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Measurements of fluctuation in drag acting on rigid cylinder array in open channel flow

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Abstract

In this study, an array of rigid cylindrical rods was used to simulate emergent vegetation stems that were subject to unidirectional open channel flows. The instantaneous drag force experienced by the rods was measured with a load cell. In addition, Particle Image Velocimetry (PIV) technique was applied to sample the flow information in a horizontal plane and wave gauges were used to record the fluctuation in the water-surface elevation. The results show that the drag fluctuation normalized by the mean value may reach as high as 133% when the Reynolds number (defined based on the stem diameter) varied in the

range from 400 to 1100. High fluctuations were also observed in the flow velocity and flow depth under similar flow conditions.

Introduction

In the past decades, various laboratory experiments have been conducted to study characteristics of open channel flows subject to submerged or emergent vegetation (Kouwen et al. 1969; Nepf 1999; Ishikawa et al. 2000; James et al. 2004; Järvelä 2004; Wilson et al. 2008; Wu 2008; Kothyari et al. 2009; Yang and Choi 2010; Cheng and Nguyen 2011). In these studies, an array of rigid cylinders was often adopted to represent the stem or trunk of vegetation. In particular, the understanding of flow characteristics around rigid cylinders provides basis for analysis of flow resistance in vegetated channels (Stone and Shen 2002). Most of the previous studies focused only on the measurement of mean flow velocity and channel resistance. In comparison, only few efforts have been reported to directly measure the drag acting on the vegetation (Ishikawa et al. 2000; Thompson et al. 2004; Kothyari et al. 2009; Tinoco and Cowen 2013).

Ishikawa et al. (2000) measured the mean drag acting on emergent cylinders using a strain gauge. Their study yielded that the drag coefficient (C_D) is related to the ratio of the mean flow velocity to the shear velocity, channel slope, as well as the vegetation density defined as the fraction of the bed area occupied by the vegetation. Kothyari et al. (2009) also measured the mean drag force using a strain gauge but expressed C_D as a function of the Reynolds number (R_D , which was defined based on the cylinder diameter and vegetation density). They observed that C_D was constant for the subcritical flow and rapidly decreased

for the supercritical flow. Tinoco and Cowen (2013) used a drag plate to measure the drag acting on both a single cylinder and an array of cylinders. They found a quadratic relationship between the drag and velocity, and the drag coefficient varied between 1.5 and 2 with the Reynolds numbers ranging from 60 to 4550.

Due to vortex shedding, significant fluctuations could be observed in the force experienced by the cylinders, relevant flow velocities and flow depth. For example, the maximum fluctuation in the flow depth could reach about 40% of the mean flow depth, as reported by Zima and Ackermann (2002) and Ghomeshi et al. (2007). Similar fluctuations could also occur in the drag, but they have not been investigated in detail. In particular, it is not clear how fluctuations in different variables (i.e., force, velocity and flow depth) are related to one another. Therefore, the main objective of this study is to provide a relatively systematic measurement of the flow through an array of emergent rigid cylinders in an open channel, based on which the correlation between these flow variables could be explored.

In this study, a load cell was used to measure the mean drag and its fluctuation experienced by an array of rigid cylinders in open channel flows. In addition, variations in flow velocity and flow depth were sampled under similar flow conditions. The experimental results show that all the fluctuations vary consistently with the Reynolds number.

Experimental Setup

Experiments were conducted with two flumes (Flume A and Flume B), of which the information is summarized in Table 1. Rigid Perspex cylinders (11.00 cm in length and 0.83 cm in diameter) were used to simulate vegetation. They were fixed into precisely machined

