

# Lee Angle Effects in Near Bed Turbulence: An Experimental Study on Low and Sharp Angle Dunes

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**Abstract** This research presents recent advances on morphodynamic modeling over gravel dunes. Boundary-layer separation over gravel fixed dunes is investigated by Acoustic Doppler Velocimetry (ADV). Using the measurements of flow over dunes at laboratory scale, examined the influence of dune lee sides on the separation of flow. Experiments were conducted in a horizontal flume. A train of 2D fixed dunes were installed on the bottom of the flume starting just downstream of the entrance on the flume. Experiments were carried out using 2 types of dunes with different lee slopes, (38 and 8 degree). The results of quadrant analyses base on the stress fraction SHf versus the hole size at two elevations near the bed and near water surface for two angles of lee side, at the central axis of the flume also investigated. Both experimental observations and quadrant results were in agreement about the influence of dune characteristics on the flow separation in different dune lee angles.

**Keywords** Quadrant analysis, Lee Angle, ADV, Separation Zone

## 1. Introduction

In rivers, complex interactions between turbulent flow, sediment transport and bed morphology give rise to various types of river bed configurations. Based on flow regimes, the river bed can be either plane or covered by ripples, dunes, or anti-dunes or combinations thereof. In sandy or gravel-bed rivers, with subcritical turbulent flow, typically river dunes are formed (e.g.[1-6]). The flow over dunes has been studied widely to understand the effect of bed shape on the flow and the mechanisms of bed and suspended load transport of sand bed rivers. However, compared to flow over smooth beds, mean flow characteristics, distributions of turbulent velocities, bed shear-stresses, and turbulence intensities differ significantly due to the bed deformation (e.g.[7],[8]). Many researches have been conducted in laboratory flumes to understand the effect of dune size on velocity distribution and separation zone (e.g.[9-12]). A general dune shape is depicted in Fig. (1).

In order to clarify the flow field near the bed, velocity profiles are presented by ADV near the bed and the objective of this study is to investigate the influence of the dune lee sides on flow separation. Moreover in this research the results of normalized quadrant magnitudes of the momentum flux are presented at the center of flume of two different dune

lee sides.

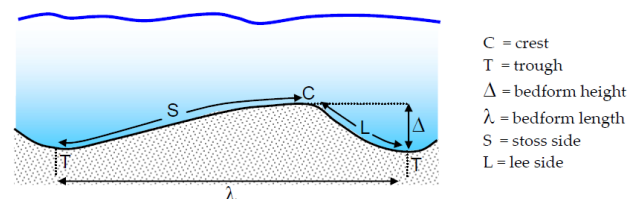


Figure 1. Longitudinal schematic of dune

## 2. Experimental Set-up

### 2.1. Physical Model

Experiments were carried out in a rectangular flume at Institute of Hydraulic Engineering and Water Resource Management of Technical University of Graz, Austria. The horizontal flume was 12 m long, 0.76 m wide and 0.95 m deep. A train of 2D fixed dunes were installed on the bottom of the flume starting just downstream of the entrance of the flume and extending 8 times over the entire length of the flume. The 2D dunes had fairly regular spacing, heights, and lengths. Dunes were prepared with well-sorted gravel particles with a  $d_{50}=5.8$  mm

Experiments were carried out by using 2 types of dunes of 1m length, with an angle of lee slope ( $\alpha$ ) of 38° and dune height ( $\Delta=4$ cm) for *Dune 1*, also with an angle of lee slope ( $\alpha$ ) of 8° and ( $\Delta=4$ cm) for *Dune 2*.

