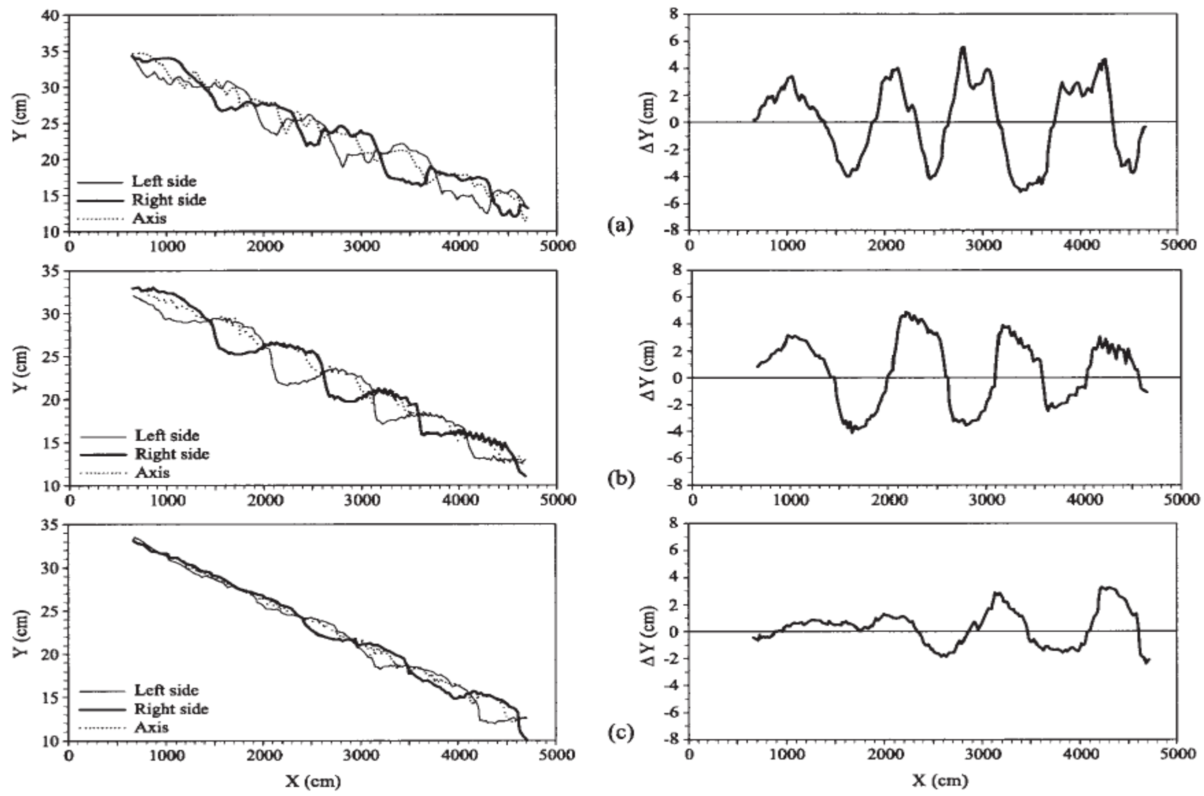


Fig. 9. Comparison between longitudinal bed profiles and differences between right-side and left-side bed elevation (Y) measured under similar hydraulic conditions during experiments with uniform (MUNI) and mixed (FC70) sediments. (a) Equilibrium phase of P2709 (MUNI) with Q = 45 L/s and i_s = 0.514%. (b) Initial phase of P1309 (FC70) with Q = 45 L/s and i_s = 0.525%. (c) Equilibrium phase of P1309 (FC70) with Q = 45 L/s and i_s = 0.525%. The data are plotted every 20 cm. (from Lanzoni, 2000, reproduced by permission of AGU)

