SPATIALLY-AVERAGED TURBULENCE CHARACTERISTICS IN FLOWS SUBJECTED TO SUCTION AND INJECTION FROM GRAVEL-BEDS

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Present study focuses on

- Spatially-Averaged Flow Field
- Third-Order Correlations of Velocity Fluctuations
- Turbulent Kinetic Energy and Energy Budget
- Bursting parameters

Clarke *et al.* (1955) and Stevenson (1963): developed a modified law of the wall to describe the velocity distribution with injection from the bed based on the Prandtl's mixing-length theory.

Rao (1971): argued that the turbulent fluctuations in the flow field increases with injection resulting in more mass exchange between fluid and bed particles, while the reverse is true with suction.

Verollet *et al.* (1977): found that the law of the wall developed by Stevenson (1963) was fitted well with the experimental data for suction velocity that was less than 0.3% of the free stream velocity.

Nezu (1977): observed that injection enhances (Krogstad and Kourakine, 2000; Kim and Sung, 2003) and suction diminishes turbulence intensities (Antonia *et al.*, 1988; Antonia *et al.*, 1995).

Ramakrishna Rao and Nagaraj (1999): concluded that the turbulence intensities for suction were higher than those for injection or no-seepage.

Oldenziel and Brink (1974) and Maclean (1991b): observed that the streamwise velocity decreases in the outer-layer and increases in the inner-layer of the flows subjected to suction.

Mendoza and Zhou (1992): observed that the injection results in increased turbulent production and upward diffusion rate (Sumitani and Kasagi, 1995; Park and Choi, 1999). It leads to a higher diffusion of turbulent energy into the flow.

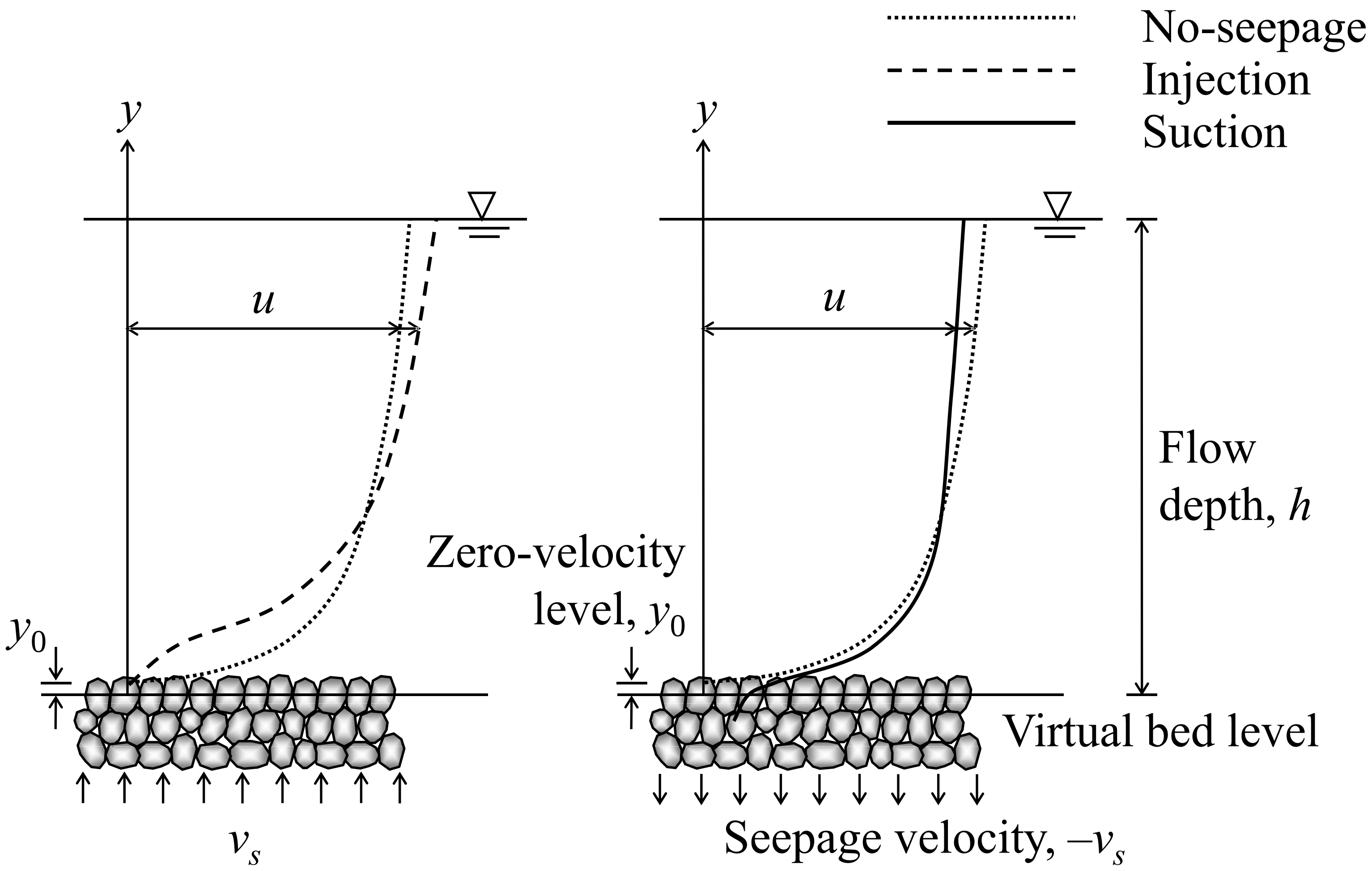
Prinos (1995): studied the effect of bed suction and reported that an increase in the near-bed velocities and a decrease in upper flow velocities. It is in agreement with the findings of Willetts and Drossos (1975) and Maclean (1991a).

Cheng and Chiew (1998) and Chen and Chiew (2004): suggested the modified logarithmic laws for the velocity distributions subjected to injection and suction.

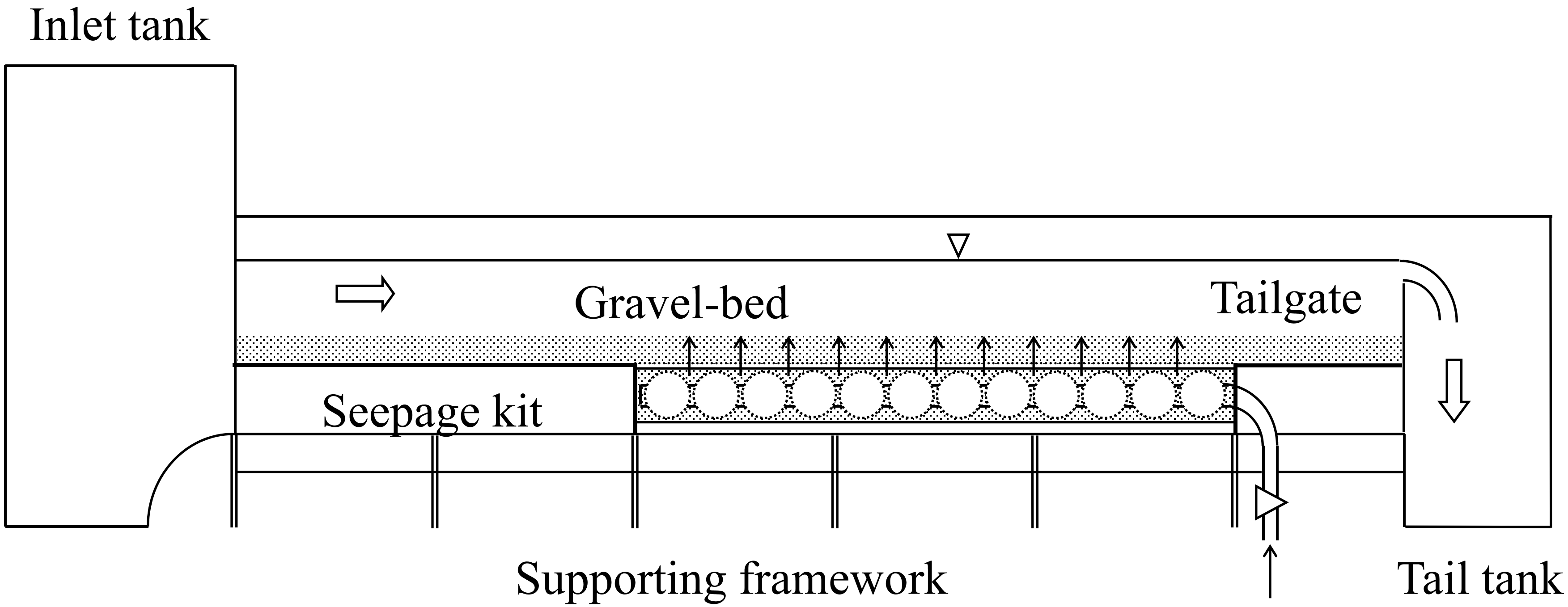
Dey and Cheng (2005): derived the Reynolds shear stress profile in a nonuniform-unsteady flow subjected to injection from the bed.

Bose and Dey (2007): studied the effect of bed injection on turbulent flow field by solving the RANS equations. In this way, the expressions for the streamwise velocity was obtained with some constants estimated using experimental data.

The spatial-averaging method can produce meaningful estimation of the near-bed turbulence characteristics that are influenced by the seepage. It explicitly defines important additional terms such as form-induced stresses (Nikora *et al.*, 2001; Mignot *et al.*, *2009*).



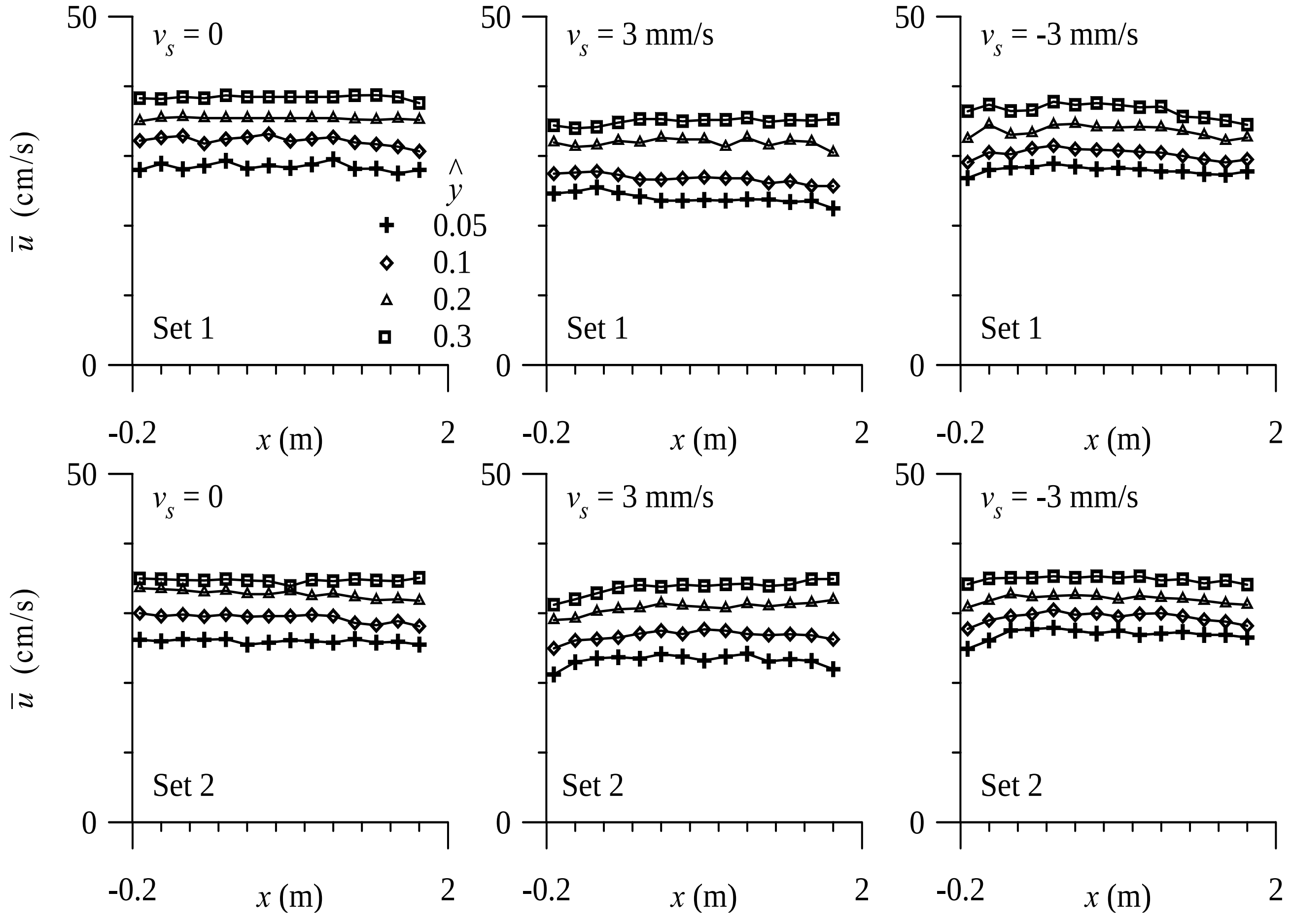
Schematic velocity distributions over a gravel-bed with different seepage conditions