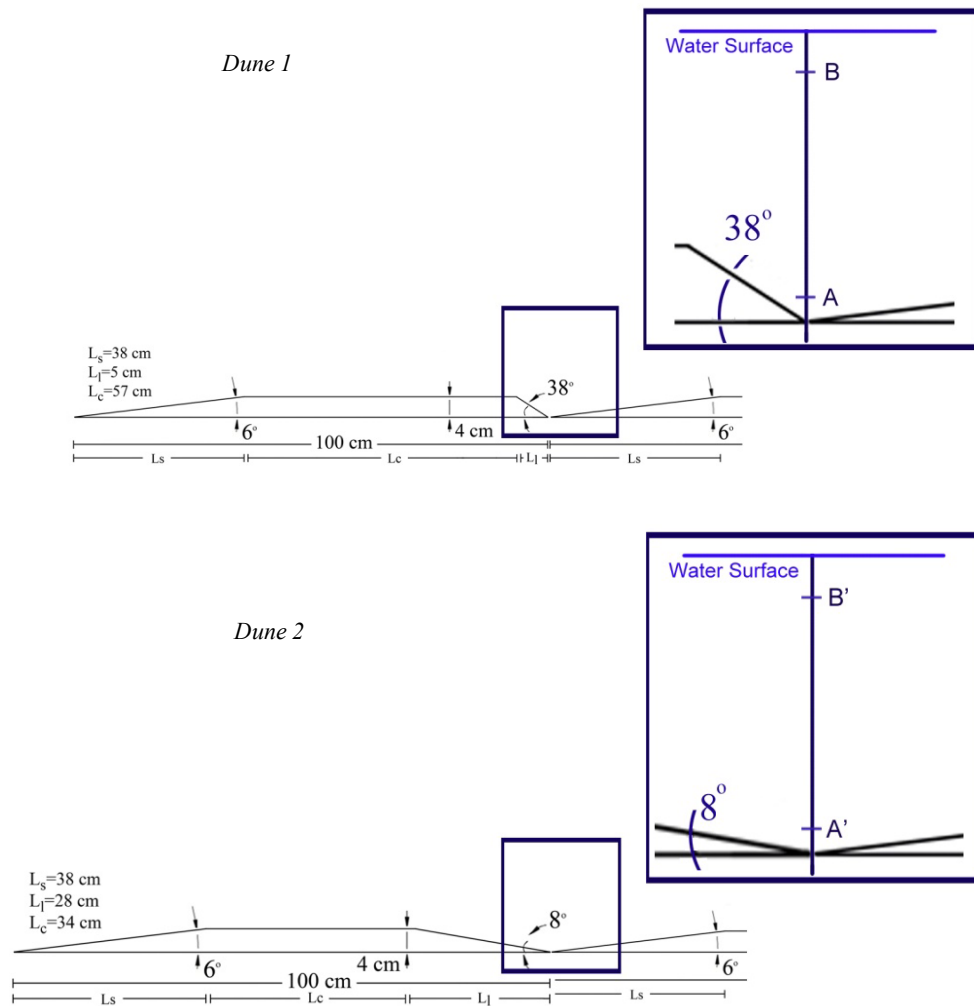
The schematic views of the dunes for this study are shown in Fig. (2).

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**Figure 2.** Sketches of dunes , sharp angle (Dune 1) and low angle (Dune 2)

Various authors have generally shown that dunes have an asymmetrical shape, with a long stoss side slope, sharp crest, short steep lee side slope causing a separation zone (e.g.[9],[11]). Laboratory and field evidence also shows that dunes can be symmetrical with stoss and lee side slopes having approximately equal length, without flow separation (e.g.[13],[14]). Therefore, in this study to find the effect of dune lee angles on separation zone, two different dunes were selected.

Dimensions of the chosen sharp angle dunes in gravel were based on field studies in[12] and[15] who have measured dune height around 4 cm and the angle of lee around 30 degree.

The flow depth was fixed at 32 cm and flow discharge, 30 lit/s, was applied in this study. The chosen water depth (h) was also taken from measured field data in[16].