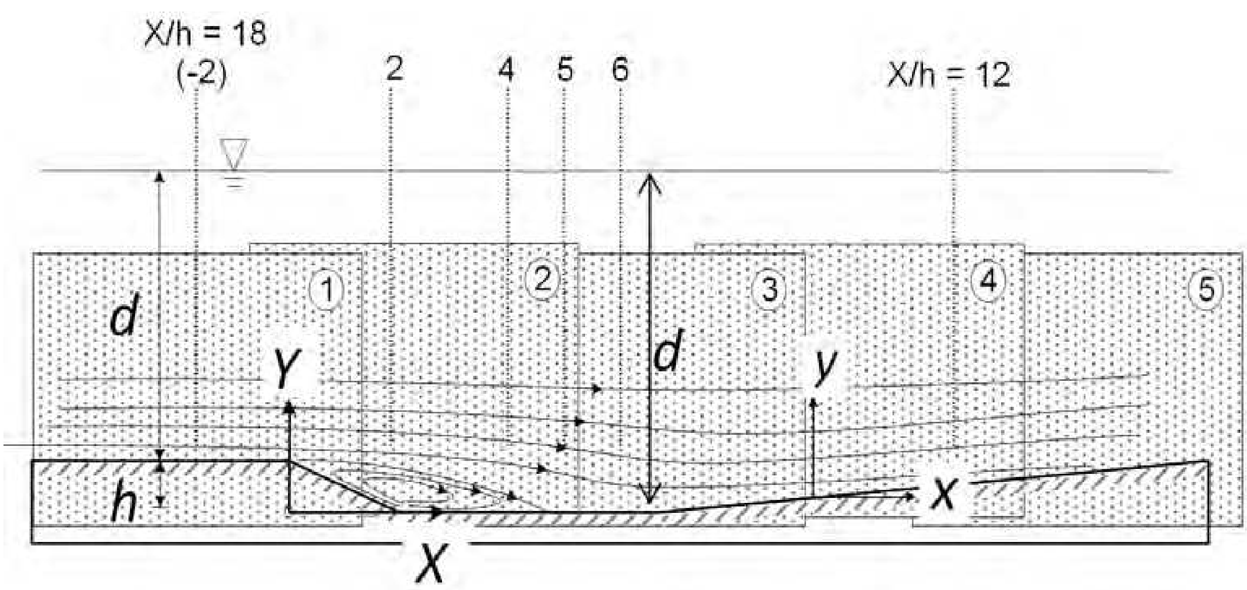


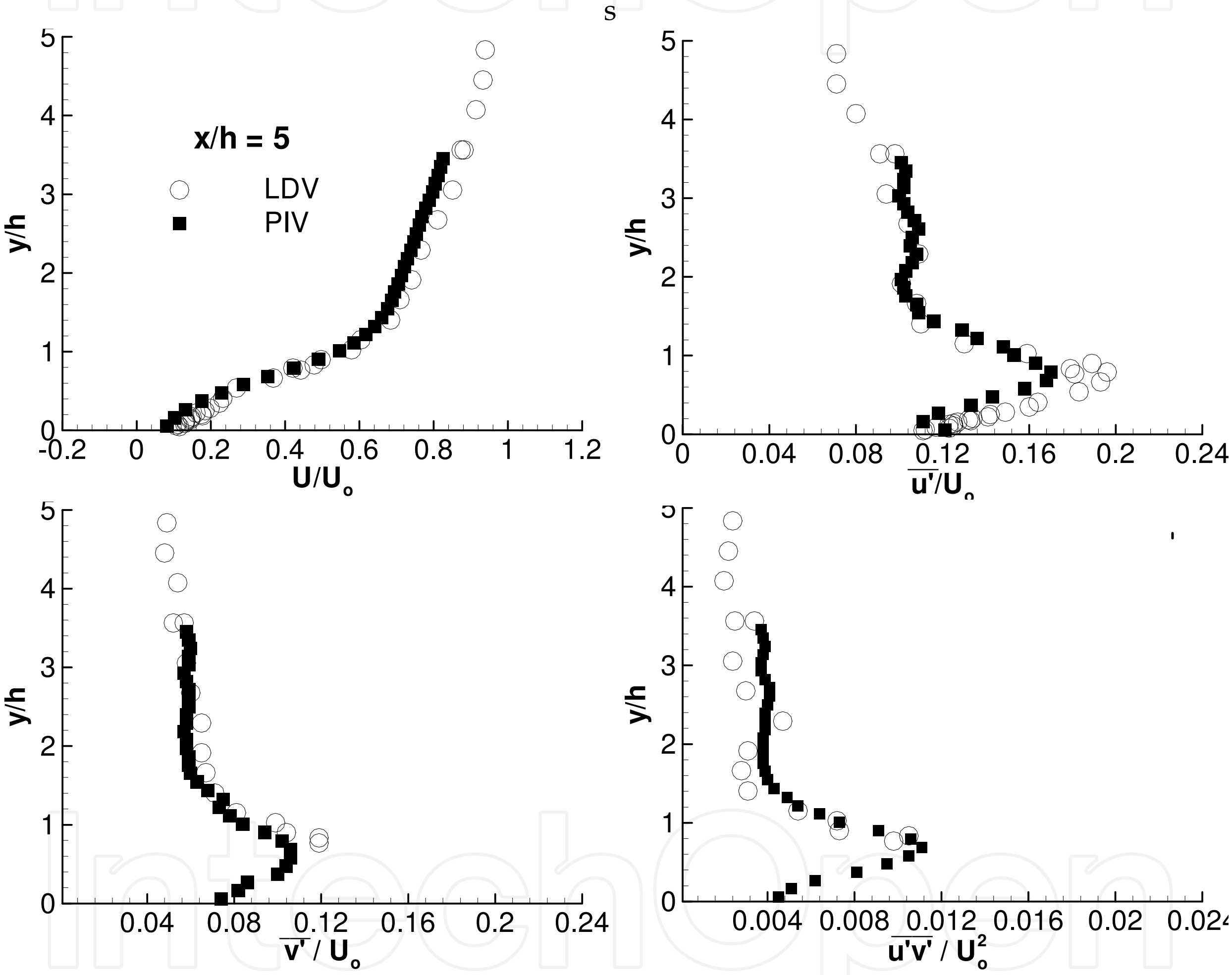
Fig. 10. Schematic of flow and notation (from Hyun et al. 2003, copyright permission of Springer)

Figure 11 (Hyun et al. 2003) shows the profiles of the x-component of mean velocity (U), the rms turbulence intensities in the x- and y-directions ($\sqrt{\overline{u'^2}}, \sqrt{\overline{v'^2}}$), and the Reynolds shear stress $(-\overline{u'v'})$ at one streamwise station (*X/h* = 5). All variables are made dimensionless by the maximum velocity U_o, held constant at 0.48 m/s in the experiments. The figure provides a direct comparison between PIV and LDV data at a station that is located close to the mean reattachment point. The limitation of the PIV field-of-view (and quality of light sheet) is clear from the extent of the data in the vertical direction. Also seen is the limitation of the two-component LDV in the near-wall region due to blockage of the beams by the dune. These limitations of the two systems are obvious, and present in most arrangements although their criticality will depend on the flow, or flow region of interest. In general, the PIV and LDV data show agreement within the expected uncertainties of the two systems in the mean velocity and turbulence intensities.

Hyun et al. (2003) opined that principal advantage of PIV is its capability to provide information about the instantaneous flow field. The flow is well illustrated by the two sets of successive instantaneous images shown in Figure 12. They correspond to two overlapping fields-of-view, taken at different times. In the region of the dune crest (Figure 12a), at time t = t_o, there appear to be two vortical structures, one just forming below the shear layer emanating from flow separation at the crest, and the other farther downstream. The former is small and nascent while the latter is larger and more diffused. With increasing time, the latter moves out of the field-of-view while the former grows in size and travels downstream at a velocity of about $0.4U_o$. In the last frame, this vortex is seen to again decrease in size. The subsequent evolution of this vortex could not be tracked due to limitation of the field-of-view - a limitation that is set by the PIV configuration. The second sequence of images (Figure 12b) shows the organized motions in a region downstream of the first. Here, strong ejection and sweep-type events are observed along with other flow structures. Further processing of the PIV images using some of the techniques suggested by Adrian et al. (2000) could provide more quantitative information, such as the length and time scales of the observed flow structures. The most obvious flow feature of the instantaneous flow is the formation of vortices just downstream of the crest below the shear layer, and their growth as they travel downstream.