Schematic of experimental setup, which shows the case of injection (upward seepage) from the bed

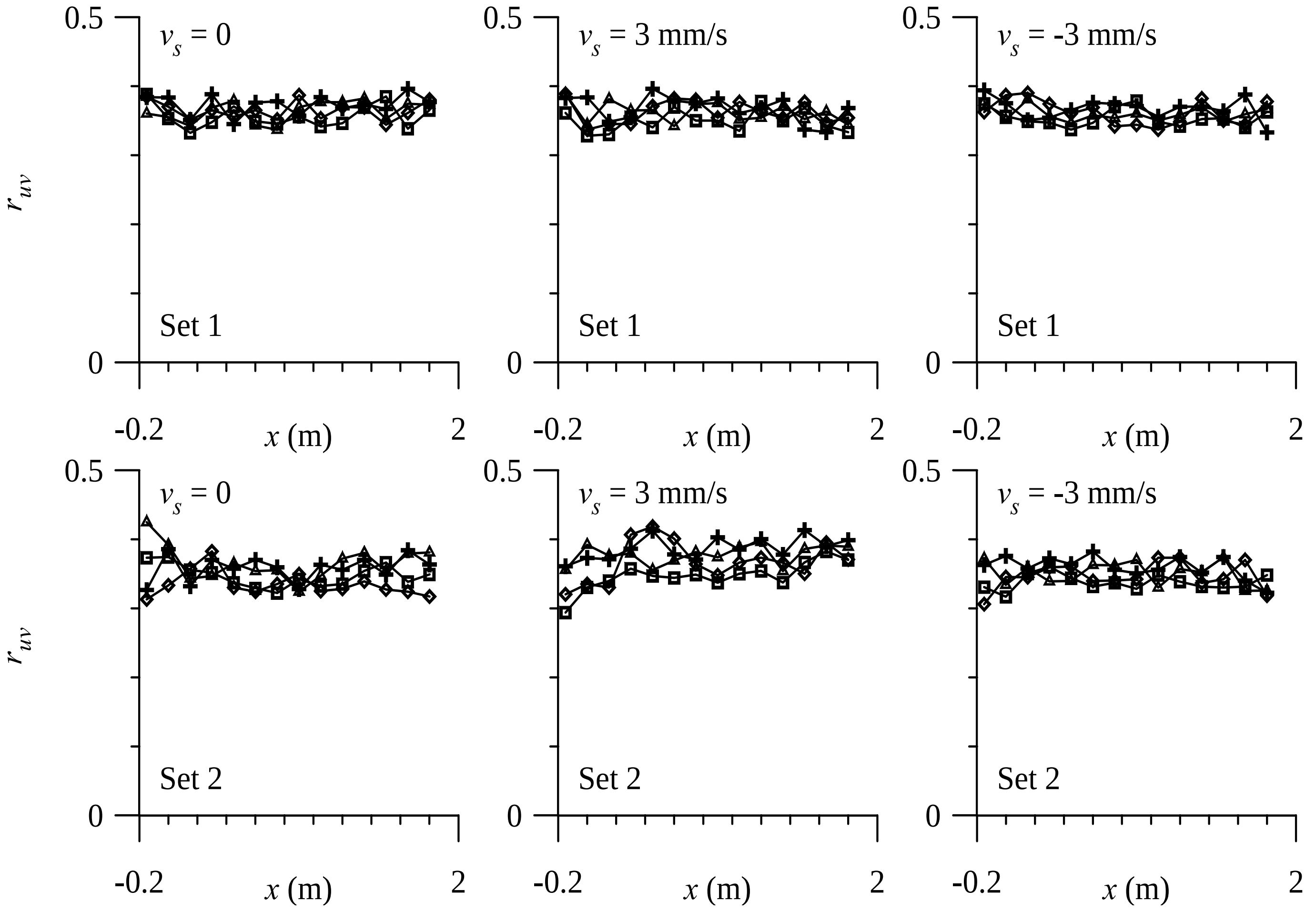
	No-seepage					Injection		Suction	
	U	h	S	d_{50}	u_*	v_s	u_*	v_s	u_*
Set	m/s	m	%	mm	m/s	mm/s	m/s	mm/s	m/s
1	0.36	0.15	0.0714	10.3	0.0329	3	0.0315	–3	0.0335
2	0.34	0.15	0.0714	14.3	0.0307	3	0.0297	–3	0.0332

Experimental parameters



Measurements were taken in the central vertical plane at the four vertical points (y/h = 0.05, 0.1, 0.2 and 0.3) for different horizontal locations (x = – 0.15, 0, 0.15, 0.3, 0.45, 0.6, 0.75, 0.9, 1.05, 1.2, 1.35, 1.5, 1.65 and 1.8 m).

Horizontal distributions of time-averaged streamwise velocity



Horizontal distributions of correlation coefficient, $r_{uv} = -\overline{u'v'}/[\left(\overline{u'u'}\right)^{0.5} \times \left(\overline{v'v'}\right)^{0.5}]$

- Comparison of the velocity and correlation coefficient data confirmed that in the central portion of the flume ($z = \pm 0.25$ m off the centerline) the flow was reasonably two-dimensional.

- To ascertain the two-dimensionality of the flow structure, measurements were also taken for various horizontal distances at different transverse locations.

- An examination of the variations of flow parameters reveals that the velocity and correlation coefficient were reasonably uniform within $0.6 \leq x \leq 1.4$ m, which was considered the zone of the Vectrino measurement for the analyses of the distributions of velocity and turbulence quantities.

- Vertical velocity distributions were measured at 40 different locations along the centerline of the flume within this zone. Each vertical was separated by a streamwise distance of approximately a gravel unit.

Spatially-averaged flow field

The decomposition of the local time-averaged flow quantity :

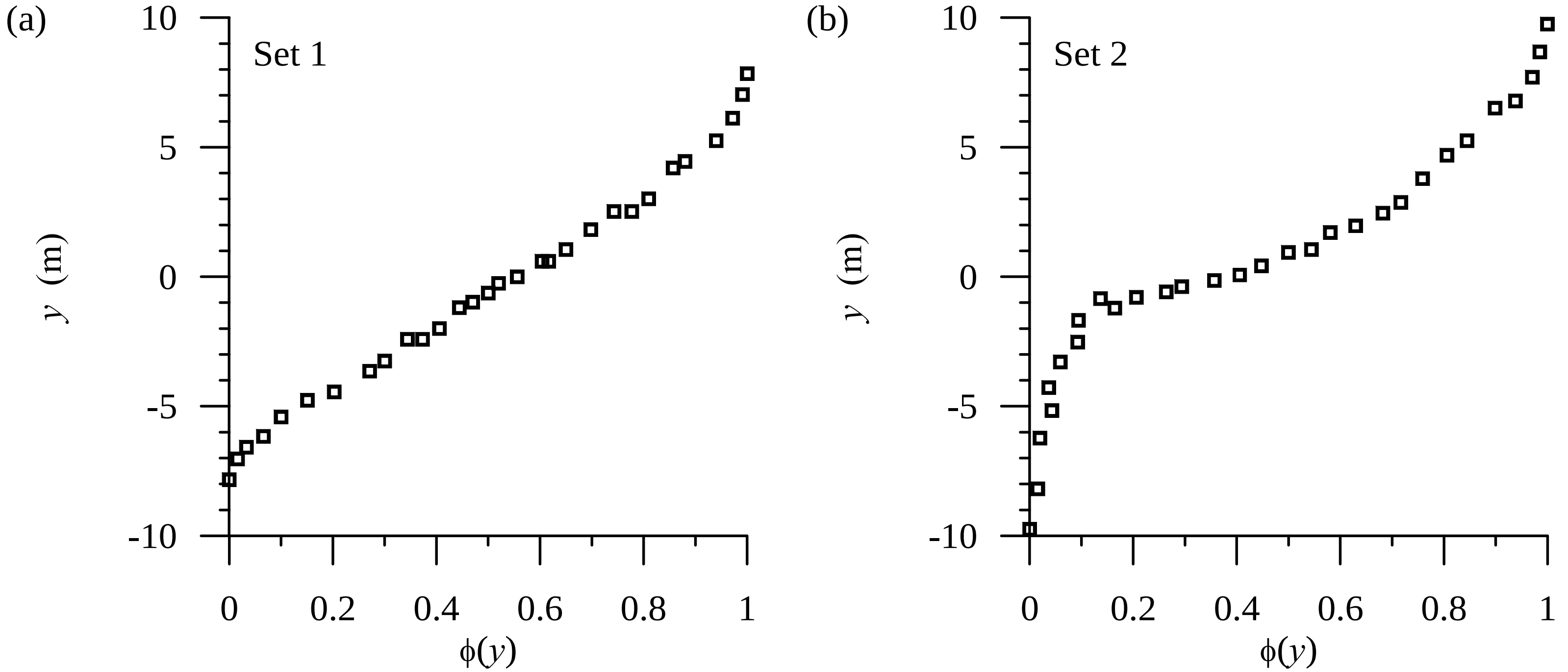
$$\bar{\theta} = \langle \bar{\theta} \rangle + \tilde{\theta}$$

$\tilde{\theta}$ is the deviation of the local time-averaged flow quantity from the spatially-averaged flow quantity $\langle \bar{\theta} \rangle$

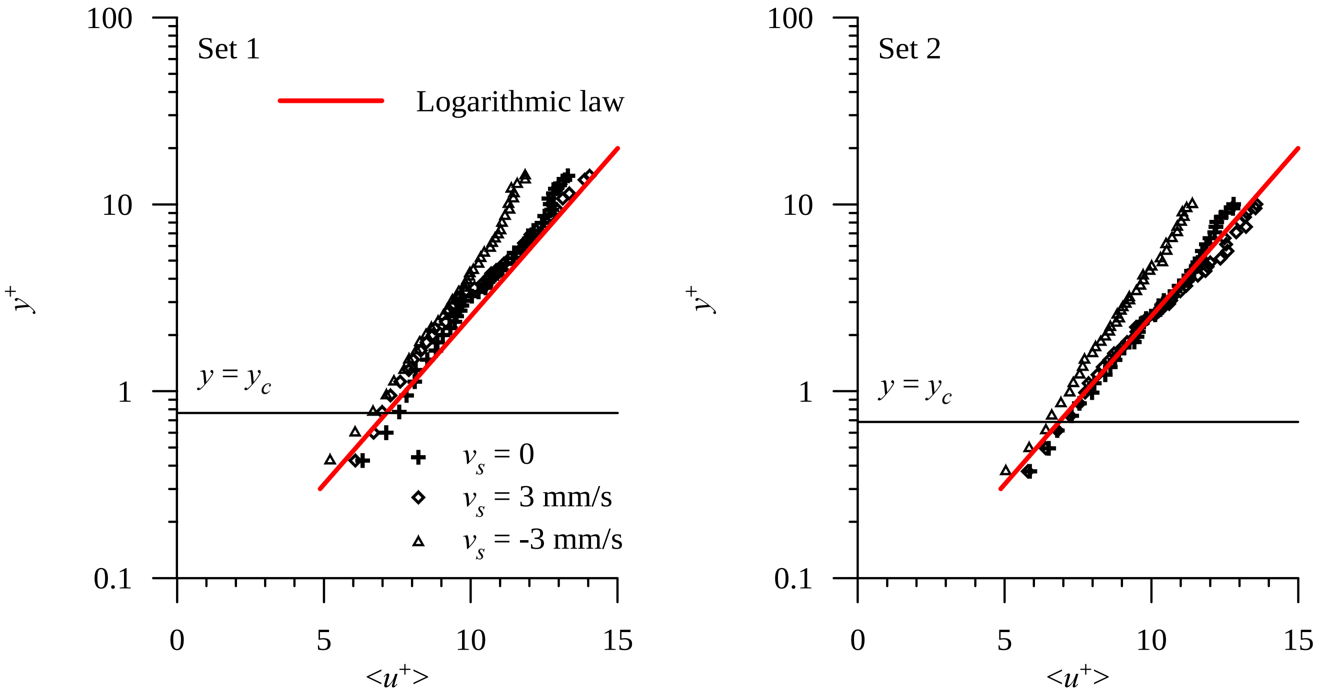
Spatial averaging is intended as area integration over a surface parallel to the bed at variable elevation or, which is equivalent, as volumetric integration over thin slabs parallel to the bed [*Nikora et al.*, 2007a,b].