Velocity measurements were conducted using a 3-dimensional side-looking Acoustic Doppler Velocimeter (ADV), developed by NORTEK. It was set on tracks above the flume and was automatically moved in vertical and horizontal directions. In total, thirteen vertical velocity profiles were measured in the centerline over 6th dune from the entrance. All three components of velocity were

measured at a 5 cm interval beside the probe. The sampling frequency was fixed at 200 Hz and WinADV was used to filter out samples with a correlation coefficient  $\leq 70\%$  and signal-to-noise ratio  $\leq 15$  db.

## 2.2. Quadrant Analysis

Three conditional sampling techniques include wavelet analysis, quadrant analysis, and variable interval time averaging (VITA) technique are well established tools for identifying structures that allow specific flow features to be extracted from experimental data. One of most frequently used conditional sampling techniques is the quadrant analysis of the Reynolds shear stress (e.g.[17-20]).

In quadrant analysis, the shear stress is decomposed into four quadrant events[17]. The events in quadrant  $i=2$  and  $i=4$  contribute positively to the downward momentum flux, and are involved in turbulence near-bed bursting[21]. These two events are usually called ejections and sweeps, respectively.

At any point in a steady flow, the contribution to the total Reynolds stress from quadrant  $i$ , excluding a hyperbolic hole region of size  $H$ , is given by

$$\langle u'w' \rangle_{i,H} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T u'(t)w'(t)I_{i,H}[u',w']dt \quad (1)$$

Where  $T$  is the sampling time period, and square brackets denote a conditional average and the indicator function  $I_{i,H}$  is defined as

$$I_{i,H}(u',w') = \begin{cases} 1 & \text{if } (u',w') \text{ is in } i\text{th quadrant and} \\ & \text{if } |u'w'| \geq H |\overline{u'w'}|, \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Where parameter  $H$  = hole size, is a threshold level in the Reynolds stress signals introduced in [17]. Using (i.e., (2)), the contribution to Reynolds stress ( $u'w'$ ) can be extracted from each quadrant for various hole sizes. The stress fraction is given by

$$S_{i,H} = \langle u'w' \rangle_{i,H} / |\overline{u'w'}| \quad (3)$$

By definition,  $S_{i,H} < 0$  if  $i$  is even (sweeps and ejections) and  $S_{i,H} > 0$  if  $i$  is odd (outward and inward contributions). In order to assess the strength of event signals, the duration of the events is also computed as

$$D_{i,H} = \frac{1}{T} \int_0^T I_{i,H}(u',w') dt \quad (4)$$

The quadrant fractions obtained from (i.e., (3)) do not take into account the event duration. The normalized magnitude

of a quadrant event, which takes into account the event duration, is determined as