holes on Perspex plates, each being 1.20 m long, 0.30 m wide, and 0.01 m thick. Three different spacings (0.03, 0.06, and 0.09 m) were applied to arrange the cylinders in staggered pattern to mimic different densities of vegetations (Cheng and Nguyen 2011). The three types of configurations are denoted as C30, C60 and C90. The vegetation densities (λ), defined as the percentage bed area occupied by vegetation, were calculated from the geometry of the pattern and they were 12.0%, 3.0% and 1.3% respectively. The configurations C60 and C90 are considered to be sparse while that of C30 is dense, according to the classification given by Nepf (1999). The length covered by vegetation was 3.90 m in Flume A and 6.00 m in Flume B. Different runs of tests were completed for configurations C30, C60 and C90; they were 20, 35 and 33, respectively, for Flume A, and 5, 20 and 9 for Flume B. Flow meters (accurate to 0.01 L/s) were used for recording flowrate and the cross-sectional averaged values are denoted as Q_{mean} . All the experiments were conducted under uniform flow conditions. For each test, a uniform flow was achieved by adjusting the bed slope, tailgate and flowrate, so that the flow depths at four different locations along the channel vegetation zone were equal to each other. Mean flow depth (h_{mean}) ranged from 6.30 cm to 9.70 cm, flow rate (Q_{mean}) from 0.65 L/s to 4.55 L/s, and channel slope from 0.0004 to 0.0102. The average pore velocity through the cylinders was then calculated as $V_{Vmean} = Q_{mean} / [Bh_{mean}(1 - \lambda)]$, where B is channel width. The diameter (d) based Reynolds number (R_D) was calculated as $R_D = V_{Vmean} d / \nu$, where ν is the kinematic viscosity of fluid, and the Froude number was calculated as $V_{Vmean} / \sqrt{gh_{mean}}$, where g is the gravitational acceleration. The test sections were selected to be at least $12h_{mean}$ away, according to Liu et al. (2008), from the upstream edge of the vegetation zone to ensure that the flow was fully developed.

Flume A was used to conduct measurements of drag forces and flow velocities. An illustrative sketch of the experimental system is shown in Fig. 1 (a) and (b). The bottom and sidewalls were made of glass to enable optical access. The drag and lateral forces acting on the cylinders were recorded with a three-component piezoelectric load cell (Kistler Model 9317B). This type of load cell has the advantage of high response and high resolution and hence has been widely used (e.g., Lam et al. 2003). The load cell was installed on a special plate that was 0.30 m long 0.30 m wide and 0.01 m thick. The center of the special plate [see Fig. 1 (b)] was 2.55 m from the upstream edge of the vegetation zone, and 1.80 m from tailgate. Inserted on the plate were transparent Perspex cylinders (11.00 cm in length and 8.00 cm in diameter), which were arranged in the same pattern as those downstream and upstream of the test section. All the transparent cylinders were installed vertically in a cantilever manner with a clearance of 0.20 cm between the lower ends of the cylinders and the channel bed. This cantilever arrangement avoided the load cell from being submerged in water.

For the vegetation configuration employed, the drag acting on the cylinder rods are considered dominant in comparison with the bed and sidewall friction. This is explained as follows. In most of the cases, the average drag coefficient can be approximated as a constant (close to 1.0), according to Cheng and Nguyen (2011) who investigated vegetation resistance with similar vegetation configurations. Therefore, the average drag is proportional to the square of the velocity through the cylinders. On the other hand, it has been found that the flow velocity (streamwise) through the rods is largely uniform in the majority of the flow depth and decreases to zero only near the bed (Nepf et al. 1998; Liu et al. 2008; Cheng and Nguyen 2011; Cheng et al. 2012). As a result, the bed effect on the drag

is negligible. This has been verified by experimental data, for example, the drag partition conducted by Cheng and Nguyen (2011) for open channel flows subject to emergent vegetation.

The force measurement setup was calibrated in-situ against a reference sensor. The point of action of the drag on average varied from 3.20 cm to 4.90 cm (when $h_{\text{mean}} = 6.30$ cm-9.70 cm) from the lower end of the cylinders. With the reference sensor, a reference force in the streamwise or lateral direction (denoted as F_x and F_y , respectively), was first applied on a cylinder at 3.00 cm and 4.50 cm from the end of the cylinder. Then the induced force (i.e. output) was recorded with the load cell. A comparison of the reference force and the recorded force is presented in Fig. 2 (a), showing that the recorded force is equal to 95% of the reference force. The calibration result also shows that the load cell could record the forces well regardless of the point at which the force acts.