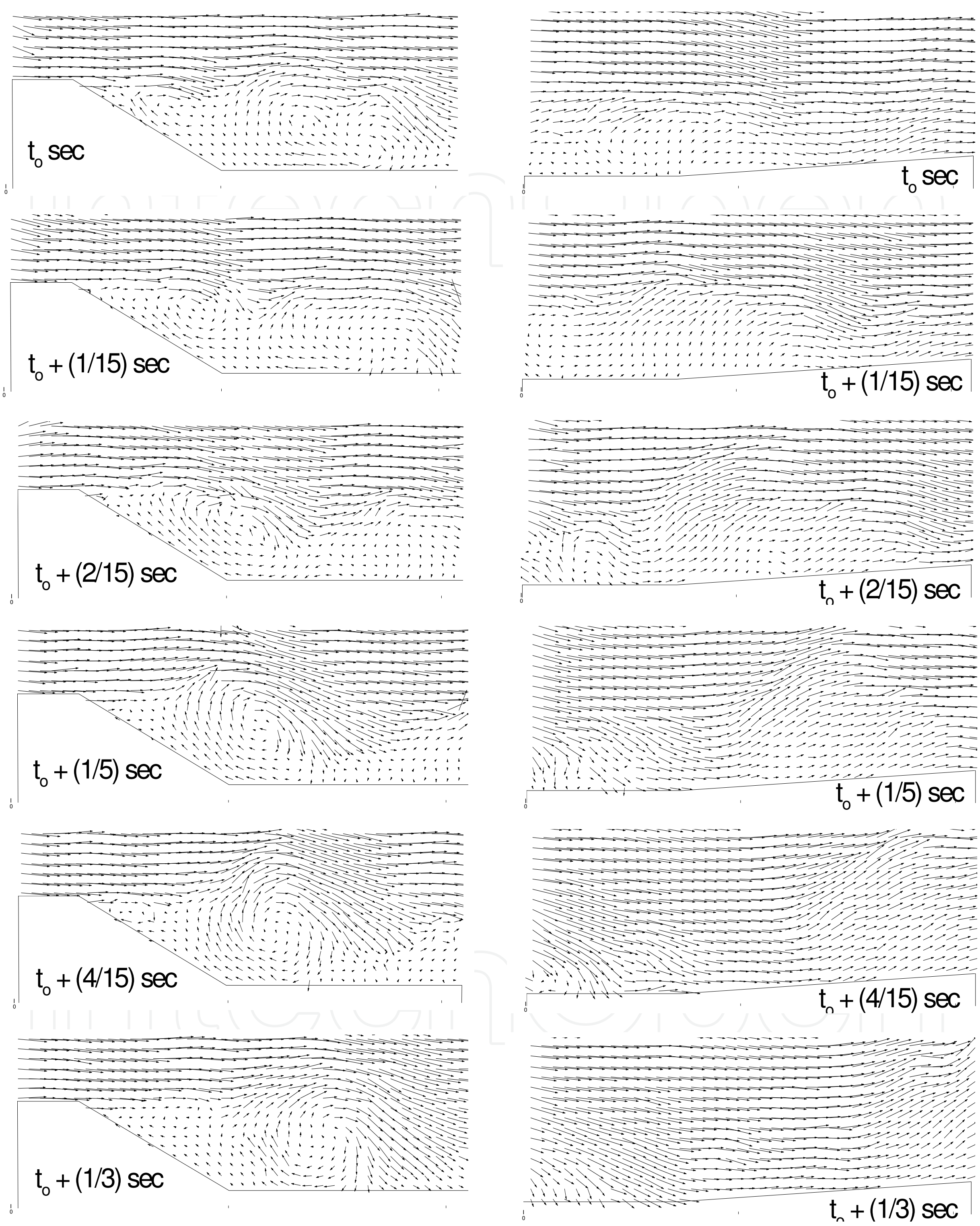
5. Modeling and numerical simulation–RANS, LES

The RANS based turbulence models such as the *k*- *ε* model, the algebraic model and the Reynolds stress model (RSM) are based on the statistical theory of turbulence, and therefore these models cannot in principle simulate coherent structures such as bursting phenomenon (Nezu and Nakagawa 1993). Johns et al. (1993) developed a numerical scheme with a one-equation turbulence model in which a transport equation was solved for eddy viscosity and their comparison of mean flow information, such as velocity profiles, Reynolds shear stress, and bed resistance with experiments were encouraging. Yoon and Patel (1996) developed a k-ω model based on the study of Wilcox (1993) that avoids the use of wall functions. Their computed velocity and turbulence fields, as well as the pressure and friction distributions along the dune are in general agreement with existing detailed experimental data in a rectangular channel with two-dimensional dunes of typical but regular shape. Cheong and Xue (1997) developed a three-layer near-wall k- ε model to account for the separated and reattached region by treating the anisotropy between normal stresses with streamline curvature correction. They opined that standard wall function treatment appears to be inadequate in the separating-reattachment region but computations are fairly satisfactory in other regions.



a) X/h = 5, X/λ = 0.25

Fig. 11. Comparison between PIV and LDV data (from Hyun et al. 2003, copyright permission of Springer)



(a) Field-of-view #2 in Figure 11 (b) Field-of-view #3 in Figure 11

Fig. 12. Instantaneous velocity field obtained by PIV (from Hyun et al. 2003, copyright permission of Springer)

Cokljat and Kralj (1997) used a k- ε model and RSM to investigate the better turbulence model for prediction of flows over river bed forms. Cokljat and Kralj (1997) used Lyn's (1993) data for validation of their numerical model and found that k- ε model of turbulence is capable of modeling the main features of the flow to acceptable level of accuracy. Mendoza and Shen (1990) used a k-ε model with wall functions but with an algebraic stress model in place of the more commonly used eddy viscosity assumption. The model was validated using experimental data obtained by Raudkivi (1966) and concluded that model satisfactorily predicted U-velocity, $\overline{uv}$, and turbulent kinetic-energy profiles, pressure and shear stress distributions of the steady turbulent flow over two-dimensional dune-like artificial bed forms. The above-mentioned models used the rigid lid assumption. Bravo and Zheng (1999) studied the standard k- ε model, RNG (Renormalization Group) k- ε model and differential RSM (Reynolds stress model) model for their applicability to predict turbulent flow over artificial bed forms. They implemented both free surface and rigid lid models to study the effects of sand grain roughness, near wall modeling, free surface, body forces and grid resolution. They found that free surface flow models gave better flow predictions and take fewer iterations to convergence than the rigid lid models. Patel and Lyn (2004) illustrated the results of both RANS computations and large eddy simulations (LES), compared the mean velocities and turbulent statistics to those measured by Hyun et al. (2003). The above-mentioned numerical models with RANS based turbulence closures provide mean flow information, such as velocity profiles, Reynolds shear stress, and bed resistance, but do not give any information about the unsteady flow structures that are important features of such flows. Lyn (2002) mentioned coherent turbulent flow structures can only be predicted either by direct numerical simulation (DNS) or large-eddy simulation (LES).

Balachandar et al. (2002) carried out experimental investigations (PIV and LDV) and complemented them with numerical simulations (LES). The LES computations used the assumption of space periodicity and approximate treatment of the free surface by simulating the flow over a single dune in a closed channel formed by the mirror reflection of the open channel on the free surface. The finite-volume LES numerical code of Cui et al. (2000) was used in the study. No-slip conditions were applied at the top and bottom walls, periodic conditions were applied at the inlet and outlet, and also along the sides of the solution domain at each instant. Convergence was claimed at each time step when the sum of the pressure and viscous resistance was in balance with the imposed pressure difference between the duct inlet and outlet. After the flow reached "steady-state", the solution was continued for about five large-eddy turnover times ($2d/u_*$, where u_* is the friction velocity) to accumulate the statistics. Measurements were compared with simulations for time averaged flow and instantaneous flow. The normalized measurements mean velocity in the x-direction, the RMS velocity fluctuations in the (x, y) directions, and the Reynolds shear stress ($-\overline{u'v'}$) by LDV and PIV are in agreement but the LES results for the longitudinal fluctuations and the shear stress are lower than the experiments (shown in Figure 13). In the case of the instantaneous flow field, the PIV shows better-defined vortices just downstream of the crest below the shear layer.