$$S_{i,H}^D = S_{i,H} / D_{i,H} \quad (5)$$

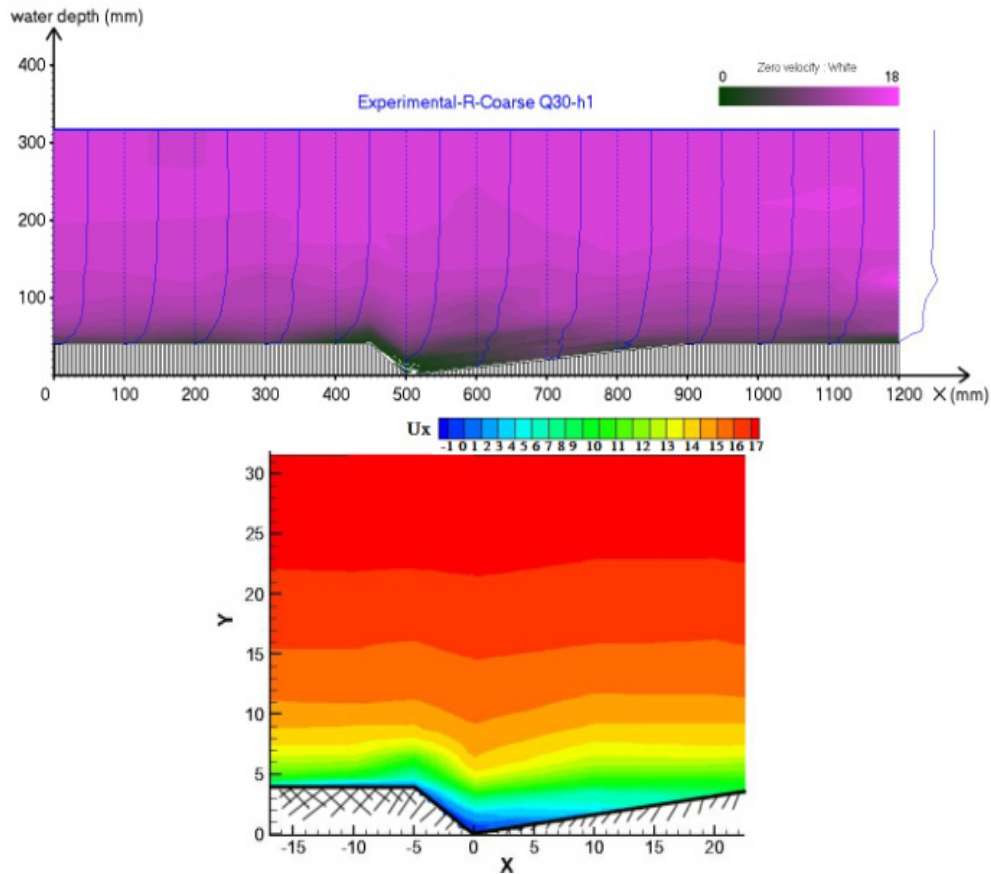
This provides a measure of the strength of event signals compared to the event fraction. All calculations to determine the contribution of each quadrant to the Reynolds shear stress were performed with Matlab.