The reason for involving multiple cylinders in the measurement of the drag is that the force experienced by a single cylinder was beyond the recordable range to response correctly. The load cell was connected with a signal amplifier controlled by a computer. The output signal was then captured with a data acquisition card (National Instruments) at a sampling rate of 1K Hz. To verify whether the load cell is accurately responsive to low frequency signals, a separate dynamic response test was also conducted with reference to a strain gauge. First, a reference (i.e. input) signal was recorded using a strain gauge sensor, which is suitable for the measurement of low-frequency response. The generated forces, F_x and F_y , were quasi-periodic, varying with a frequency of about 1 Hz. Then the induced force (i.e. output) was measured using the load cell. Fig. 2 (b) and (c) show the results of the input signals, in comparison with the output signals measured by the load cell. It can be seen that

the agreement between the input and output signals is excellent, which validated the force measurement system employed in the experiments. To obtain meaningful statistics of the measured data, a plot of probability density function (pdf) of the recorded force with the sampling duration of 1 s, 40 s, 80 s and 120 s is shown in Fig. 3 for illustration. As the duration increases up to 40 s, 80 s and 120 s, the statistics values (the mean value and standard deviations) become consistent. Finally, a sampling duration of 120 seconds was used for each run in this study. Water temperature remained at $22.8 \pm 0.2^\circ\text{C}$ throughout all the force and velocity measurements.

The Particle Image Velocimetry (PIV) technique (LaVision model) was used to measure the flow velocity in this study. A horizontal 2-D flow field was illuminated through the side wall of the flume with a double cavity Nd:YAG laser light sheet at 532 nm wavelength (Litron model, power ~ 135 mJ per pulse, duration ~ 5 ns). The location of the laser light sheet was about 5.0 cm above the channel bed. A 12-bit charge-coupled device (CCD) camera with the spatial resolution of $1.6\text{K} \times 1.2\text{K}$ pixels was used to record images from below the channel bed at a frame rate of 15 Hz. Seeding particles of $13\text{ }\mu\text{m}$ diameter, made of hollow glass spheres, were added in the flow as tracers. Particle images from the CCD camera were processed by LaVision Davis PIV package to obtain the velocity vectors. The field of view was $164\text{ mm} \times 123\text{ mm}$ and the spatial resolution was $1.66\text{ mm} \times 1.66\text{ mm}$. For each case, a series of 1050 instantaneous flow fields was acquired at the sampling frequency of 15 Hz. This frequency was found to be sufficient as the dominant frequency of velocity fluctuation was less than 5 Hz in this study. Prior to measurements, a calibration had been conducted against a calibration plate provided by the PIV manufacturer. The maximum uncertainty in displacement was calculated to be 0.1 pixels. Normalizing this

uncertainty with the mean displacement of the particles (about 5 pixels) yielded a relative error of 2% for the instantaneous streamwise and transverse velocities (u and v). A detailed description of the PIV post-processing procedure and uncertainty analysis is available in Wang and Tan (2008).

Fig. 4 shows a representative snapshot of the PIV images and the coordinate system used, in which water flows from left to right. The square is the area selected for analysis because it is the central area which had the least blockage of light. Four circles represent the positions of the four cylinders. The spacing is defined as the center-to-center distance between two neighbouring cylinders. The origin of the coordinate was located at the centre of the upstream cylinder. When the laser was emitted from the side of the flume, some cylinders, though transparent, affected the laser so that the PIV results in the shaded rectangular area were of poor quality and thus excluded for the analysis. The dominant frequency of lateral velocity fluctuation was calculated by applying FFT analysis to the v component that was measured at the points about $1.5d$ downstream of cylinders on the wake axis.