A recent DNS on an artificial dune-type wavy bed was carried out by Hayashi et al. (2003) to examine coherent structures and "boil of the first kind" in a low Reynolds number flow

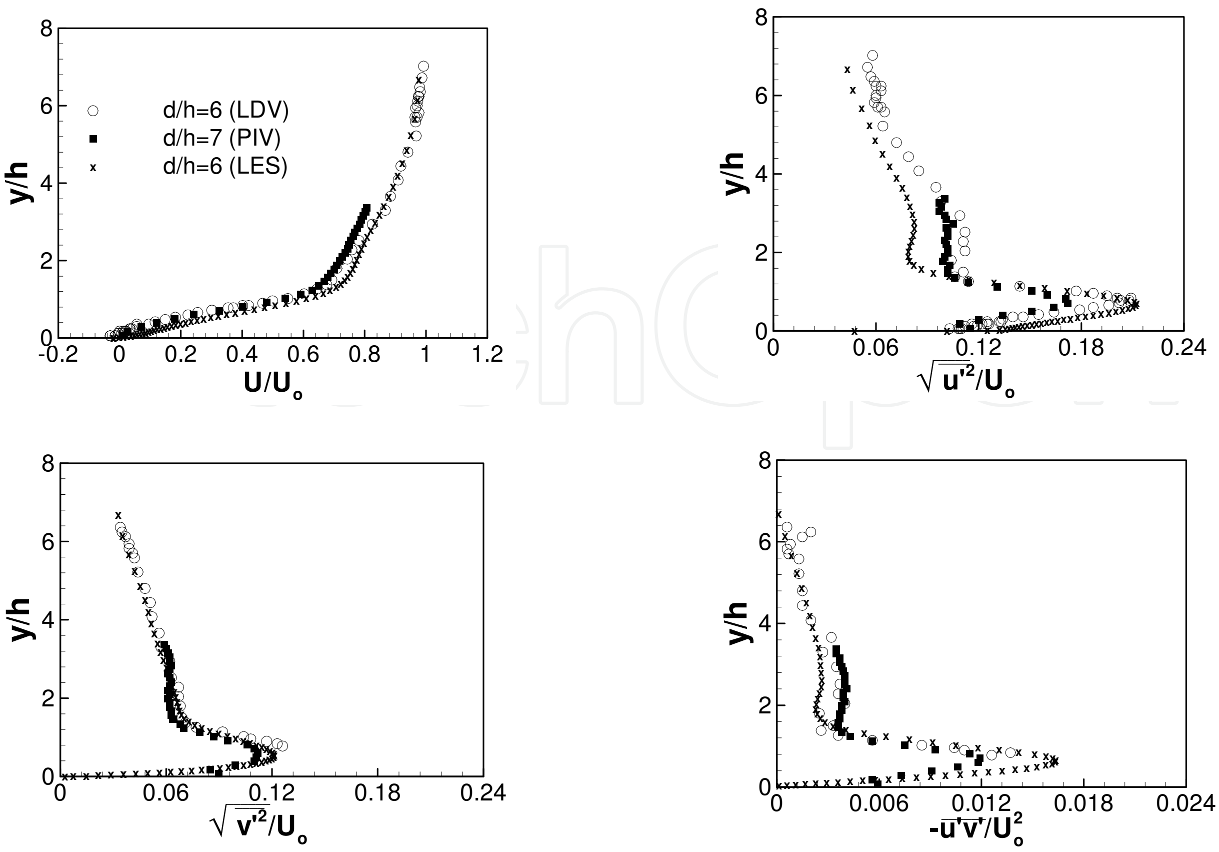


Fig. 13. Comparison of LDV, PIV and LES results at x/h=4 (from Balachandar et al., 2002)

(*Re* = 3300) and presented mean flow and turbulent structures of the open channel flow over bed forms. Hayashi et al. (2003) also found the presence of hairpin-shaped vortices, vortex patterns that showed both a normal and reverse hairpin shapes. Yue et al. (2006) used LES to study high-Reynolds number open-channel flow (*Re* = 5.7x10^4) over an idealized, two-dimensional laboratory-scale dune to investigate the unsteady flow structures as well as the mean-flow details and turbulence statistics. In a qualitative manner, they detected sweeps and ejections as well as formation of near-bed streaks and free surface structures and movement. They found that LES predicts the secondary peaks lying farther out from the bed, as observed in the experiments, their magnitudes are substantially under predicted. As the secondary peaks are remnants of the primary ones on the previous dunes, the discrepancy leads to the conclusion that the present LES does not adequately account for the upstream history. Williams (2007) carried out large eddy simulation of flow over a 2-D dune by using a surface adaptive curvilinear finite volume method to solve free-surface flows. The computed mean velocity profiles and normalized RMS plots of stream wise velocities were in good agreement with available experimental data of Balachandar et al. (2002) and PIV and LES offer a very graphic view of the instantaneous structures in the flow, as shown in Figure 14. Stoesser et al., (2008) investigated large eddy simulations of instantaneous flow over 2-D dunes (the geometry of the dunes is identical to that used previously by Balachandar et al. 2002) and found splats and evolution of hairpin vortices from kolk-boil vortexes around and beyond the point of reattachment.

6. Formation of coherent structures

Experimental and field investigations have documented the macro-turbulent characteristics of spatially varied flow over the bed forms and the formation of "kolks" and "boils" proposed by Matthes (1947). The "kolks" and "boils" are the upward tilting vortices of both fluid and sediment originating downstream of dune crests and at the point of reattachment. Bennett and Best (1995) suggested that the bursting events due to turbulent flow are associated with zone of Kelvin-Helmholtz instabilities developed at the zone of flow separation in front of ripple lee.

6.1 Turbulent structures by quadrant analysis

To evaluate the role of coherent structures, it is a common practise to divide the *u-v* sample space of the fluctuating velocities into four quadrants. Such representation has potential to reveal the relative contribution of the turbulent structures (events) from different quadrants to the total Reynolds shear stress. Flow visualization studies on rough wall bounded flows by Grass (1971) documented a streak that migrates slowly away from the wall and at some point detaches from it completely. This process of upward lifting of low-speed fluid away from the solid wall is commonly referred to as *ejection*. During the ejection process, the instantaneous local velocity (U_i) is lower than the time-averaged local velocity (U). Whenever ejection occurs, in order to satisfy continuity, high speed fluid moves towards the wall ($U_i > 0$) from outer flow regions and this event is called a *sweep*. It is only possible to detect ejection events when $u < 0$ and $v > 0$ are observed simultaneously. In the same way, sweep events can be detected by simultaneously observing a high-speed fluid parcel ($u > 0$), moving towards the bed ($v < 0$). There are two other events that also contribute to the total Reynolds shear stress. They are known as outward interactions ($u > 0,\ v > 0$) and inward interactions ($u < 0,\ v < 0$).