The roughness geometry function $\phi(y) = A_f/A_0$

Here, A_f is the area occupied by the fluid at an elevation y within total area A_0



Roughness geometry function $\phi(y)$



In the wall-shear layer, the streamwise velocity in injection is lower and that in suction is greater than that in no-seepage.

Vertical distributions of $\left\langle u^+ \right\rangle$

Spatially-averaged Reynolds shear stresses

The double-averaged momentum balance in the streamwise direction as

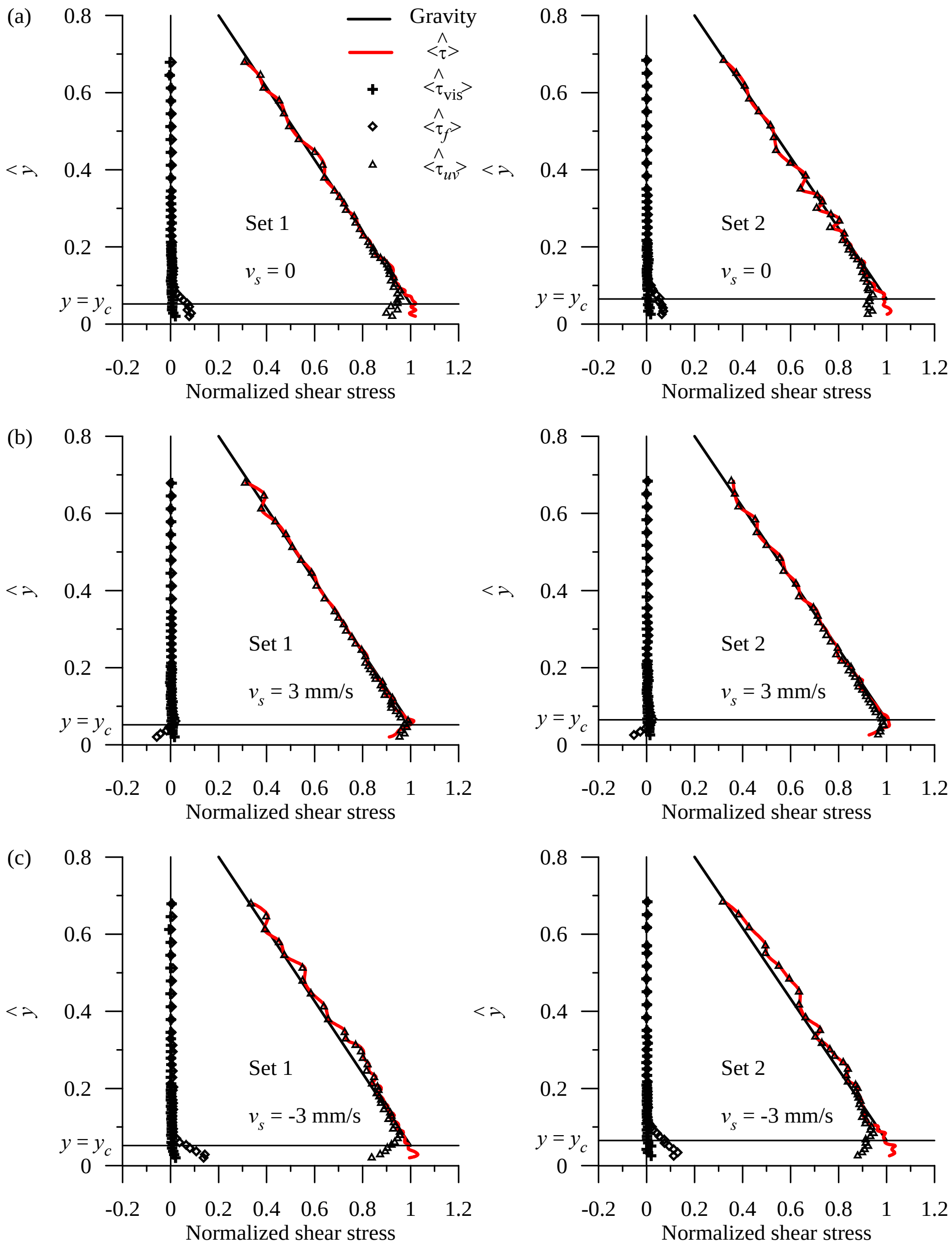
$$f_x - \phi \rho g S = \partial \phi \left(\left\langle \tau \right\rangle - \rho \left\langle \overline{u} \right\rangle \left\langle \overline{v} \right\rangle \right) / \partial y$$

Total Shear Stress

= Reynolds Shear stress + Form-induced Shear Stress + Viscous Shear Stress

$$\begin{aligned} \left\langle \tau \right\rangle &= \left\langle \tau_{uv} \right\rangle + \left\langle \tau_{f} \right\rangle + \left\langle \tau_{vis} \right\rangle \\ &= \left(-\rho \left\langle \overline{u'v'} \right\rangle \right) + \left(-\rho \left\langle \tilde{u}\tilde{v} \right\rangle \right) + \left(-\rho \upsilon \left\langle \partial \overline{u} / \partial y \right\rangle \right) \end{aligned}$$

$-\rho \langle \overline{u} \rangle \langle \overline{v} \rangle$ is added to account for the average momentum transfer due to the nonzero average vertical velocity component in seepage cases.



- A damping in the distributions of Reynolds shear stress below the roughness crest level is observed.

- The damping is greater in suction and lower in injection than that in no-seepage.

- The form-induced stress are developed below the roughness crest level and has a decelerating effect in no-seepage and suction and an accelerating effect in injection.

- due to very slow seepage, the $-\rho\langle\overline{u}\rangle\langle\overline{v}\rangle$ is obtained negligible

Vertical distributions of normalized spatially-averaged Reynolds shear stresses

Normalized spatially-averaged turbulence intensities

Streamwise turbulence intensity $\left\langle \hat{\sigma}_u \right\rangle = \left\langle \left(\overline{u'u'} \right)^{0.5} \right\rangle / u_*$

Vertical turbulence intensity $\left\langle \hat{\sigma}_v \right\rangle = \left\langle \left(\overline{v'v'} \right)^{0.5} \right\rangle / u_*$

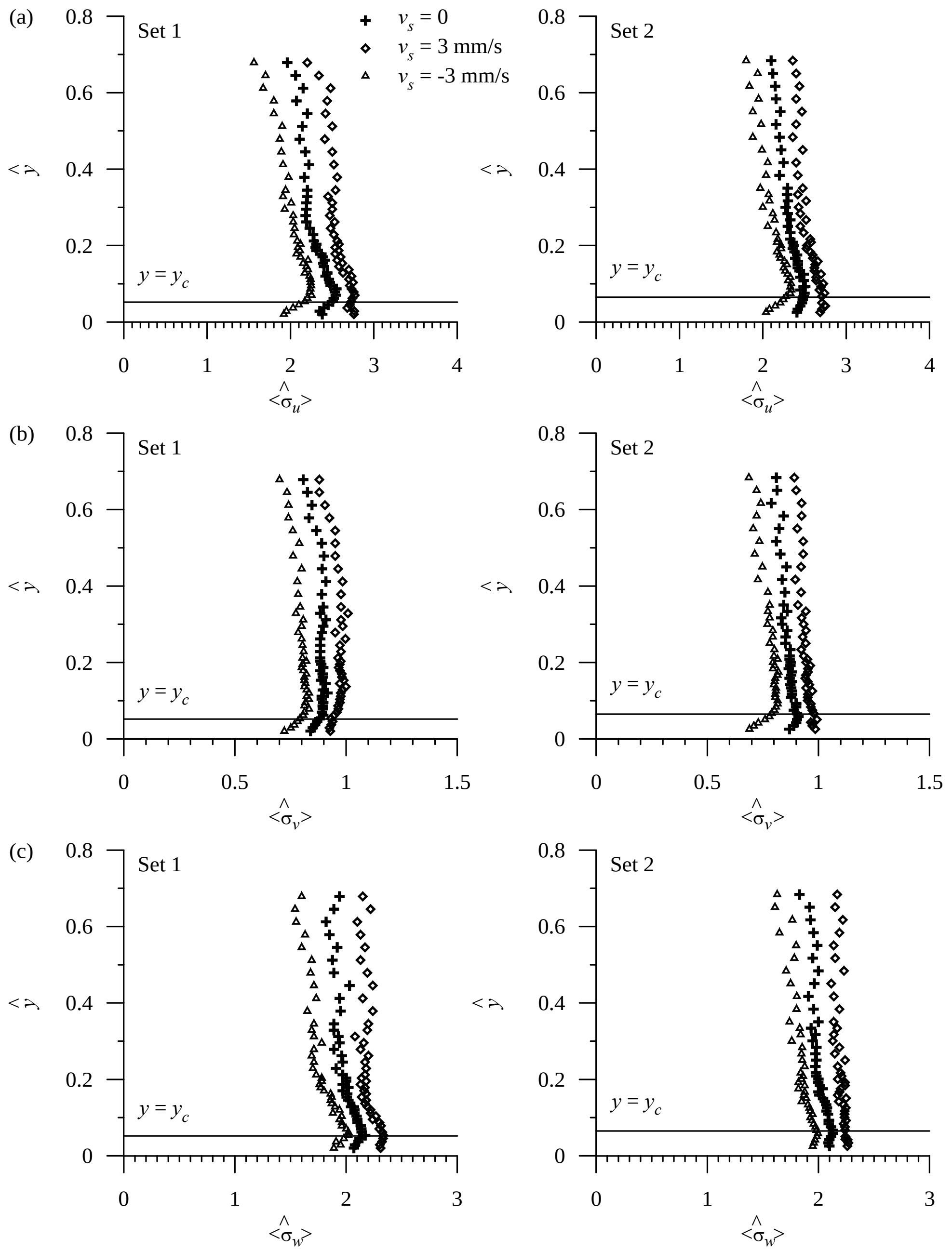
Transverse turbulence intensity $\left\langle \hat{\sigma}_w \right\rangle = \left\langle \left(\overline{w'w'} \right)^{0.5} \right\rangle / u_*$

Normalized form-induced intensities

Streamwise form-induced intensity $\left\langle \tilde{\sigma}_u \right\rangle = \left\langle \left(\tilde{u}\tilde{u} \right)^{0.5} \right\rangle / u_*$

Vertical form-induced intensity $\left\langle \tilde{\sigma}_v \right\rangle = \left\langle \left(\tilde{v}\tilde{v} \right)^{0.5} \right\rangle / u_*$