### 3. Results

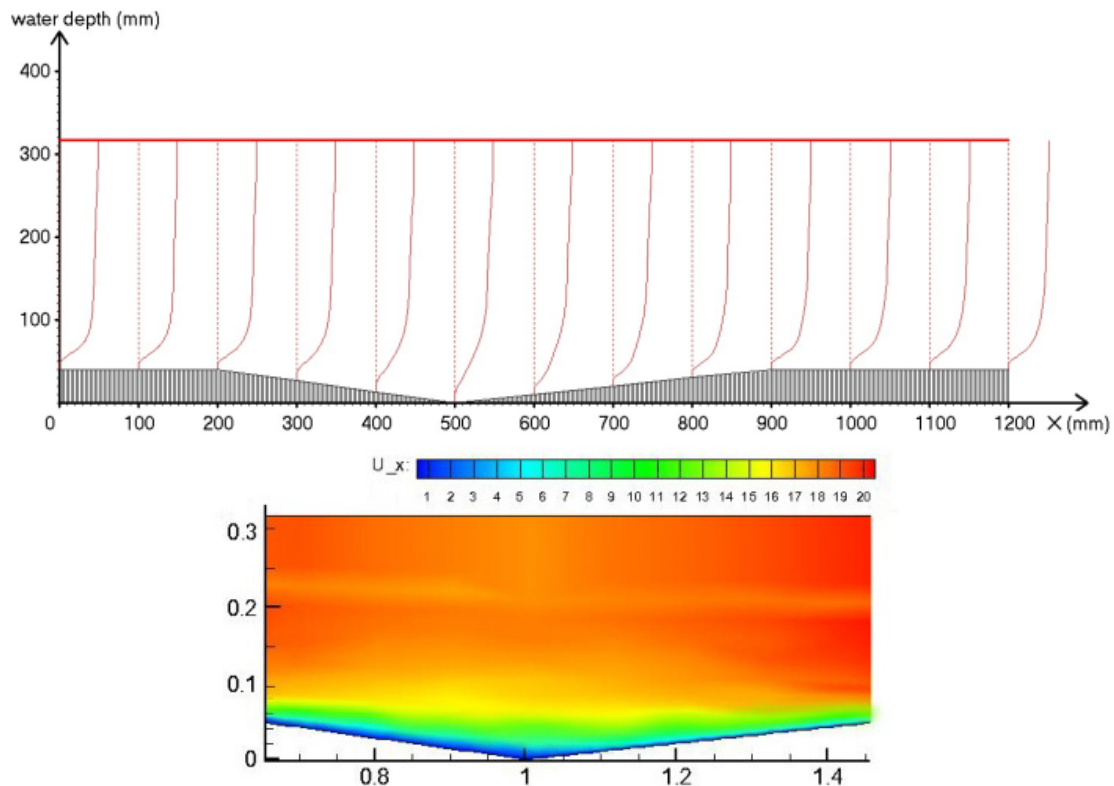
#### 3.1. Contour Maps

In this section ADV results are studied. To achieve a better graphical scheme, new graphical software was developed. Fig. (3) shows the measured velocity profiles over sharp angle dunes and ( $\Delta=4\text{cm}$ ), collected by ADV for a flow rate of 30 lit/s and water depth of 32 cm.

The negative velocity profiles which cause the separation region is created downstream of the crest. The measured velocity profiles using ADV for the same hydraulic situation over low lee angle dunes with flat crest are presented in Fig. 4.



**Figure 3.** (Left) Measured velocity profiles with ADV over sharp angle dunes ( $\Delta=4\text{ cm}$ ,  $\alpha=38^\circ$ ), (Right) Contour map of negative velocities in the interaction of two dunes



**Figure 4.** (Left) Measured velocity profiles over low lee angle dunes ( $\Delta=4$  cm,  $\alpha=8^\circ$ ), (Right) Contour map of positive velocities in the interaction of two dunes

The ADV results indicated the absence of a zone of time-averaged permanent reverse flow on the low-leeside. Recent field measurements suggest that the shape of dunes has a significant influence on the separation zone and the length of the consequent recirculation region. Comparison of Figs. (3) and (4) shows no separation zone in low lee angles. Reference[10] investigated the low leeside angle of dunes in the Jamuna River; Reference[22] studied dunes in the Rhine and Waal rivers with leeside slopes of 2 to 8 degrees; and Reference[23] carried out research over dunes in the Mississippi River. None of these studies reveal the separation zone.

Table 1 shows the length of the separation zone for different dunes in various discharges and water depths. The length of flow separation,  $L$ , was measured from the crest, where the flow separates, to the flow reattachment point.

In *Dune 1*, the velocity profiles were measured by ADV with two repetitions for each hydraulic condition, could present the separation lengths as  $L=(1.4-3.8)\Delta$ , which confirm the previous studies (e.g.[9] and[24]) who had presented the separated length as  $L=(3.5-4.5)\Delta$ .

The results of *Dune 1* also reveal a larger separation length for higher flow discharge at the same water depth. Also, for the same flow discharge and lower water depth the separation is much bigger so that by reducing the water depth (around half) the ratio of  $L/\Delta$  becomes double.

This study reveals that flow over low-angle dunes (*Dune 2*) has no separated permanent flow on the leeside (the same as the results of Best in 2004).