At every measurement location, the Reynolds shear stress is calculated and further decomposed as a sum of different events according to the procedure described by Lu and Willmarth (1973). By using the concept of a hyperbolic hole of size H, defined by $|uv| = Hu_{rms}v_{rms}$, the contribution from a particular quadrant can be written as

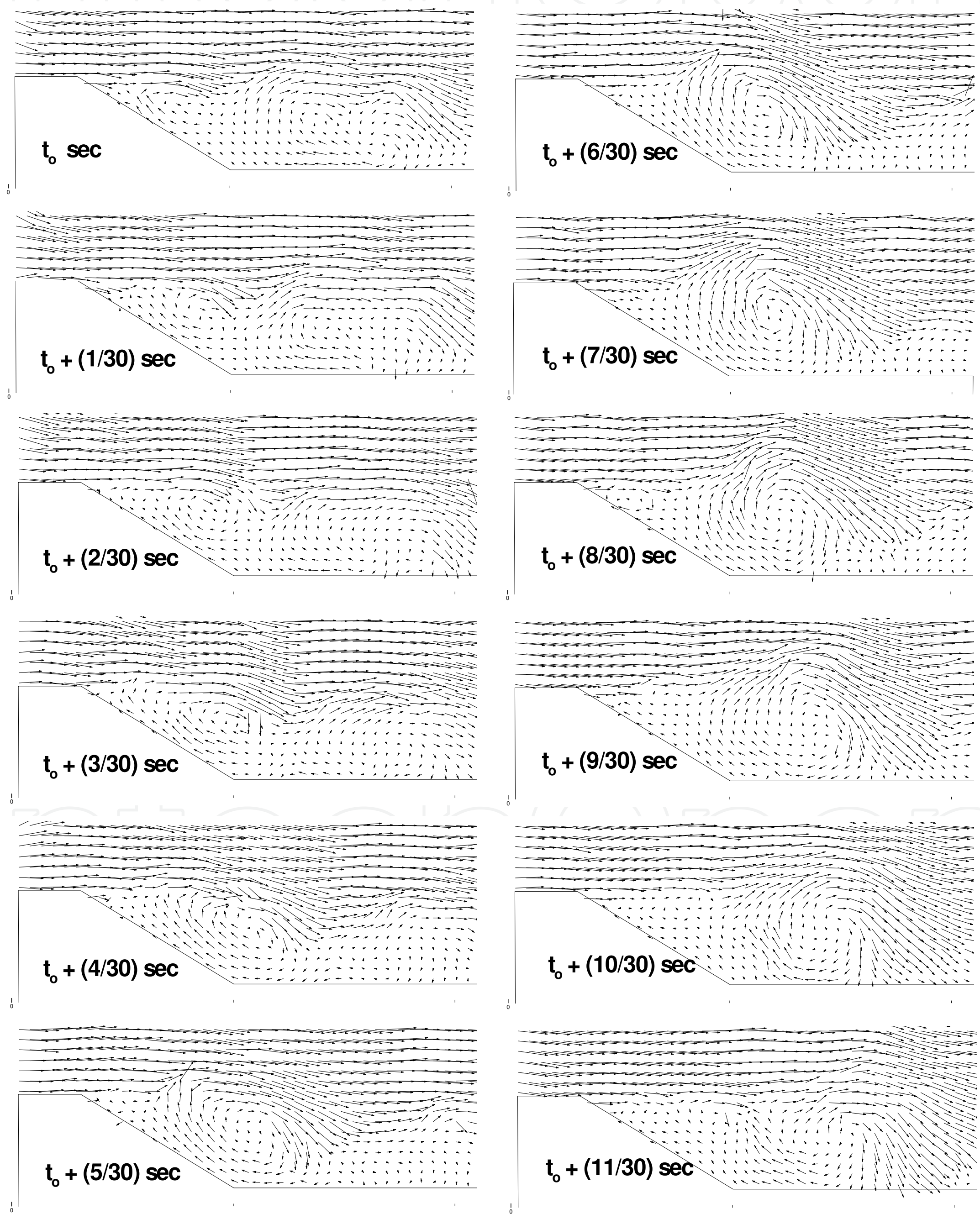
$$\overline{(uv)}_{Q_i,H} = \lim_{T\to\infty} \frac{1}{T}\int_0^T u(t)v(t)I(t)dt \tag{1}$$

Here, $I(t)$ is a detection function defined as:

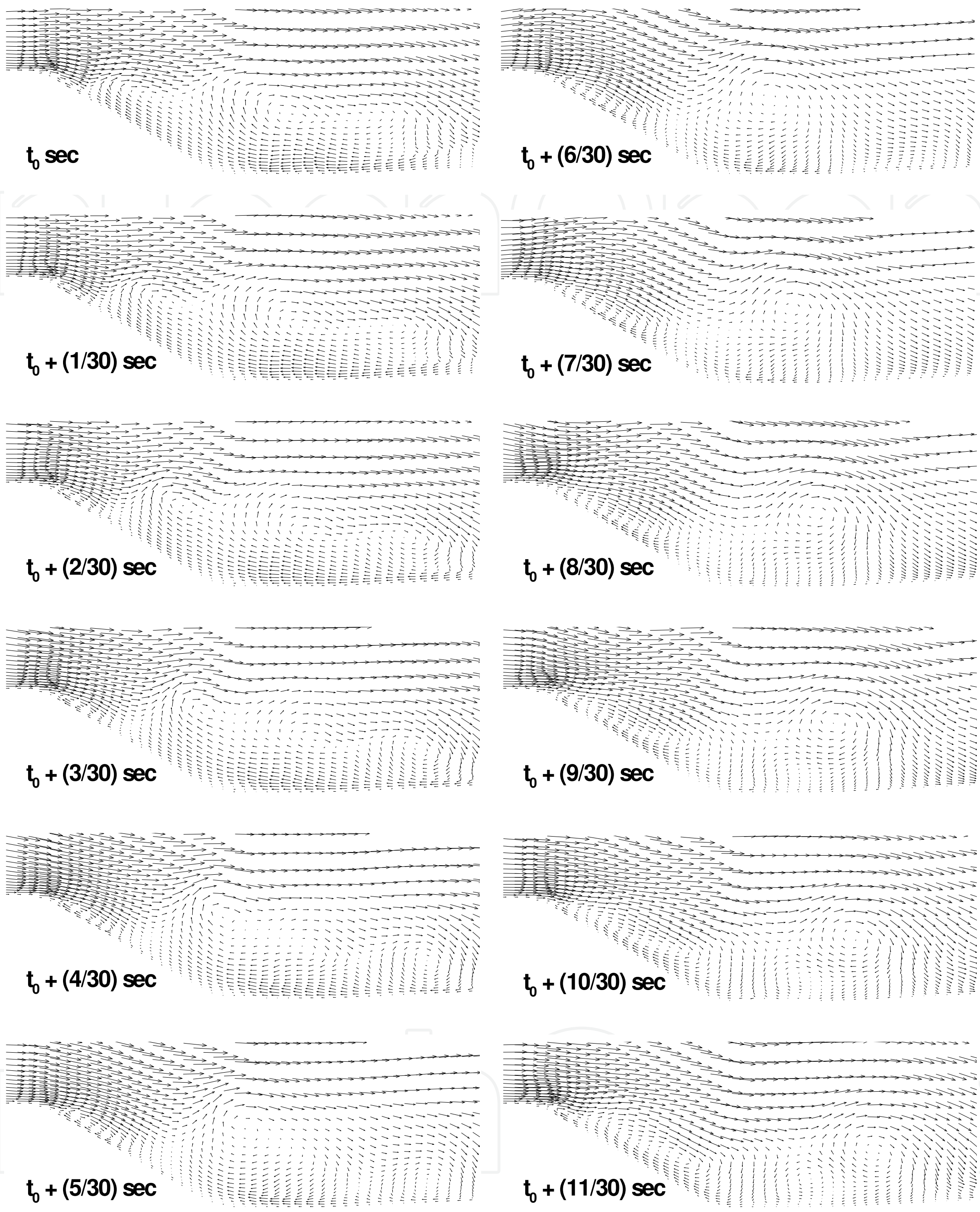
$$I(t) = \begin{cases} 1 & when \quad |uv|_Q \geq Hu_{rms}v_{rms} \\ 0 & otherwise \end{cases} \tag{2}$$

It is assumed that the velocity used to compute $\overline{(uv)}_{Q,H}$ is a function of time only. The parameter H defines a threshold value, which separates the extreme events from the random background turbulence. By increasing the value of H more extreme/strong events are identified. In the present study, quadrant decomposition yields Reynolds stress contribution to each quadrant for a given value of H denoted as $\overline{(uv)}_{Qi}(y)$ and is represented as Q_i (i = 1 to 4) for convenience.