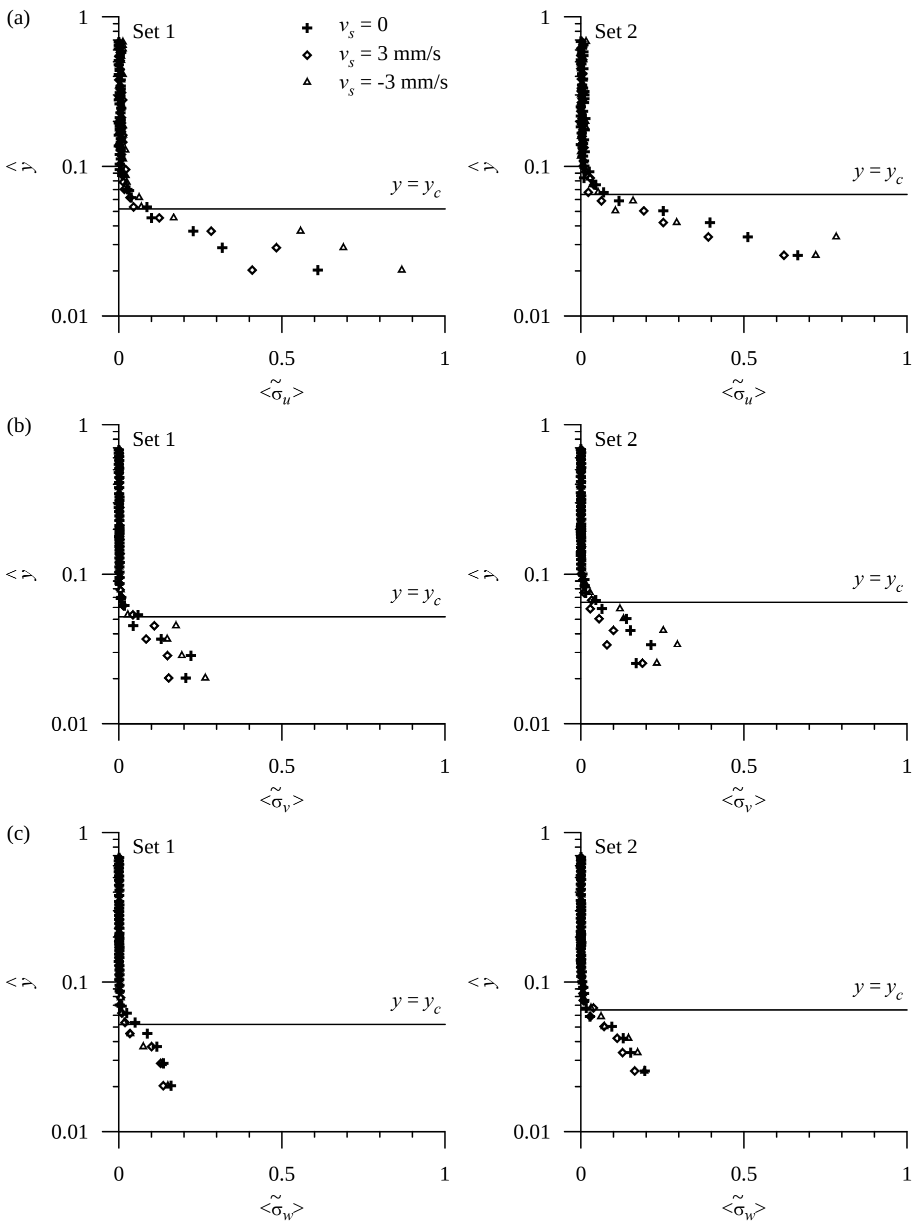
Transverse form-induced intensity $\left\langle \tilde{\sigma}_w \right\rangle = \left\langle \left(\tilde{w}\tilde{w} \right)^{0.5} \right\rangle / u_*$



Distributions of normalized turbulence intensities

- The turbulence intensities in injection are greater and those in suction are lower than those in no-seepage. It is in agreement with the findings of *Nezu* [1977], *Antonia et al.* [1988], *Antonia and Zhu* [1995], *Krogstad and Kourakine* [2000] and *Kim and Sung* [2003].

- For $y \leq y_c$, a damping in the distributions of turbulence intensities is evident. The damping rate increases in suction and decreases in injection



Distributions of normalized spatially-averaged form-induced intensities

- The distributions for Sets 1 and 2 are quite similar when scaled by u_*.

- The form-induced intensities increase for $y \leq y_c$.

- The form-induced intensities increase in presence of suction and decrease in injection.

Third-Order Correlations of Velocity Fluctuations

Spatially-averaged third-order correlations $\langle M_{ij} \rangle$ can be expressed as

$$\left\langle M_{ij} \right\rangle = \left\langle \overline{\hat{u}^{i}\hat{v}^{j}} \right\rangle$$

$$\left\langle M_{30} \right\rangle = \left\langle \overline{\hat{u}^{3}} \right\rangle$$

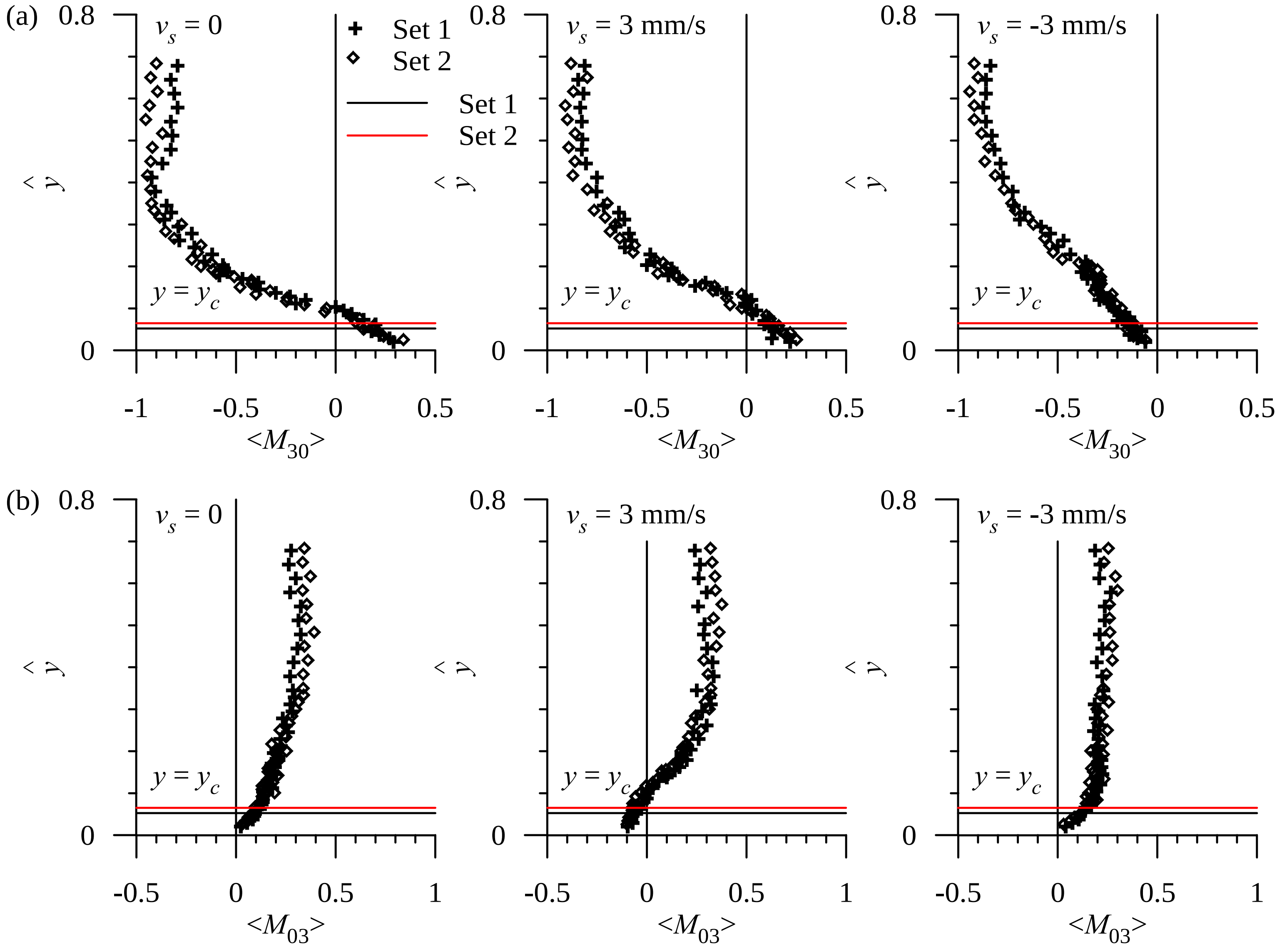
$$\left\langle M_{21} \right\rangle = \left\langle \overline{\hat{u}^{2}\hat{v}} \right\rangle$$

$$\left\langle M_{12} \right\rangle = \left\langle \overline{\hat{u}\hat{v}^{2}} \right\rangle$$

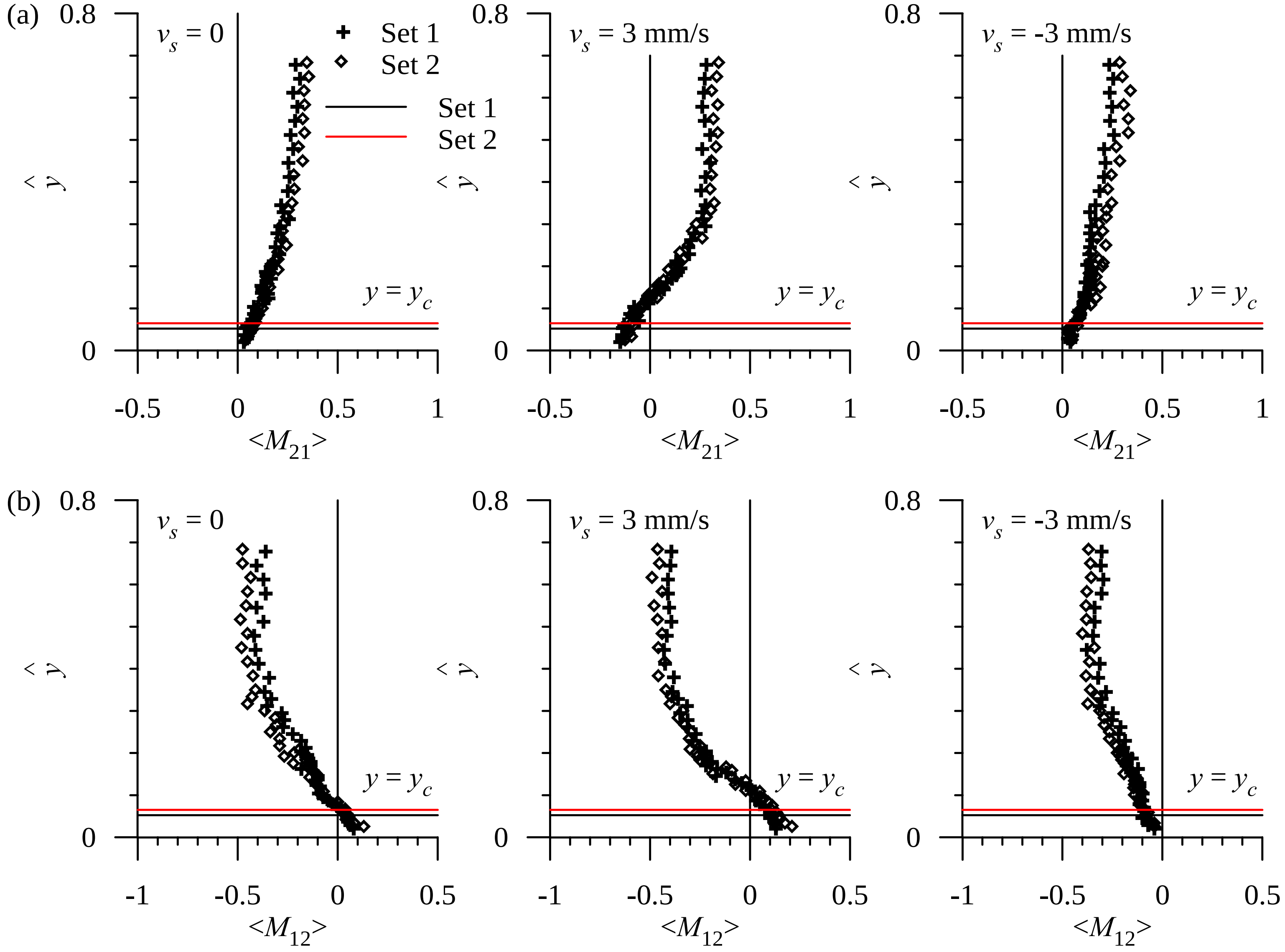
$$\left\langle M_{03} \right\rangle = \left\langle \overline{\hat{v}^{3}} \right\rangle$$

Negative values of $\langle M_{30} \rangle$ suggest the deceleration of streamwise flux of $\overline{u'u'}$

Positive value of $\langle M_{12} \rangle$ corresponds to the downstream transport of $\overline{v'v'}$



Distributions of spatially-averaged third-order correlations
(skewness or flux of Reynolds normal stresses)



Distributions of spatially-averaged third-order correlations
(transport of Reynolds normal stresses)

- In flows with no-seepage and injection value of $\langle M_{30} \rangle$ starts with a positive value near the bed changes over at $y/h \approx 0.1$ and then it becomes negative thereafter, increasing gradually with y/h.