It should be mentioned that because of unavailability of wave gauges, we could not measure the fluctuation in the flow depth at the same time when conducting drag and flow measurements with Flume A. Then Flume B [see sketch in Fig. 1 (c)], which was 12.00 m long and 0.30 m wide, was used to conduct supplementary tests for measuring the fluctuation in the flow depth. In the supplementary tests, the flow condition including the channel slope, flowrate and flow depth was made comparable to that in Flume A (see Table 1). With similar flow conditions and vegetation configurations, the use of the two flumes does not affect the statistical results, e.g. rms values, varying with the Reynolds number, as presented later in

this paper. The wave gauges of the resistance type, comprising of three probes, were installed at the test section, which was 3.00 m (i.e. over 30 times the flow depth) from the upstream edge of the vegetation zone and 4.00 m from the tailgate. Each probe had two pieces of parallel metal sticks which was able to conduct electricity when submerged in water. The two sticks, 1.00 cm apart, formed a plane that was aligned with the sidewall. The planes associated with the three probes were located at a distance 1.90 cm, 11.60 cm and 26.30 cm from one sidewall of the flume. The locations were selected to observe the maximum fluctuation of the flow depth that may appear at different points across the y direction. The probes were connected with an amplifier to increase the output level of voltage signals and further connected to a computer for recording. DEWESoft data acquisition device was used to take recordings at a frequency of 100 samples per second. The probes were calibrated in still water before pump was turned on.

Data Analysis

With the time averaged drag, F_{Dmean} , acting on the cylindrical stems, the time averaged drag coefficient (C_{Dmean}) is defined as

$$C_{Dmean} = \frac{2F_{Dmean}}{\rho d h_{mean} V_{mean}^2} \quad (1)$$

where ρ is the fluid density. By normalizing the drag fluctuation F_D' in the same way as shown in Eq. (1), the fluctuation in the drag coefficient (C_D') can be expressed as (Gopalkrishnan 1993; Sumer and Fredsøe 2006),

$$C_D' = \frac{2F_D'}{\rho d h_{mean} V_{mean}^2} \quad (2)$$

where the superscript prime (') denotes the instantaneous fluctuations. Using Eqs (1) and (2), one gets

$$\frac{C_{Drms}}{C_{Dmean}} = \frac{F_{Drms}}{F_{Dmean}} \quad (3)$$

where $C_{Drms} = \sqrt{C_D'^2}$ and $F_{Drms} = \sqrt{F_D'^2}$ are the root-mean-square (rms) values. The other rms variables of interest include h_{rms} used for quantifying flow depth fluctuations, and u_{rms} and v_{rms} for quantifying streamwise and lateral velocity fluctuations. The variations of F_{Drms} , C_{Drms} , h_{rms} and u_{rms} with flow conditions are discussed in the following sections. The relationship among the various rms parameters is also of the authors' interest; however it cannot be fully explored in this study as the experiments were conducted in two flumes.

Results

Reynolds number serves as an important parameter to study the variation of the drag acting on an isolated cylinder (Kundu and Cohen 2002). Similar variations and the Reynolds number dependence could be expected in the presence of the cylinder array as considered in this study. To characterize the flow through the cylinders, the average pore velocity (V_{Vmean}) is used to define the Reynolds number as $R_D = V_{Vmean}d/\nu$. In the following, variations of the normalized parameters including F_{Drms}/F_{Dmean} , u_{rms}/V_{Vmean} and h_{rms}/h_{mean} with R_D are examined.