**Table 1.** The Measured separation zone in different dunes and flow structure

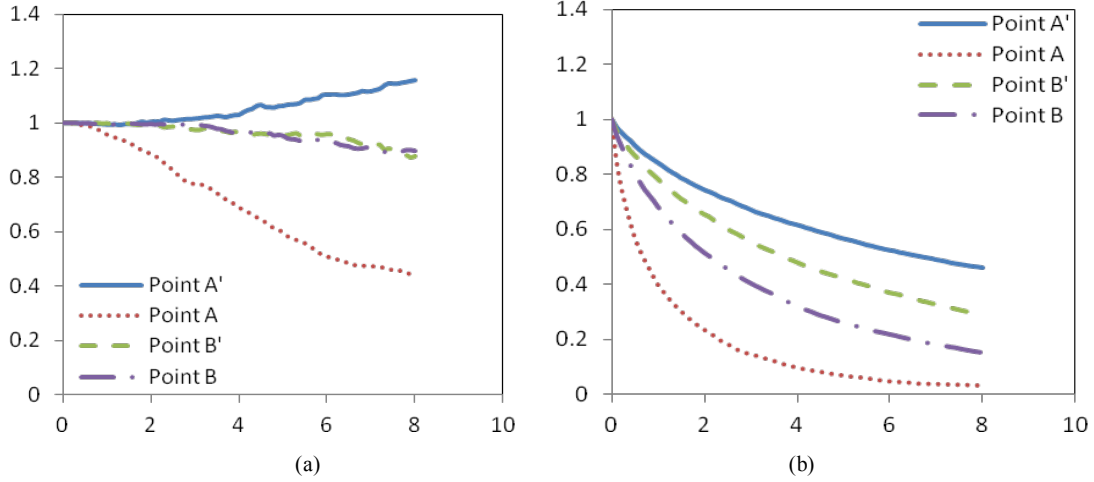
No. Dune	Q (lit/sec)	Water depth (cm)	Max Velocity (cm/s)	Measured Separation Zone (L) (cm)	L/ $\Delta$
1	30	31.7	19	5.5, 5.4	1.4
1	30	19.5	36	10, 12.1	3
1	60	31.7	36	7.8, 6.6	1.9
1	60	19.5	69	15.5, 14.9	3.8
2	30	31.7	19	0	0
2	30	19.5	33	0	0
2	60	31.7	38	0	0