- The negative peak values of $\langle M_{30} \rangle$ for all the cases are approximately –0.9, and they occur at $y/h = 0.5$-0.6.

- The mean trends of $\langle M_{03} \rangle$ and $\langle M_{21} \rangle$ are positive over the entire flow depth with no-seepage and suction, whilst those are negative near the bed ($y/h \leq 0.1$) and positive for $y/h > 0.1$ 1 in flows subjected to injection.

- $\langle M_{12} \rangle$ starts with a small positive value near the bed, becoming zero at $y = y_c$ and 0.1 for no-seepage and injection, respectively, and then it changes to a negative value.

- The negative magnitude of $\langle M_{12} \rangle$ gradually increases with y/h. Near the bed, $\langle M_{12} \rangle \approx 0.1$ for no-seepage and $\langle M_{12} \rangle \approx 0.15$ for injection indicate that the injection affects $\langle M_{12} \rangle$.

- The distributions of all $\langle M_{ij} \rangle$ above the wall-shear layer, $y/h > 0.2$ are closely correlated with each other, but changes are apparent within the wall-shear layer due to the influence of seepage.

- The third-order correlations show that in the near-bed flow layer with injection, a streamwise acceleration is associated with a downward flux suggesting sweeps having a downward transport of the streamwise Reynolds normal stress.

- In contrast, in the near-bed flow layer with suction, a streamwise deceleration is associated with an upward flux suggesting ejections having a downstream transport of streamwise Reynolds normal stress.

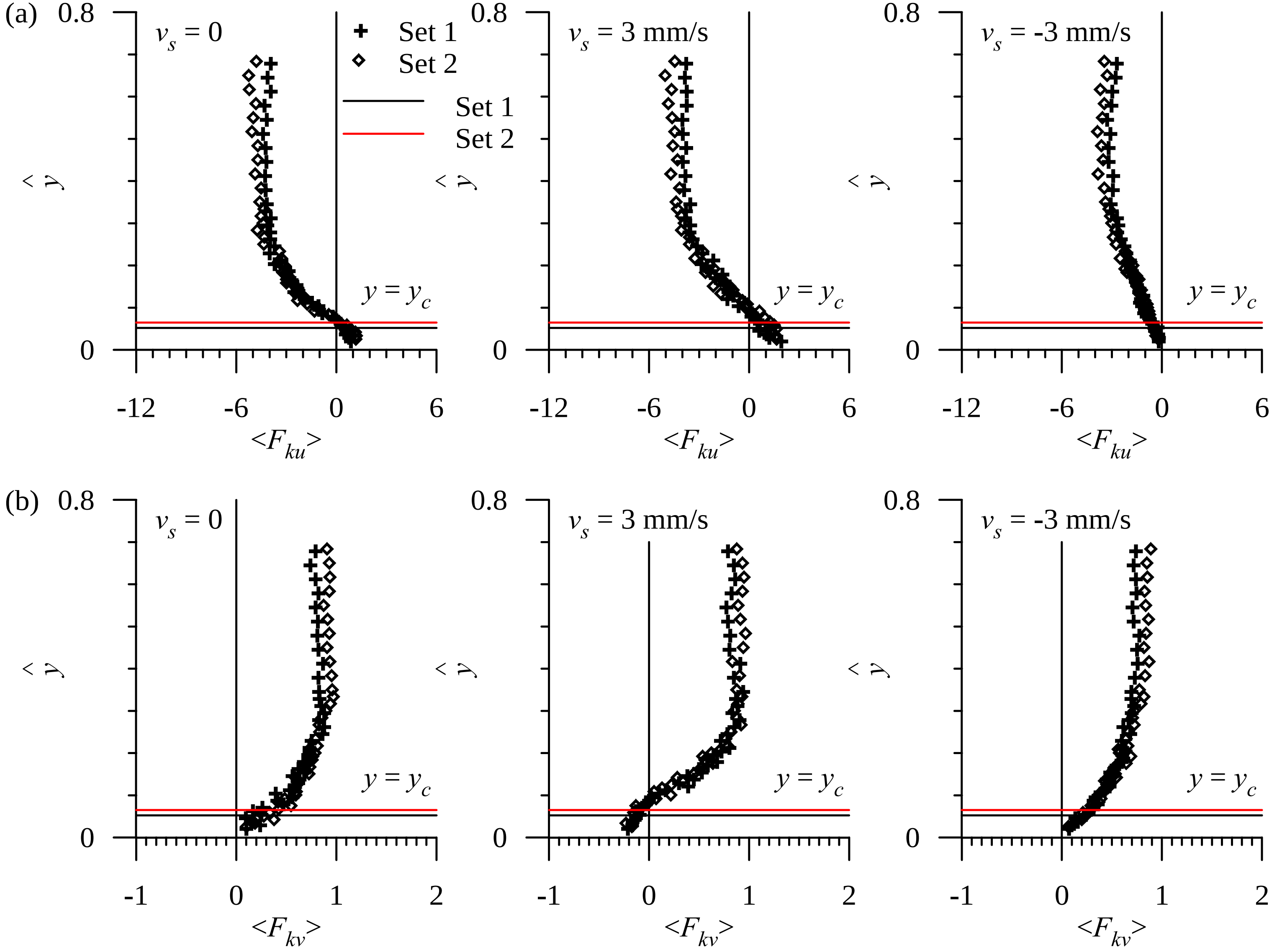
Turbulent Kinetic Energy :

The spatially-averaged streamwise and vertical flux of the turbulent kinetic energy are given by

$$\left\langle f_{ku}\right\rangle = 0.5\left(\left\langle \overline{u'u'u'}\right\rangle + \left\langle \overline{u'v'v'}\right\rangle + \left\langle \overline{u'w'w'}\right\rangle\right)$$

$$\left\langle f_{kv}\right\rangle = 0.5\left(\left\langle \overline{v'v'v'}\right\rangle + \left\langle \overline{v'u'u'}\right\rangle + \left\langle \overline{v'w'w'}\right\rangle\right)$$

To establish a kinematic equilibrium, the transport of energy arises from the energy-reach to the energy-want zone through a changeover zone



Distributions of spatially-averaged flux of turbulent kinetic energy in flows subjected to different v_s

- $\langle F_{ku} \rangle$ for injection and no-seepage conditions is positive in the near-bed flow layer, indicating that the streamwise flux of energy transports towards the downstream.

- $\langle F_{ku} \rangle$ for suction is negative over the entire flow depth, suggesting an upstream transport of energy flux.

- The positive value of $\langle F_{kv} \rangle$ over the entire flow depth for no-seepage and suction indicates an upward transport of flux.

- In the near-bed flow layer ($y/h < 0.1$), a negative value of $\langle F_{kv} \rangle$ in flows subjected to injection implies the downward transport of flux.

- Therefore, the most important aspect of the near-bed flows with injection is that positive $\langle F_{ku} \rangle$ and negative $\langle F_{kv} \rangle$ compose $Q4$ events. On the other hand, positive values of both $\langle F_{ku} \rangle$ and $\langle F_{kv} \rangle$ form outward interactions for no-seepage, while negative $\langle F_{ku} \rangle$ and positive $\langle F_{kv} \rangle$ produce $Q2$ events for suction.

Turbulent energy budget

Turbulent production : $\left\langle t_P \right\rangle = -\left\langle \overline{u'v'} \right\rangle \partial \left\langle \overline{u} \right\rangle / \partial y$

Turbulent energy diffusion : $\left\langle t_D \right\rangle = \partial f_{kv} / \partial y$

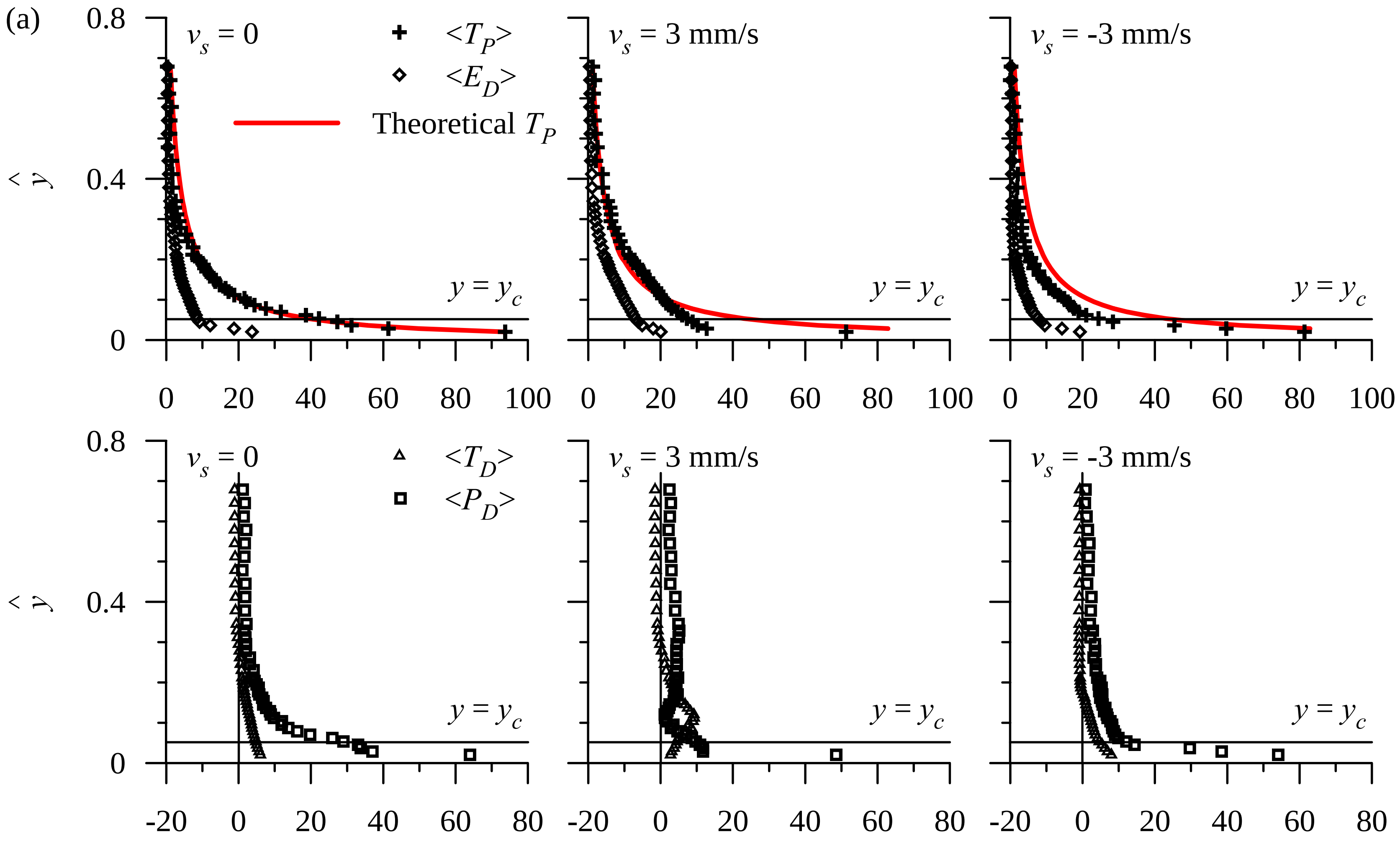
Turbulent dissipation : $\left\langle \varepsilon \right\rangle = \dfrac{15\upsilon}{u^2} \overline{\left(\dfrac{\partial u'}{\partial t} \right)^2}$