Figure 15 shows the contributions by the four quadrants events (Balachandar et al., 2007) for the flow past the dune shown in Figure 4. At each station, the local maximum value of the mean shear stress is used as the normalizing scale. As expected, at X/h = -2, the contributions from Q_1 and Q_3 are small, and the fact that the contributions are negative indicates the presence of flow structures that transfer energy from the turbulence to the mean flow. All along the dune, the contributions by Q_1 events are more or less similar. With increasing distance from the dune crest, there is a very slight increase in the contributions from Q_1 events, especially along the separating shear layer, and immediately upstream and downstream of reattachment. As pointed out by Bennett and Best (1995), these events are probably associated with structures brought towards the bed along the separating shear layer. These events provide one possible mechanism by which sediment can be eroded.



a) PIV



b) LES

Fig. 14. Time sequence of instantaneous velocity field (from Balachandar et al., 2002)

Detailed experimental observations (Balachandar et al., 2007; Best, 2005a, b; Kostachuck and Church, 1993; Rood and Hickin, 1989) revealed that Q_2 events are most likely associated with much of the entrainment and transport of sediment. The variation of Q_2 events over the wavelength of the dune was studied by Balachandar et al., (2007). It was found that the contributions of quadrant 2 events are dominant at all X/h locations as shown in Figure 15. In the figure, F represents the fractional contribution to the total shear stress by each quadrant. With increasing distance from the crest, the Q_2 profiles indicate large gradients, especially near the crest line. These high-magnitude events correspond to the source of the dune-related bursting phenomena reported previously (Jackson 1976). Similar to Q_2 events, the Q_4 events show large changes in the vicinity of the shear layer. In Figure 15a, for $y/d <$ 0.3, the Q_4 profiles show a trend that is opposite to that of the Q_2 profiles. Ahead of reattachment (X/h = 2 and 4), and slightly above the crestline, the magnitude of the Q_4 events tends to be close to the Q_2 events.

Studying several results such as that in Figure 15, differences due to flow depth were noticeable in the contributions of all four quadrants. However, as noted with respect to Figure 15, the contributions of Q_2 events are very important and most likely associated with much of the entrainment and transport of sediment. Therefore, the effect of depth on Q_2 events is presented in Figure 16 over the wavelength of the dune. The results are shown in a two-column format with h as the normalizing scale in the left column and d as the normalizing scale in the right column. Ahead of separation (Figures 16a,c and e), the Q_2 profiles show a similar trend at all flow depths, each showing a near-wall peak in the vicinity of y/h = 1. This is identified with the remnants of the turbulence activity carried over from the previous dune. This trend continues well after reattachment, indicating the persistence of the Q_2 events on the stoss side of the dune. At stations ahead of the dune crest, a peak in the Q_2 profiles (Figures 16 d and f) around y/d = 0.2 indicates the sustenance of turbulence generated by the previous dune, carried over to the next dune. This value is not influenced by the bed roughness. Overall it is concluded that the characteristics of the shear layer, the length of the reattachment zone and the Q_2 events control the turbulence structure over the dunes.

Balachandar and Patel (2008) carried out LDV measurements to obtain more detailed information on the effect of bed roughness superimposed on a train of well-formed dunes. The fractional contribution to the mean Reynolds shear stress by quadrant 2 (Q_2: $u < 0$, $v > 0$) events are shown in Figure 17. The figure is presented in three-column format with one type of wall condition being represented in each column. In all the graphs, with increasing distance from the dune surface, the Q_2 values gradually increase towards the free surface. The profiles show large gradients, especially near the crest line. In all the graphs shown in Figure 17, the tendency is to have two local peaks (indicated as A and B, see, middle column of Figure 17). Except for the first row of graphs (X/h = -2), peak A, closer to the bed ($0.16 < y/d < 0.23$), corresponds to the location of the separating streamline; whereas peak B, away from the bed ($0.5 < y/d < 0.62$) is an indicator of a large-scale event in the outer region. The peaks at X/h = -2 (first row) correspond to the turbulence activities carried over from the previous dunes. Comparing the three columns of graphs, the peaks are located farther away from the bed with increasing bed roughness. As seen in the middle column of graphs, the high magnitude Q_2 events correspond to the source of the dune-related bursting phenomenon reported previously (Jackson 1976; Yalin 1972). It is also possible that the separating shear layer is associated with streamwise vortices generated along the braids between the Kelvin-Helmhotz instabilities (Lasheras and Choi 1988; Metcalfe et al. 1987). The Q_2 events influence the vertical convection of sediment and can be responsible for much of the vertical mixing in the rivers.