Drag fluctuation

With the data obtained in this study, the normalized drag fluctuation F_{Drms}/F_{Dmean} (or drag coefficient fluctuation C_{Drms}/C_{Dmean}) is plotted against R_D in Fig. 5. The value of F_{Drms}/F_{Dmean} for group C30 is about 0.1. It reaches as high as 1.33 for C90 when R_D equals 1006, and reduces to around 0.20 with R_D greater than 1063. Significant fluctuations (mostly above 40%) were observed for C60 and C90 for $R_D = 373 - 1063$. The high values of F_{Drms}/F_{Dmean} could be caused by the occurrence of resonance when the frequency of vortex shedding approximately equals that of low mode lateral standing waves (Tinoco and Cowen 2013). In the presence of multiple cylinders, the study of normalized rms drag is limited [e.g., Stoesser et al. (2010) and Tinoco and Cowen (2013)]. Thus this study introduced the values reported for a single isolated cylinder to illustrate the significance of present fluctuations. The results reported in the literature (Zdravkovich 1997; Sumer and Fredsøe 2006) show that C_{Drms} is about 0.05 for R_D in the range of $7 \times 10^3 - 1 \times 10^7$. However, Mulcahy (1984) reported that $C_{Drms} = 0.25$ for R_D in the range 3×10^4 to 2×10^5 . The variation in the mean drag force could be caused by resonant cross flow oscillations, which is an important consequence of vortex shedding (Griffin 1984). For a given R_D , the mean drag coefficient C_{Dmean} for a single cylinder could be calculated using an empirical formula proposed by Cheng (2013). By normalizing C_{Drms} reported by Mulcahy (1984), Zdravkovich (1997) and Sumer and Fredsøe (2006) with the mean drag coefficient, it is obtained that C_{Drms}/C_{Dmean} varies from 0.02 to 0.18 for a single isolated cylinder at R_D in the range of $7 \times 10^3 - 1 \times 10^7$.

Velocity fluctuation

Fig. 6 shows typical distributions of the normalized streamwise rms velocity (u_{rms}/V_{Vmean}) along the wake axis for the three types of configuration at different R_D . The values in the blocked area (see Fig. 4) were obtained by extrapolating the downstream and upstream values and shown as markers with lines (see Fig. 6). Fig. 6 (a) shows the pattern of u_{rms}/V_{Vmean} for C30 with $R_D \sim 520 - 706$. The u_{rms}/V_{Vmean} appears to be minimum right downstream of a cylinder. As x/d increases, it gradually increases to a maximum value at $x/d \approx 1.5$, decreases until $x/d \approx 2.5$, and then starts to increase as flow approaches the downstream cylinder. Fig. 6 (b) shows how the pattern of u_{rms}/V_{Vmean} varies as the Reynolds number increases for configuration C60. When R_D is 373, the value of u_{rms}/V_{Vmean} is almost constant along the wake axis. For $R_D = 730$, a minimum u_{rms}/V_{Vmean} is found downstream of a cylinder. As x/d increases, u_{rms}/V_{Vmean} increases to a maximum value at about $x/d = 1.8$, and then starts to decrease until about a constant value of 0.2. For $R_D = 1018$, a maximum value occurs right downstream of a cylinder and it reduces rapidly to about 0.17 as $x/d \leq 2.7$, and then it remains almost constant. The pattern for $R_D = 1300$ is similar to that of $R_D = 730$. Fig. 6 (c) shows the distribution of u_{rms}/V_{Vmean} for C90. For $R_D = 771$ and 1006, a minimum value occurs behind a cylinder. It increases to a maximum value at about $x/d = 2$, and then it remains almost a constant value until $x/d \approx 9$. Then it starts to decrease as it approaches the downstream cylinder. For $R_D = 1518$, as x/d increases, u_{rms}/V_{Vmean} rapidly reduces from the maximum near the cylinder to a constant value at about $x/d = 2$. When $R_D = 2005$, the value of u_{rms}/V_{Vmean} varies slightly along the wake axis.

Next, the normalized rms streamwise and lateral velocities, u_{rms}/V_{Vmean} and v_{rms}/V_{Vmean} are spatially averaged. They are denoted by $\langle u_{rms} \rangle / V_{Vmean}$ and $\langle v_{rms} \rangle / V_{Vmean}$ respectively and shown in Fig. 7. The values of $\langle v_{rms} \rangle / V_{Vmean}$ are generally higher than those

of $\langle u_{rms} \rangle / V_{Vmean}$. For example, $\langle u_{rms} \rangle / V_{Vmean}$ is about 0.2 while $\langle v_{rms} \rangle / V_{Vmean}$ is about 0.3 for C30. For C60, $\langle u_{rms} \rangle / V_{Vmean}$ is approximately 0.2 while $\langle v_{rms} \rangle / V_{Vmean}$ increases up to 0.5. For C90, both $\langle u_{rms} \rangle / V_{Vmean}$ and $\langle v_{rms} \rangle / V_{Vmean}$ are close at a level about 0.18. The presence of stems enhanced the lateral dispersion of dissolved and particulate material by meandering the path of fluid particles and by enhancing turbulence intensity (Tanino and Nepf 2008).