The pressure energy diffusion $\langle p_D \rangle$ is calculated algebraically from the equation of the turbulent energy budget as : $\left\langle P_D \right\rangle = \left\langle t_P \right\rangle - \left\langle \varepsilon \right\rangle - \left\langle t_D \right\rangle$

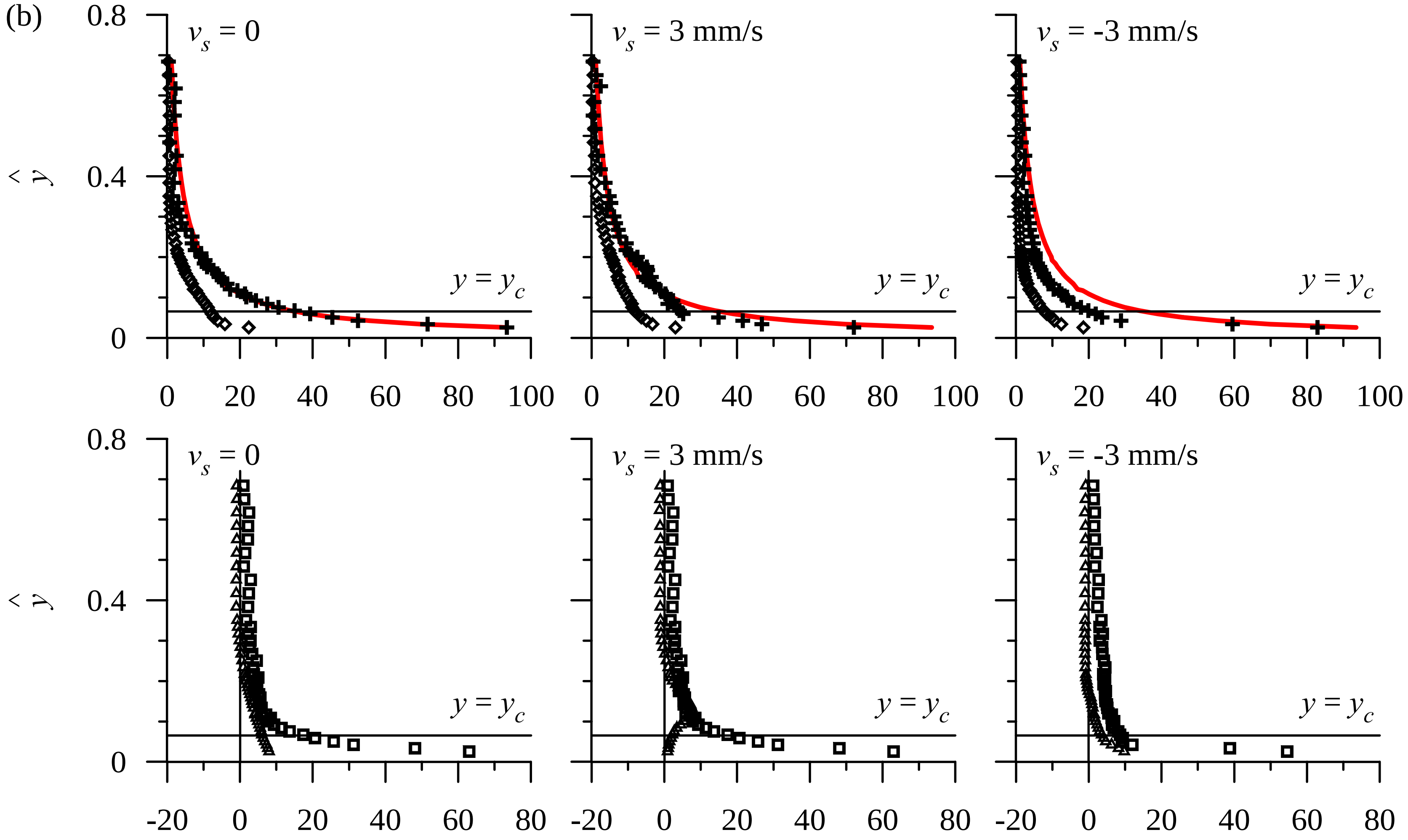
Multiplying by a factor h/u_*^3, the symbols $\langle T_P \rangle$, $\langle E_D \rangle$, $\langle T_D \rangle$ and $\langle P_D \rangle$ represent the normalized forms of $\langle t_P \rangle$, $\langle \varepsilon \rangle$, $\langle t_D \rangle$ and $\langle p_D \rangle$, respectively

Theoretical estimation of the turbulent production :

$$\left\langle T_P \right\rangle = \left(\kappa \hat{y} \right)^{-1} \left(1 - \hat{y} \right) / \left(1 - \hat{y}_c \right)$$



Spatially-averaged turbulent energy budget in flows subjected to different v_s for (a) Set 1



Spatially-averaged turbulent energy budget in flows subjected to different v_s for (b) Set 2

- The theoretical $\langle T_P \rangle$ is in agreement with the data plots for no-seepage. A departure of the experimental data plots from theoretical $\langle T_P \rangle$ is evident for $y = y_\mathrm{c}$ for injection and over the entire flow depth for suction.

- Within the wall-shear layer, $\langle E_D \rangle$ for no-seepage condition is slightly greater than suction and lower than injection.

- The turbulent dissipation lags from the turbulent production. The magnitude of the turbulent energy diffusion in injection drops down significantly below the roughness crest level; and in no-seepage and suction, it augments sharply within this region.

- $\langle T_D \rangle$ changes sign at the top of the wall-shear layer ($y/h \approx 0.23$) for no-seepage and injection, but it becomes negative at $y/h \approx 1.5$ for suction.

- It is noticeable that the points of changeover for no-seepage and injection lie above those for suction. Interestingly, $\langle P_D \rangle$ increases sharply for $y \leq y_c$.

Quadrant analysis

A simple method for the quantitative assessment of the coherent structures is the quadrant analysis.

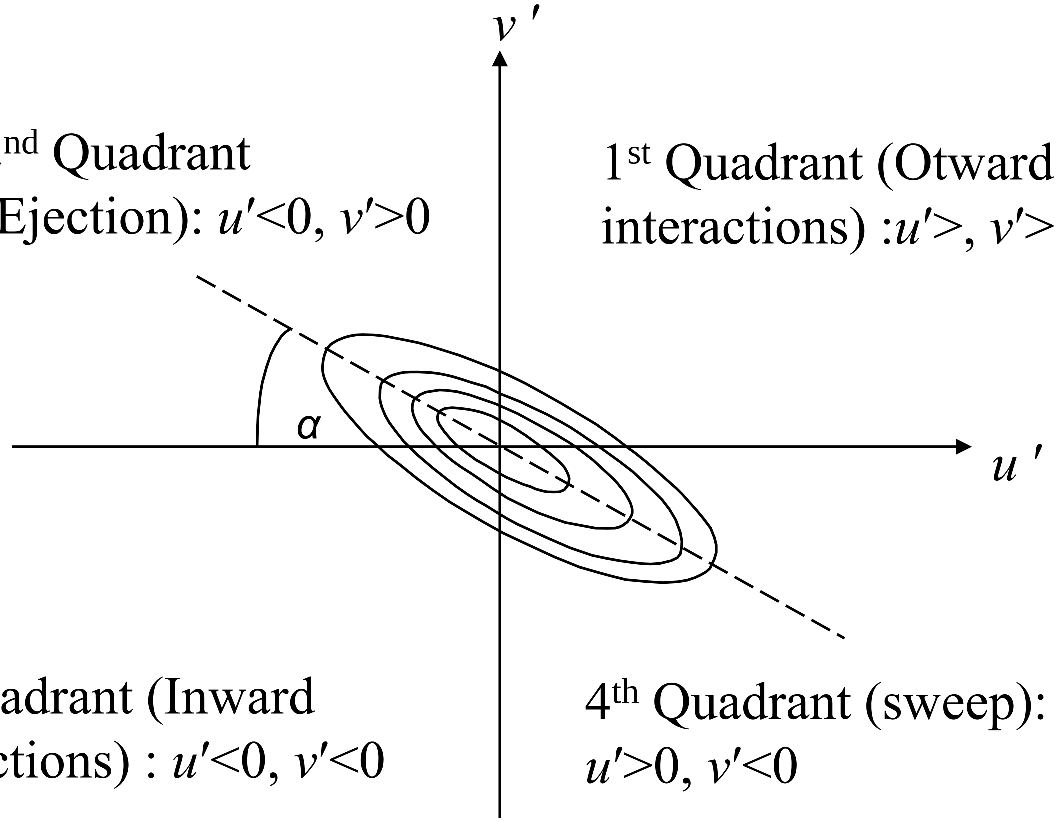
Four quadrants are defined as:

- $Q1$, first-quadrant $(u' v')_1$, where $u'>0$ and $v'>0$, denoting an event in which high speed fluid moves toward the centre of the flow field (outward interaction).

- $Q2$, second-quadrant $(u' v')_2$, where $u'<0$ and $v'>0$, denoting an event in which low-speed fluid moves toward the centre of the flow field, away from the wall (ejection).

- $Q3$, third-quadrant $(u' v')_3$, where $u'<0$ and $v'<0$, denoting an event in which low-speed fluid moves toward the wall (inward interaction); and

- $Q4$, fourth-quadrant $(u' v')_4$, where $u'>0$ and $v'<0$, denoting an event in which high-speed fluid moves toward the wall (sweep).



2^{nd} Quadrant (Ejection): $u'<0$, $v'>0$

1^{st} Quadrant (Otward-interactions) :$u'>$, $v'>0$

3^{rd} Quadrant (Inward interactions) : $u'<0$, $v'<0$

4^{th} Quadrant (sweep): $u'>0$, $v'<0$

Joint probability function of the location of the velocity fluctuation vector in the (u', v') plane**.**

A detection function is given by:

$$\lambda_{i,H}(z,t) = \begin{cases} 1, & \text{if } (u', v') \text{ is in quadrant } i \text{ and if } \left|u'v'\right| \geq H(\overline{u'u'})^{0.5}(\overline{v'v'})^{0.5} \\ 0, & \text{otherwise} \end{cases}$$

At any point, contributions to the total Reynolds shear stress production from the quadrant *i* outside the hyperbolic hole region of size *H* is given by