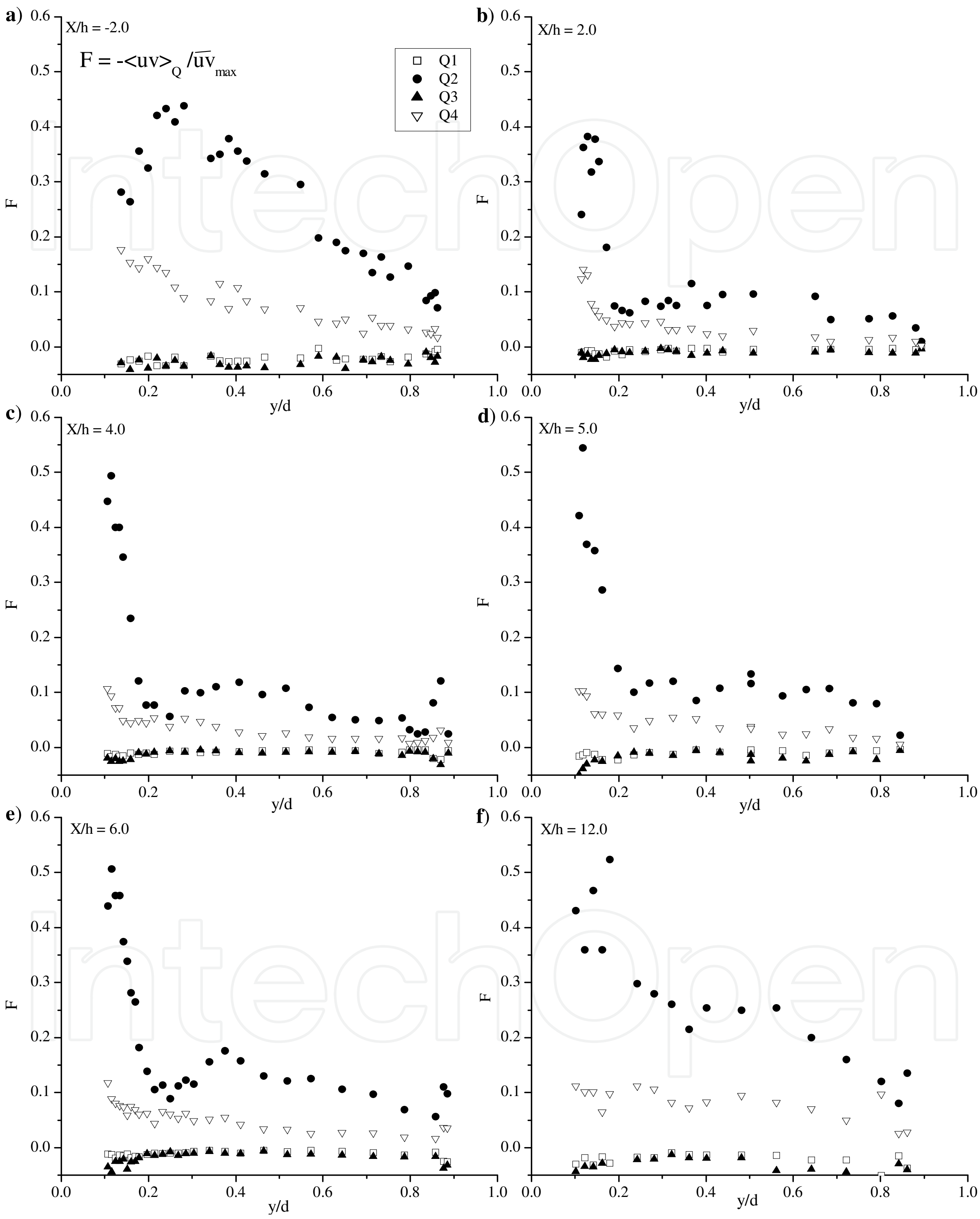


Fig. 15. Fractional contribution by the four quadrants (d_1/h = 6). (a) X/h = -2.0; (b) X/h = 4.0; (c) X/h = 4.0; (d) X/h = 5.0; (e) X/h = 6.0; (f) X/h = 12.0. (from Balachandar and Patel 2008, copyright permission of NRC research press)

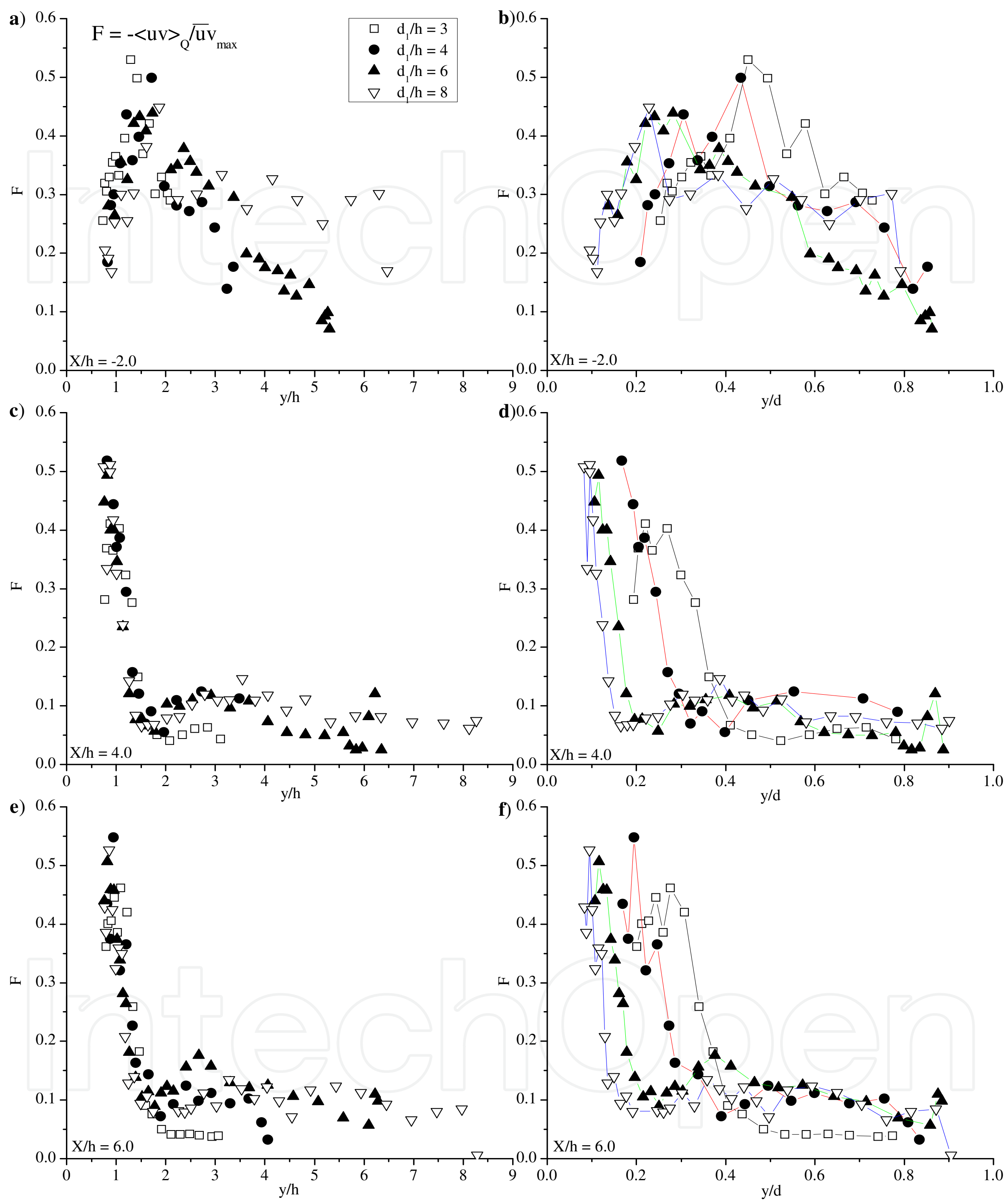


Fig. 16. Effect of depth on fractional contribution to quadrant 2: (a, c, e) using the dune height, h, as the normalizing length scale and (b, d, f) using the depth of flow d as the normalizing length scale. (from Balachandar and Patel 2008, copyright permission of NRC research press)