Turbulence kinetic energy (TKE)

In this study, the spatially averaged turbulence kinetic energy per unit mass due to turbulence can be calculated as $TKE = (\langle u_{rms} \rangle^2 + \langle v_{rms} \rangle^2 + \langle w_{rms} \rangle^2) / 2$, where $\langle w_{rms} \rangle$ is the spatial average of the vertical rms velocity. Because only two components could be captured using PIV technique, Zhu (2006) and Van Hout et al. (2007) used a 2D surrogate for the turbulent kinetic energy. Similarly in this study, $\langle u_{rms} \rangle$ and $\langle v_{rms} \rangle$ are available from the measured flow field, and the TKE for the horizontal plane is estimated as $TKE = (\langle u_{rms} \rangle^2 + \langle v_{rms} \rangle^2) / 2$. Furthermore, the calculated TKE could be normalized using V_{Vmean}^2 . The variation of TKE / V_{Vmean}^2 with R_D is shown in Fig. 8. The magnitude of TKE / V_{Vmean}^2 is about 0.08 for C30 with R_D in the range of 520 - 733; it varies from 0.053 to 0.148 for configuration C60 with R_D in the range of 373 - 1338; and from 0.020 to 0.038 for C90 with R_D in the range of 685 - 2005. The flow was slowed down by the associated energy losses due to the turbulence (Huthoff et al. 2007), which is effective for erosion control and turbidity removal.

Water surface elevation fluctuation

It was noted that during the experiments, standing waves occurred among the cylinder under some flow conditions. Similar surface fluctuation, its amplitude and the respective flow conditions have been reported by Zima and Ackermann (2002) and Ghomeshi et al. (2007). The water depth exhibits significant variance in the transverse direction. The probes installed at the different locations thus could record different amplitudes of the free-surface oscillation. Only the highest rms values were used to characterise the average free-surface fluctuations, since the maximum value of depth is to a certain degree reflecting the amplitude of surface fluctuation. Fig. 9 shows the variation of h_{rms} normalized by the average flow depth (h_{mean}) with R_D ranging from 278 to 2402. As R_D increases, h_{rms}/h_{mean} increases when $R_D < 600$. It reaches a peak about 0.06 at $R_D \approx 600-800$. It decreases when $R_D > 800$, and then tends to be a constant around 0.005 when $R_D > 2000$. The range of R_D related to the maximum values of h_{rms}/h_{mean} (see Fig. 9) coincides with that for the peak values of F_{Dms}/F_{Dmean} .

Discussion

For a single isolated cylinder subject to a cross flow, the drag force oscillates at a frequency which is twice that of the lateral force (Sumer and Fredsøe 2006). However, such a relationship becomes unclear for the case of multiple cylinders as observed in this study. We applied FFT analysis to the time series of the drag force recorded for all the runs in Flume A, but could not observe any dominant frequency for the drag force. This may be due to that each individual cylinder may experience a different instantaneous drag fluctuation, which may reduce or enhance the overall fluctuation of the drag recorded by the load cell.