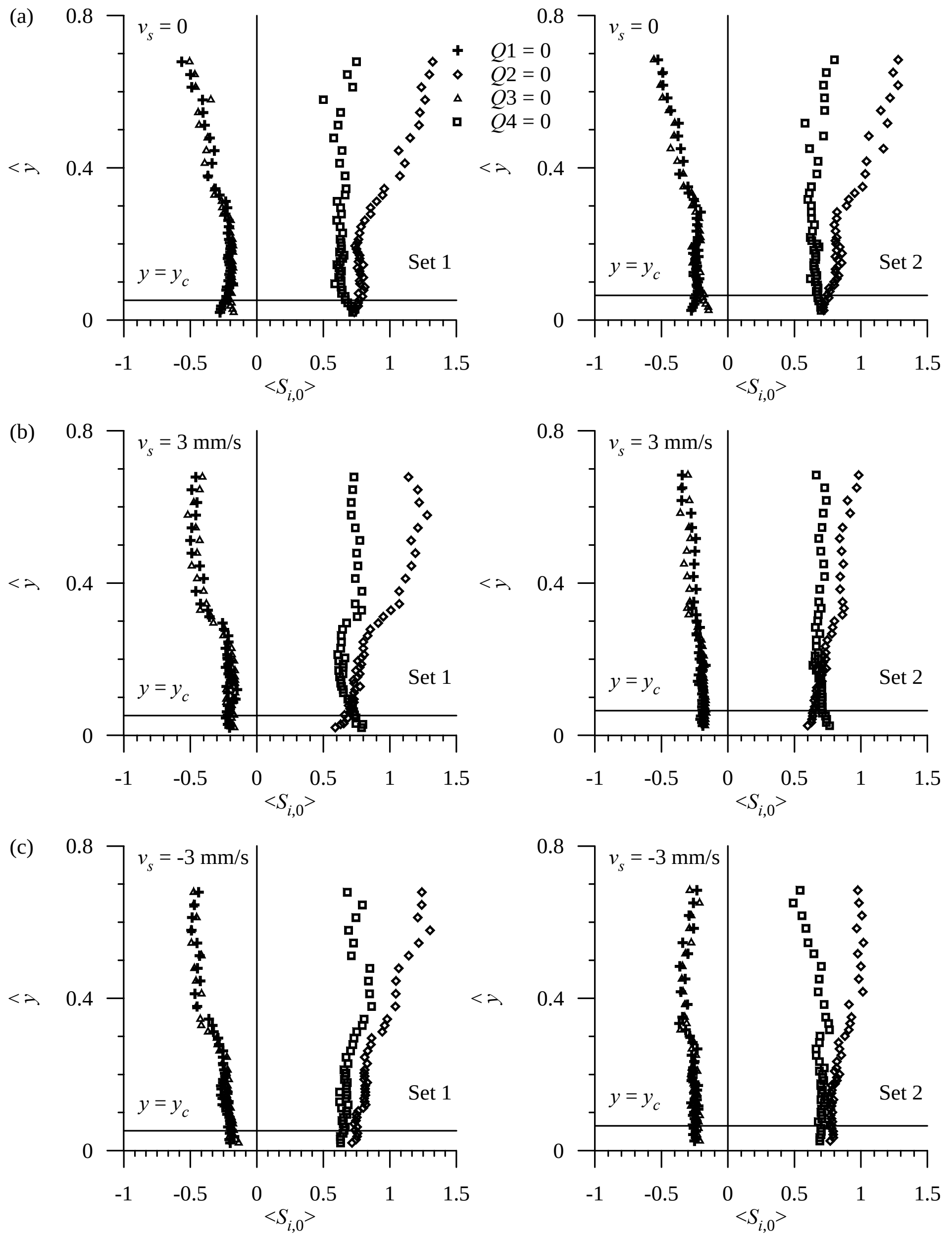
$$\overline{u'v'}^{i,H} = \lim_{T\to\infty} \frac{1}{T} \int_0^T u'(t)v'(t)\lambda_{i,H}(y,t)dt$$

The fractional contribution *Si*,*H* of the Reynolds shear stress to each event is

$$S_{i,H} = \frac{\overline{u'v'}^{i,H}}{\overline{u'v'}}$$

The sum of contributions from different bursting events at a point is unity, that is

$$\sum_{i=0}^{i=4} [S_{i,H}]_{H=0} = 1$$

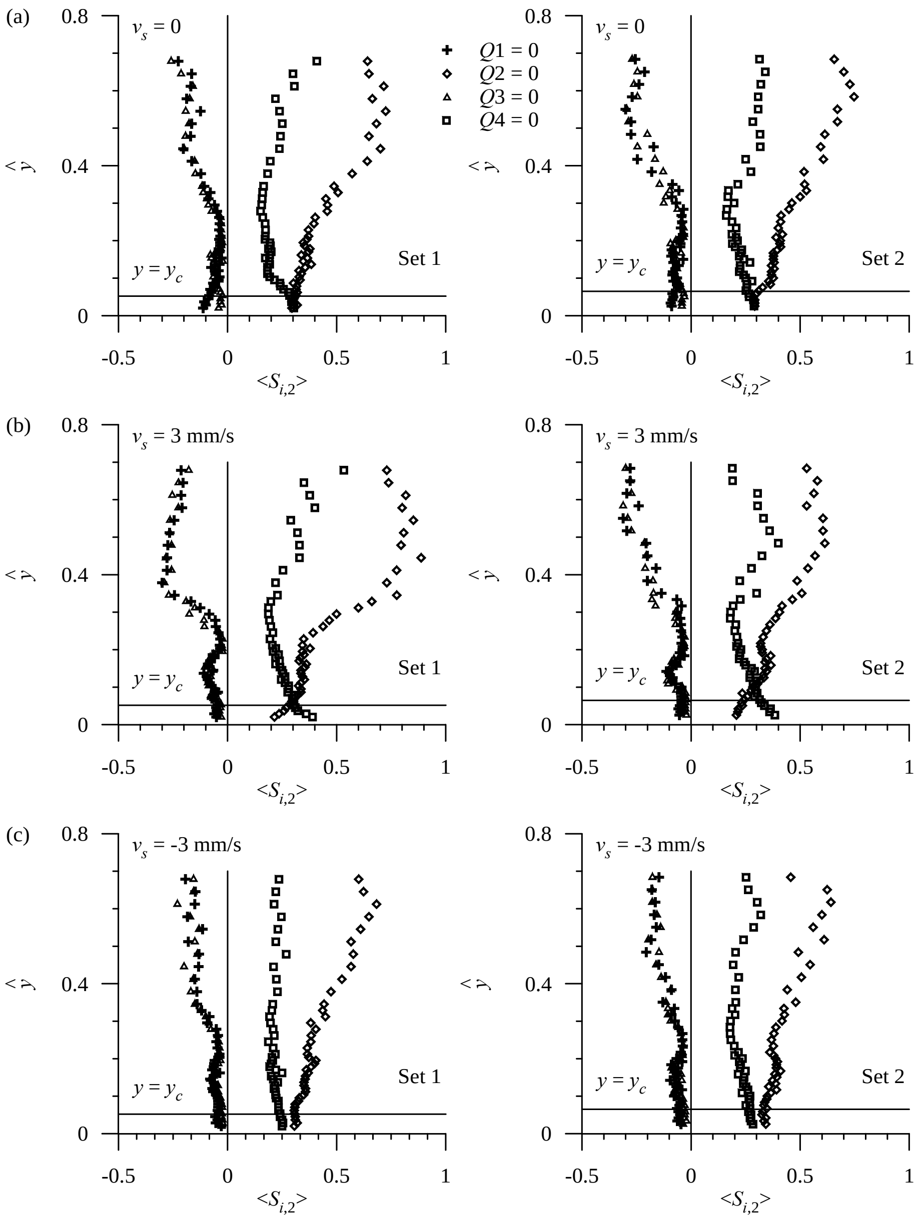


- In no-seepage case, only an outward faster moving process in the form of outward interactions is prevalent close to the bed.

- For injection, an inrushing faster moving process, that is sweeps, prevails near the bed. This interesting flow feature with wall-injection was also observed by *Haddad et al.* [2007].

- For suction, an ejecting slower moving process, that is ejections, exits in the near-bed. This is in agreement with the observations of *Djenidi et al.* [2002].

Variations of conditional spatially-averaged Reynolds shear stresses for $H = 0$



- To determine the stronger events (discarding the weaker ones), the hole-size *H* = 2 is used.

- A similar characteristic feature of *Q*2 and *Q*4 events is prevalent in the near-bed flow layer for *H* = 0 and *H* = 2. The contributions from *Q*1 and *Q*3 events remain insignificant.

Variations of conditional spatially-averaged Reynolds shear stresses for *H* = 2

Time-durations and frequencies of the ejection and sweep

The nondimensional mean time-durations of ejection and sweep events are represented by:

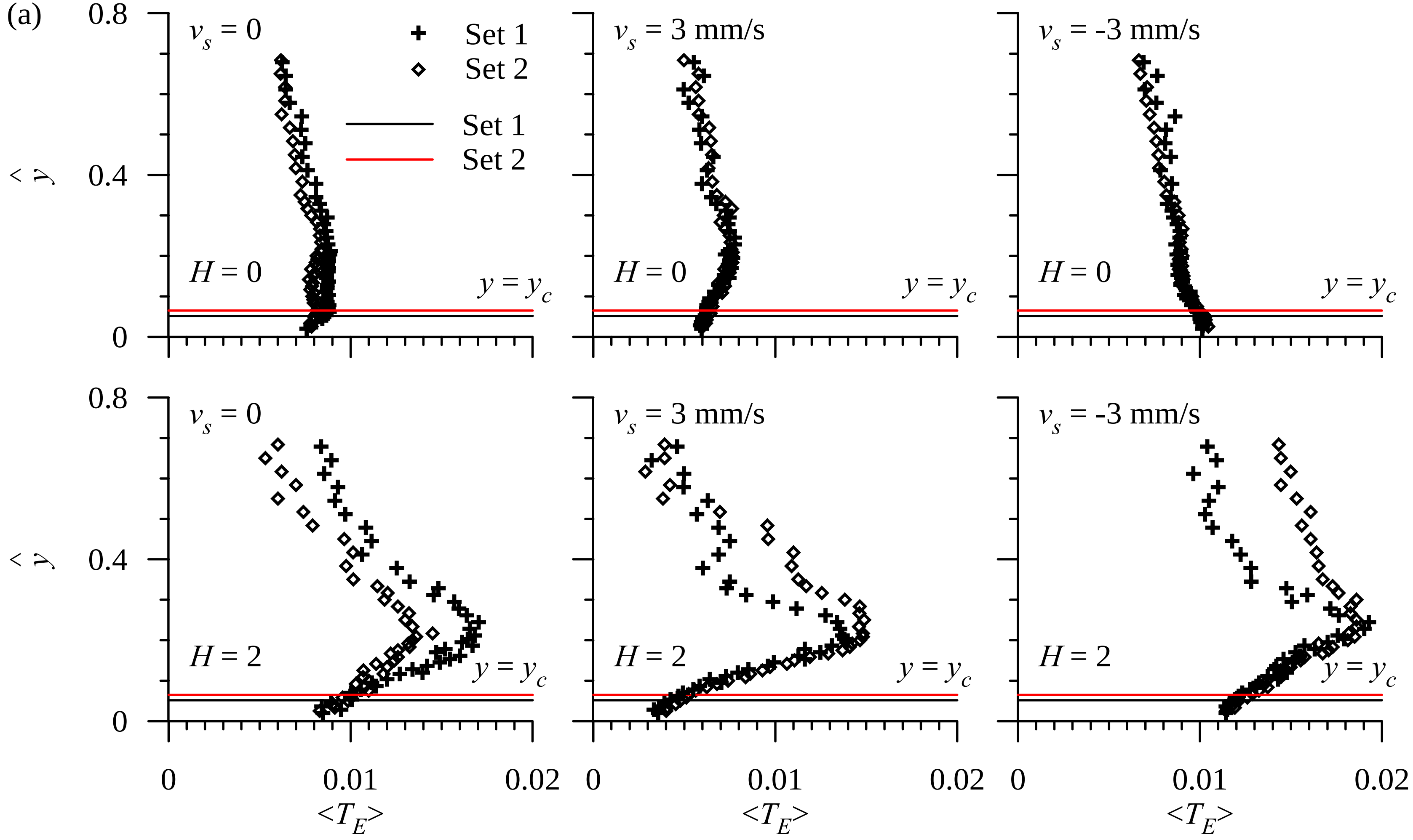
$$\langle T_E \rangle = \langle t_{Eu_*} \rangle / h \quad \text{and} \quad \langle T_S \rangle = \langle t_{Su_*} \rangle / h$$

In the near-bed flow layer, the mean duration of bursting increases in suction and decreases in injection