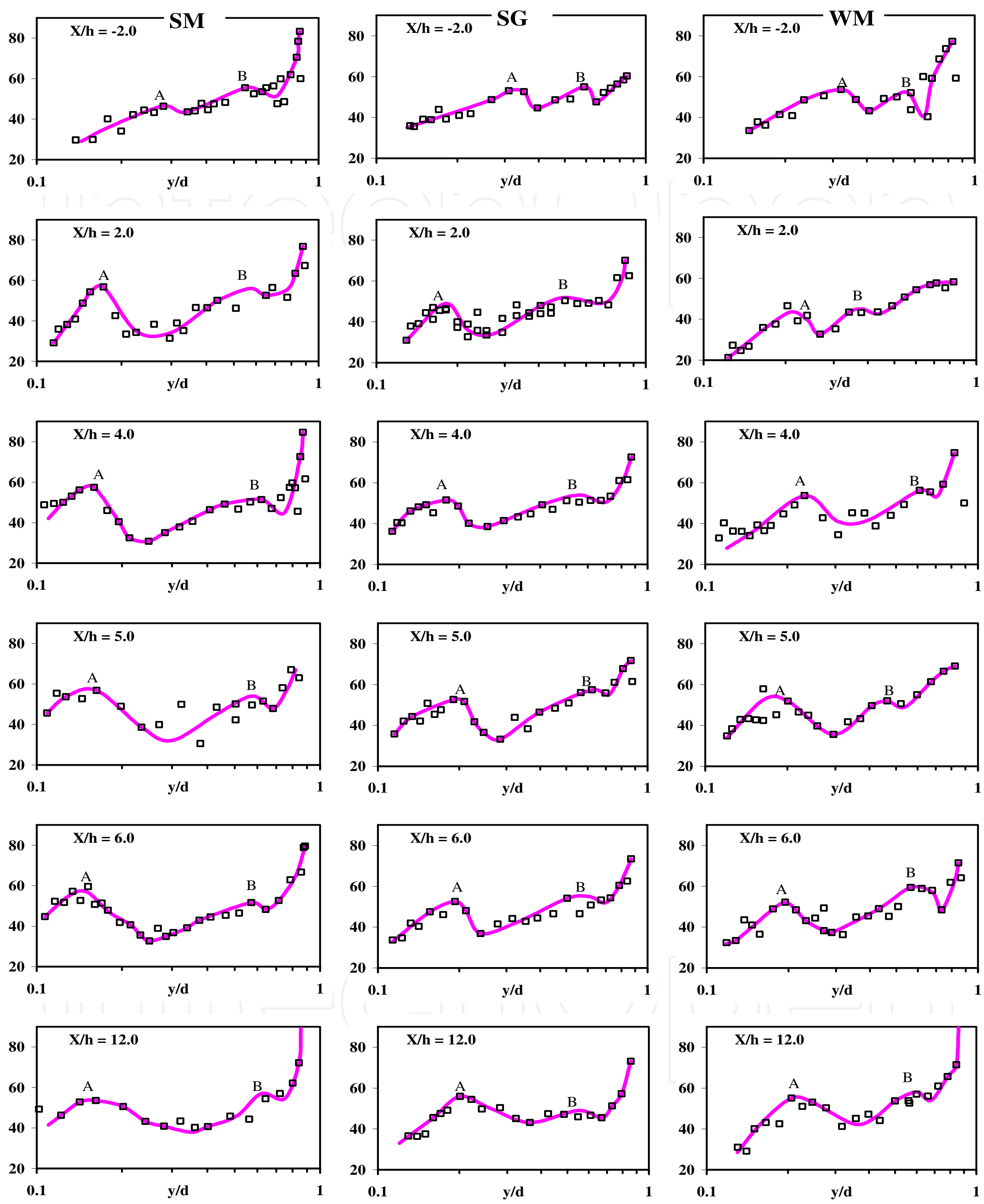


Fig. 17. Contribution to shear stress by quadrant 2. SM - train of smooth bed dunes manufactured from Plexiglas; SG - sand grain test; WM - wire mesh test. (from Balachandar and Patel 2008, copyright permission of NRC research press)

7. Future research topics

The ASCE taskforce subcommittee (2002) and Best (2005 a) have suggested several important research directions to further understand, quantify and model the dynamics of flow over dunes. The taskforce opined the need to synthesize the knowledge gained with the advances in measurement techniques and simulation technologies to quantify the development of dunes, amount of sediment transport and bed changes. Efficiency of the available theoretical models to simulate the formation of the bed forms with uniform and heterogeneous sediment needs to be ascertained for laboratory and field data. Presently, 2-D dunes are modeled in laboratory and simulations but changes in the transverse direction should be included in the simulations (Parsons et al. 2005). Most of the dune studies are concentrated on flow separation and flow field on lee side of dunes, however near-bed turbulence characteristics on the stoss side are not fully understood. Carling et al. (2000) found that evidence of large-scale, coherent low frequency flow structures and separated boundary layers above the stoss side of the large dunes. The knowledge gained in understanding of coherent structures should be utilized in future research (Stoesser et al. 2008 and Yue et al. 2005) on modeling of sediment transport and evolution of bed in open channels. Another important research direction is to study the scaling effects between laboratory and field studies of flow over dunes (Best and Kostaschuk 2002). Measurements and simulations of formation of bed forms should be studied during varying discharge regimes because most of the sediment transport and bed form changes takes place during the floods (Ten Brinke et al. 1999). Low angle dunes are common in big rivers such as Jamuna river in Bangladesh (Kostaschuk et al., 2004) therefore modeling and laboratory studies on low angle dunes are required. Venditti et al. (2005) concluded that movement of the entire bed form is controlled by superimposed bed forms therefore morphodynamics of super imposed bed forms over migrating dunes needs to be studied theoretically and experimentally. Yue et al. (2005) opined that more realistic simulations of the interaction of the free surface with the bed is needed to understand the coherent structures and sediment transport. Kostaschuk et al. (2008) suggested to carry out further research with respect to amount of suspended sediment on formation and as well as migration of dunes. The future research may also include simulation of 2-D and 3-D flow over dunes using DES (detached eddy simulation) which is computationally more efficient (Xu et al., 2007) than LES modeling.

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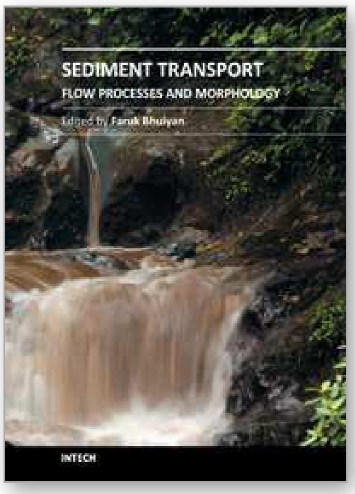

Sediment Transport - Flow and Morphological Processes
Edited by Prof. Faruk Bhuiyan

ISBN 978-953-307-374-3
Hard cover, 250 pages
Publisher InTech
Published online 26, October, 2011
Published in print edition October, 2011

The purpose of this book is to put together recent developments on sediment transport and morphological processes. There are twelve chapters in this book contributed by different authors who are currently involved in relevant research. First three chapters provide information on basic and advanced flow mechanisms including turbulence and movement of particles in water. Examples of computational procedures for sediment transport and morphological changes are given in the next five chapters. These include empirical predictions and numerical computations. Chapters nine and ten present some insights on environmental concerns with sediment transport. Last two contributions deal with two large-scale case studies related to changes in the transport and provenance of glacial marine sediments, and processes involving land slides.