The fluctuation of the lateral velocity is believed to be closely related to that of the lateral force and water surface elevation. To further understand how different fluctuating variables are related to each other, FFT techniques were applied to obtain the dominant frequency. For the tests conducted in Flume A, dominant frequencies (f) were clearly found for both the lateral force and lateral velocity for 44 runs. Similarly, we also found dominant frequencies for the water surface fluctuation for 27 runs of all the tests conducted in Flume B. The results expressed in terms of Strouhal number ($St=fd/V_{Vmean}$) are shown in Fig. 10. It seems that the normalized frequencies, though derived from the different time series, vary with R_D in a similar fashion. The value of St first decreases with increasing R_D when $R_D < 600$, and then increases when $R_D = 600 - 800$. It finally decreases to about 0.2 when $R_D > 1000$. In particular, it is noted that the variation of St has a transition at the Reynolds numbers ranging from 600 to 800. This is exactly the range where the maximum fluctuation occurs in the drag, velocity and flow depth. This affirms that the periodical and amplified fluctuation is strongly related with the vortex shedding. Further efforts should be made to explore flow phenomena including the vortex shedding and surface waves in the transition. These oscillations in water depth, velocity and turbulence have potential to create morphological features and improve fish habitat (Sadeque et al. 2009).

Conclusions

This study investigated the mean drag and its fluctuation that was experienced by an array of emergent rigid cylinders in an open channel flow. The rms drag was found to be significant (up to 133% of the mean drag) for the Reynolds number in the range of 400-1100. The drag fluctuation was closely related to the flow velocity, the flow depth and their

fluctuations. The observations show that high fluctuations also occur in the flow velocity and flow depth for the Reynolds number of the same range. Finally, the data analysis yields that consistent variations in the dominant frequency can be derived from the measured fluctuations in the lateral force, lateral velocity and flow depth.

List of Symbols

C_D = instantaneous drag coefficient

C_{Dmean} = average drag coefficient

C_D' = drag coefficient fluctuation

C_{Drms} = rms of C_D'

d = cylinder diameter

f = frequency

F_D = instantaneous drag

F_{Dmean} = average drag

F_D' = drag fluctuation

F_{Drms} = rms of F_D'

F_X = force on cylinder in x direction

F_Y = force on cylinder in y direction

h = instantaneous flow depth

h_{mean} = average flow depth

h' = flow depth fluctuation

h_{rms} = rms of h'

Q_{mean} = average flowrate

R_D = cylinder Reynolds number = $V_{Vmean}d/\nu$

S = channel bed slope

St = Strouhal number

u_{mean} = time-mean streamwise velocity

u_{rms} = rms of streamwise velocity fluctuation

$\langle u_{rms} \rangle$ = spatially averaged u_{rms}

$\langle v_{rms} \rangle$ = spatially averaged v_{rms}

V_{Vmean} = average pore velocity, $Q_{mean}/[Bh_{mean}(1-\lambda)]$

$\langle w_{rms} \rangle$ = spatially averaged w_{rms}

x = longitudinal direction

y = transverse direction

λ = vegetation density, percentage bed area occupied by cylinders

ρ = fluid density

ν = kinematic viscosity of fluid

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Table 1. Summary of flow conditions

Flume	Length x width (m x m)	Length covered by cylinders (m)	Group	Vegetation density	Number of Runs	Number of Runs with clear dominant frequency	Flow depth (cm)	Flowrate (L/s)	Slope	Cylinder Reynolds number	Froude number
Flume A Measurement of drag and flow velocity	5.00 x 0.308	3.90	C30	12.0%	20	12	6.40 - 9.40	1.10 - 2.20	0.0034 - 0.0073	520 - 733	0.07 - 0.10
			C60	3.0%	35	32	6.40 - 9.70	0.84 - 4.55	0.0009 - 0.0073	373 - 1338	0.06 - 0.19
			C90	1.3%	33	N.A.	6.30 - 9.70	1.78 - 6.78	0.0009 - 0.0072	685 - 2005	0.09 - 0.27
Flume B Measurement of free surface fluctuation	12.00 x 0.300	6.00	C30	12.0%	5	5	6.60 - 8.35	0.65 - 1.05	0.0004 - 0.0066	278 - 435	0.04 - 0.06
			C60	3.0%	20	18	6.80 - 9.00	0.85 - 4.38	0.0004 - 0.0102	341 - 1543	0.04 - 0.19
			C90	1.3%	9	4	6.20 - 9.10	2.86 - 6.58	0.0044 - 0.0102	1375 - 2402	0.20 - 0.32