### 3.2. Quadrant Analysis ( $Q=30$ lit/s & Water Depth=31.7 cm)

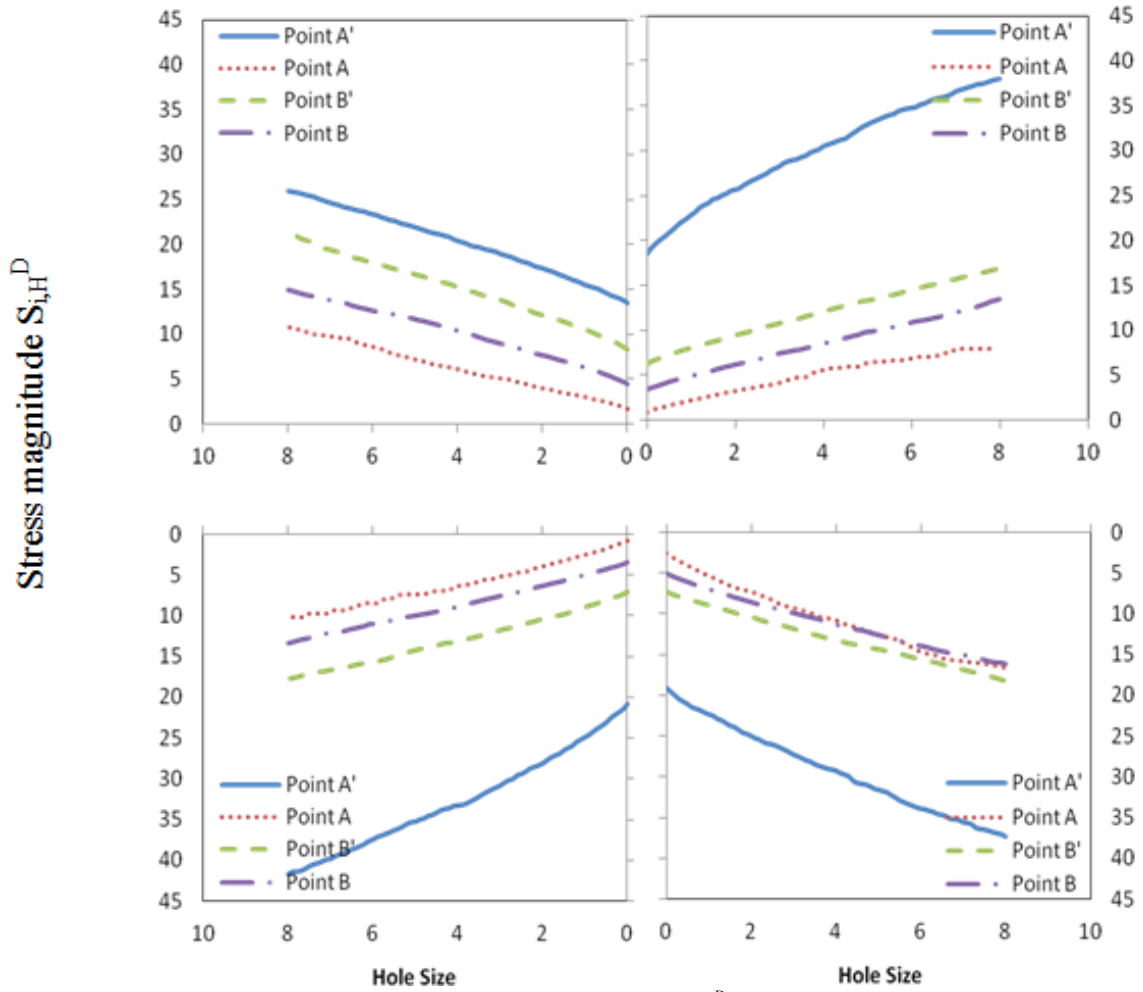
The relative importance of short-lived events of large magnitude is demonstrated by performing a quadrant analysis with an excluded hole regions of various sizes (Shaw et al 1983). Fig. (5-a) shows the stress fraction  $S_H^f$  (sum of the four quadrant fractions) versus the hole size at two elevations  $y/h=0.01$  (Points A and A' in Fig. 2) and  $y/h=0.7$  (Point B and B' in Fig. 2) for two angles of lee side, low angle  $8^\circ$  and sharp angle  $38^\circ$ , at the central axis of the flume. The changes of hole size from zero to 2.5 has no effect on the stress fraction ( $S_H^f$ ) and as expected, increasing the hole size decreases the sum of the four quadrant fractions ( $S_H^f$ ) expect for the point at near the bed in low angle (for point A' with  $y/h=0.016$ ). This can also be attributed to negative sign Reynolds stress at  $y/h=0.13$  in Fig.5. The stress fraction

decreases more quickly near the bed than near the water surface with the change of hole size for sharp angle. For point A with  $y/h = 0.009$ , near the bed for sharp angle, about 50% of the stress is from large magnitude events ( $H=5$ ), and for other values of  $y/h$ , the same percentage of the stress is

from stronger events ( $H \geq 8$ ). Also we can see a slow decrease or increase for those point that stream wise velocity is positive in them, but for one point that sign stream wise velocity is negative, its change is sharp.



**Figure 5.** The sum of all four quadrant fractions with an excluded varying hole size. (a) Stress, (b) Duration



**Figure 6.** Stress magnitudes  $S_{i,H}^D$

Fig. (5-b) shows the duration  $D_H$  versus the hole size at the two elevations for two angles of lee side. As showed in Fig (5-b), for low angle shape, duration change rate is slower at near the bed than that point near the water surface. Reversely for sharp angle shape, this rate is slower for the point at near the water surface. In all at the same of stress fraction profiles, for point A with  $y/h=0.009$  that negative velocity and thus flow separation is occurred, duration rate with variation  $H$  is sharp. It means the 78 percent of momentum flux is occurred with a sharp slope until  $H=2$ . Fig. (5-b) shows that a relatively large fraction of the total stress occurs in small durations (fractions of total time). For example, in Fig. (5-b) at  $H=5$ , one half of the stress fraction is due to the events occurring 8% of the duration for sharp angle at near the bed (point A with  $y/h < 0.009$ ). Similar results were reported by Shaw et al. (1983) and Yue et al. (2007), demonstrating that much of the momentum flux is transported during periods of strong turbulence activity occurring over short durations. This result was not observed for relative depth values for low angle shape, (A' and B' points, e.g.  $y/h=0.016$  &  $0.74$ ).