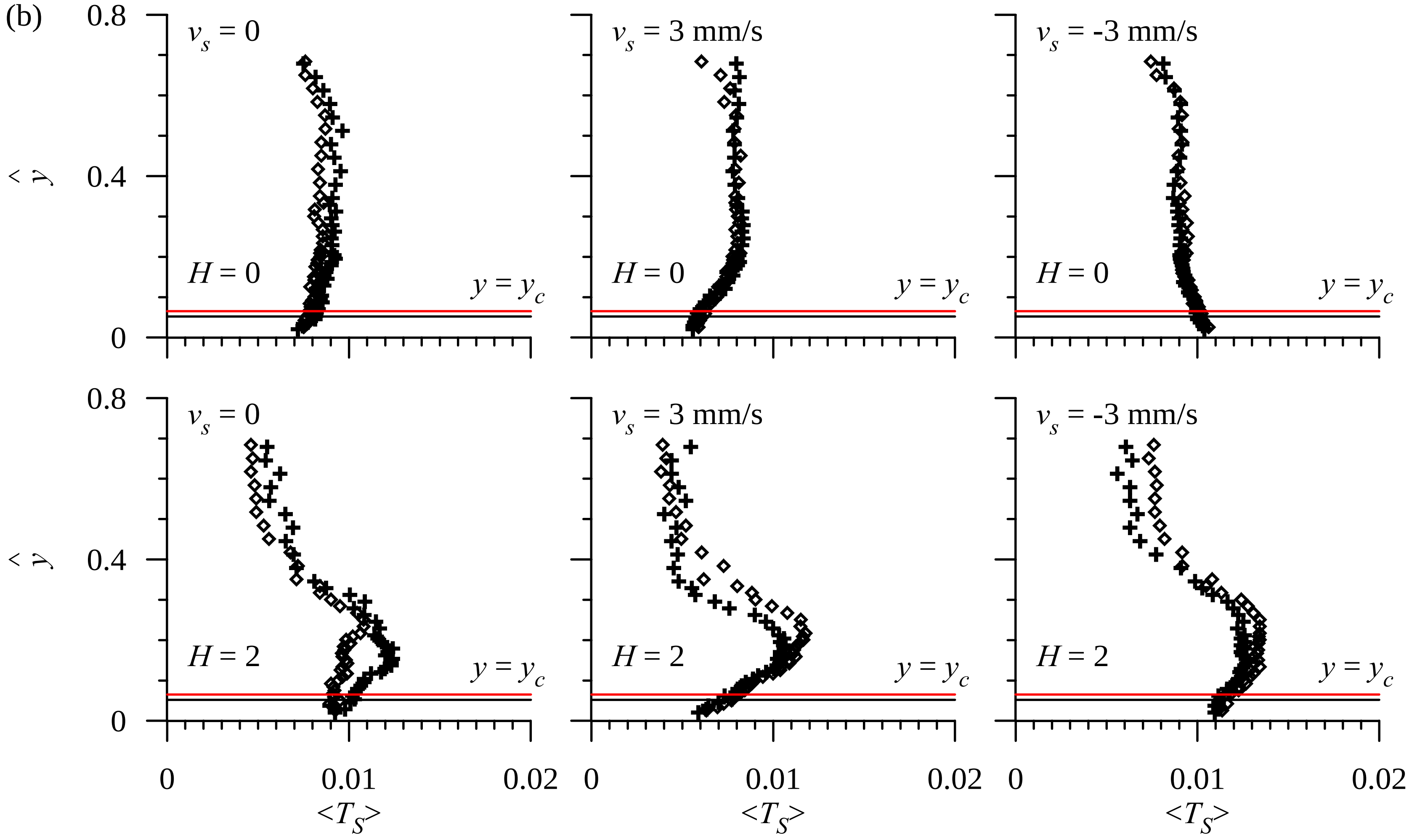
The nondimensional mean frequencies of ejection and sweep events are

$$\langle f_E \rangle = \langle i_E^{-1} \rangle h / u_* \quad \text{and} \quad \langle f_S \rangle = \langle i_S^{-1} \rangle h / u_*$$

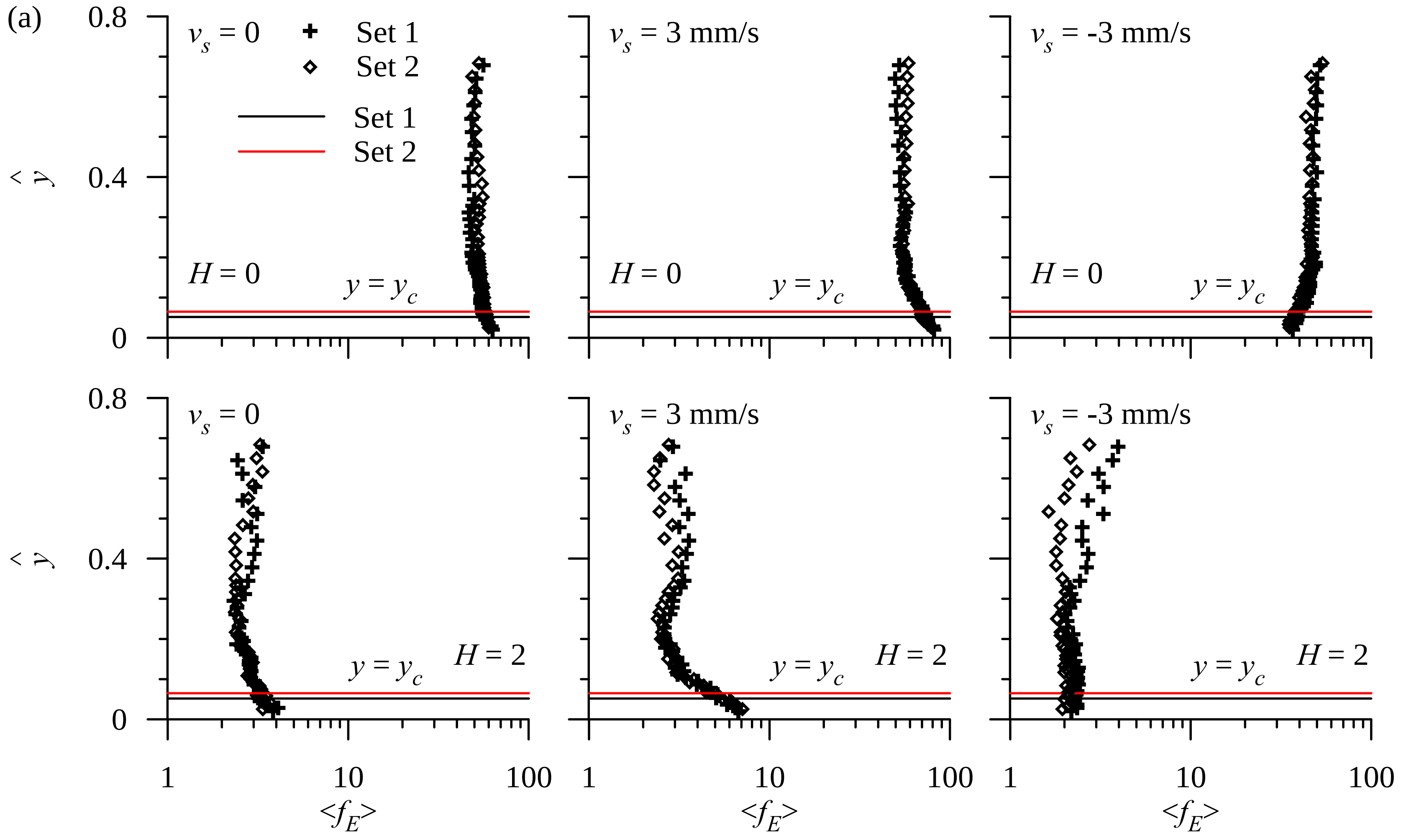
The bursting frequency increases in injection and decreases in suction



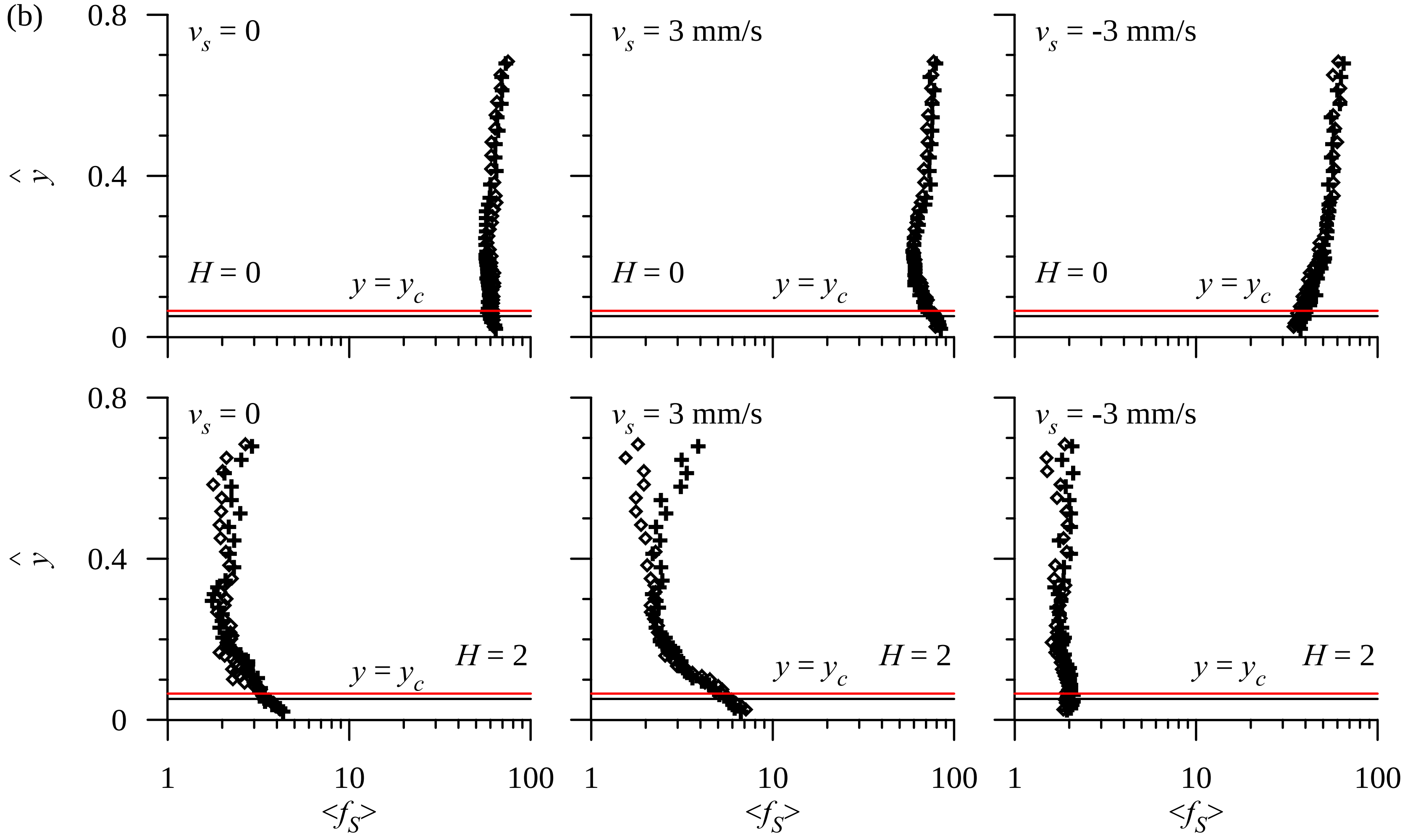
Mean durations of $Q2$ events, $\langle T_\mathrm{E} \rangle$



Mean durations of $Q4$ events, $\langle T_\mathrm{S} \rangle$



Mean frequencies of $Q2$ events, $\langle f_E \rangle$



Mean frequencies of $Q4$ events, $\langle f_S \rangle$

In the near-bed flow layer, the mean duration of bursting increases in suction and decreases in injection

The bursting frequency increases in injection and decreases in suction

Findings applicability to the sediment transport context

- For possible implications in sediment mobility, the turbulence characteristics in flows subjected to injection and suction from gravel-beds are of significant importance.

- For instance, *Q*2 events that are correlated with sediment suspension pick the sediments up from the bed and carry them through the main flow domain [*Cellino and Lemmin*, 2004], whereas *Q*4 events are associated with the initiation of sediment motion and bed-load transport [*Dey et al.*, 1999].

- The injection from the bed modifies the velocity distribution to reduce the bed shear stress increasing the stability of the bed particles.

- It is to reduce the effective submerged weight of the sediment particles decreasing the stability of them. For suction, the effect is reversed.

- These two effects contradict towards the resulting stability of the sediment particles. Therefore, the resulting stability depends on the predominating effect of one of them under the seepage condition.

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Thank You