The normalized quadrant magnitudes of the momentum flux defined in equation (5) are presented at the center of flume in Fig. (6) where the magnitude of the momentum flux augments with the hole size because of short durations at the large hole sizes and the relatively high magnitude of the events. Fig. (6) shows that for sharp angle ( $38^\circ$ ) the sweep interaction has the largest stress magnitude until  $H=5$  near the water surface (Point B with  $y/h=0.72$ ) and after  $H=5$  the relationship is reversed. While for other three interactions, they have larger stress magnitude near the water surface for all  $H$  values. On the other hand for low angle ( $8^\circ$ ), all of interactions have the largest values at near the bed. Those differences are high for three of interactions (outward, inward, and sweep) that it maybe caused by negative shear stress. In all the largest stress magnitude is for inward interaction at near the bed in low angle shape where the Reynolds stress value is negative. Totally for sharp lee angle, sweep is predominant event for both near bed and near the water surface points; but for low lee angle near the bed, where there is not any separation phenomenon, outward and inward events have large contribution to shear stress values.

## 4. Discussion

This study reveals that flow over low-angle models shows no separated permanent flow on the leeside of dunes (the same as the results in [25], since sharp angle dunes over the bed have a considerable effect on the flow structure and they cause the flow to or not to separate in different flow regimes.

With regard to the length of the measured separation zone, the average ratio of  $L/\Delta$  is different from 1.4 to 3.8 in *Dune (I)* which are less than the values reported in the literature (5.8 in [26] and 6 in [11]) and close to other studies [24].

On the basis of the laboratory experiments, this research also presents the effect of water depth and roughness on the flow structure over dunes. Comparing the separation lengths

of the same two dunes (the same dimensions and particle) with the same water velocity shows that if the water depths are not the same in these two mentioned situation, the larger separation zone belongs to the lower water depth conditions.

The quadrant analyses of normalized quadrant magnitudes of the momentum flux show that for sharp lee angle dunes which have a separation zone, the sweep interaction has the largest stress magnitude and for low lee angle dunes without separation, the inward interaction has the largest stress magnitude near the bed. The result of the percentage of each quadrant in different zones near beds (A & A') and water surfaces (B & B') are presented in tables 2 and 3.

**Table 2.** The percentage of zones near bed

	Point A'				Point A			
	H=0	H=2	H=4	H=8	H=0	H=2	H=4	H=8
Outward	22.84	21.96	21.85	22.42	19.06	10.97	4.19	0
Ejection	24.45	24.09	24.11	24.63	29.95	37.85	36.23	16.04
Inward	30.81	31.69	31.54	30.56	17.51	8.38	7.19	3.77
Sweep	21.90	22.26	22.51	22.39	33.49	42.79	52.40	80.19

**Table 3.** The percentage of zones near water surface

	Point B'				Point B			
	H=0	H=2	H=4	H=8	H=0	H=2	H=4	H=8
Outward	24.28	23.24	22.58	21.59	23.19	22.06	21.00	16.24
Ejection	25.97	26.43	27.04	27.59	26.83	28.20	28.86	31.21
Inward	22.83	22.69	22.92	23.27	22.84	20.90	19.04	16.75
Sweep	26.92	27.65	27.46	27.55	27.14	28.84	31.10	35.80

Moreover for low lee angle, the rate of duration changes slowly at points near the bed reversely for sharp lee angle this value reduced quickly at same points and changes gradually at points near water surface.

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