

Entrainment of sediment particles by very large-scale motions

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1 Stereoscopic particle image velocimetry (PIV) configured in two orthogonal planes was
2 utilised to capture the flow structure at the instant of entrainment of spherical bed
3 particles in open-channel flow. Experiments were conducted with lightweight target
4 particles amongst a bed of coplanar fixed spheres with diameters of 16 mm. The protru-
5 sions of the target particles were set to give an average entrainment rate of $1/60\text{s}^{-1}$.
6 These protrusions were established from extensive initial experiments which utilised
7 an automated mechanism to place spheres on the bed of the flume and record the
8 time elapsed until they were entrained by the flow. The results showed that at lower
9 flow depth to particle diameter ratios, bed particles are more stable and require larger
10 protrusions to entrain at the same rate as at a larger depth. This effect is consistent with
11 observations of reduced velocity variance and reduced drag force variance for lower flow
12 submergences. The PIV measurements indicated that particle entrainment is associated
13 with very large-scale motions which extend up to 50 flow depths in the streamwise
14 direction. Contributions of smaller scale velocity and pressure spatial fluctuations are
15 suppressed by a spatial averaging effect related to the particle size, and a temporal
16 averaging effect related to the time taken to fully entrain a particle from its resting pocket.
17 These observations are relevant to sediment transport modelling. However, further data
18 are required to clarify the role of particle lift forces, and particle shape in the entrainment
19 process.

20 **Key words:**

21 1. Introduction

22 The interplay between turbulent flows and mobile beds is a classical problem related to
23 a number of practical engineering challenges including: the design of stable channels and
24 structures such as bridge piers; aquatic habitat management; and flood impact assessment
25 (e.g. Graf 1984; Raudkivi 1998; Nikora *et al.* 2012). Traditional methods of assessing
26 bed stability and transport rates such as Shields' (1936) threshold curve or Einstein's
27 (1950) stochastic approach result in large uncertainties when applied to field conditions.
28 One key constraint to developing refined sediment transport models is that the physical
29 mechanisms involved in the entrainment and motion of sediment particles are not yet
30 well understood at the scale of an individual grain. These mechanisms are the focus of
31 our study. Below we provide some pertinent background information starting with large
32 and very large scale turbulent motions which are likely to induce particle entrainment.

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1.1. Large- and very-large scale motions

Kim & Adrian (1999) identified that the pre-multiplied streamwise velocity spectra (kS_u , where k is wavenumber and S_u is streamwise velocity auto-spectra) in pipe flows had a bi-modal shape and referred to the structures contributing to the respective spectral peaks as large-scale-motions (LSMs) and very-large-scale motions (VLSMs). The bimodal spectral characteristic was subsequently identified also in boundary layer and closed-channel flows (e.g. Hutchins & Marusic 2007; Monty *et al.* 2009) and recently in open channel flows (Cameron *et al.* 2017). In the case of boundary-layer flows, VLSMs are typically referred to as ‘superstructures’ where they are thought to be confined to the logarithmic flow layer. In other flow types VLSMs can be identified throughout the whole flow domain. Kim & Adrian (1999) proposed that LSMs identified with streamwise wavelengths of 2-3 times the pipe radius were associated with packets of hairpin shaped vortices and that VLSMs that were found to extend 12-14 pipe radii resulted from the preferential alignment of several hairpin packets. Evidence from boundary-layer (Hutchins & Marusic 2007) and open-channel (Cameron *et al.* 2017) flow studies that VLSMs are associated with meandering depth-scale counter-rotating vortical structures, however, suggests a different formation mechanism, possibly associated with a flow instability (e.g. Hwang & Cossu 2010). Compared to pipe, channel, and boundary layer flows, the VLSMs identified in open channel flow appear to be much longer, often extending up to 50 flow depths in the streamwise direction, although the reasons for the scale difference is yet to be identified. Evidence of the existence of VLSMs in open-channel flows challenges the conventional assumption that the largest turbulent structures are just a few flow depths long (e.g. Nezu & Nakagawa 1993; Roy *et al.* 2004; Nezu 2005; Franca & Brocchini 2015). One reason that the presence of VLSMs in open-channels has been missed until recently is likely due to the fact that their reliable identification requires high-resolution and very long-term measurements (several hours for typical laboratory scale conditions), which were not possible previously. Nevertheless, there have been indirect circumstantial indications in a number of earlier studies reflecting the presence of VLSMs in open-channel flows (e.g. Zaitsev 1984; Grinvald & Nikora 1988; Franca & Lemmin 2005; Nezu 2005).

1.2. Origin and scales of drag forces acting on bed particles

Recent experiments (Cameron *et al.* 2019) demonstrated that the pre-multiplied frequency spectrum of drag force fluctuations (fS_D , where f is frequency and S_D is drag force auto-spectra) acting on spherical bed particles has a bimodal shape, with a low frequency peak corresponding to the presence of very-large-scale motions (VLSMs) in the flow, and a higher frequency peak corresponding to the action of turbulent pressure spatial fluctuations (figure 1a). The low frequency peak in figure 1(a) is sensitive to the particle protrusion (P) reflecting increased exposure of the particle to the flow. The high frequency peak, in contrast, is much less sensitive to P suggesting that the pressure fluctuations penetrate below the roughness tops exposing the full frontal area of the particle regardless of the protrusion. It is important to distinguish that the spatial pressure fluctuations referred to here are those that exist in the turbulent flow overlying a sediment particle rather than those that can be measured at the particle surface which result from the interaction of the flow field with the particle. The contribution of VLSMs and pressure spatial fluctuations to drag forces on particles was not previously recognised despite a number of studies exploring forces on sediments (e.g. Schmeeckle *et al.* 2007; Detert *et al.* 2010; Dwivedi *et al.* 2011a; Celik *et al.* 2014). Their contribution should be

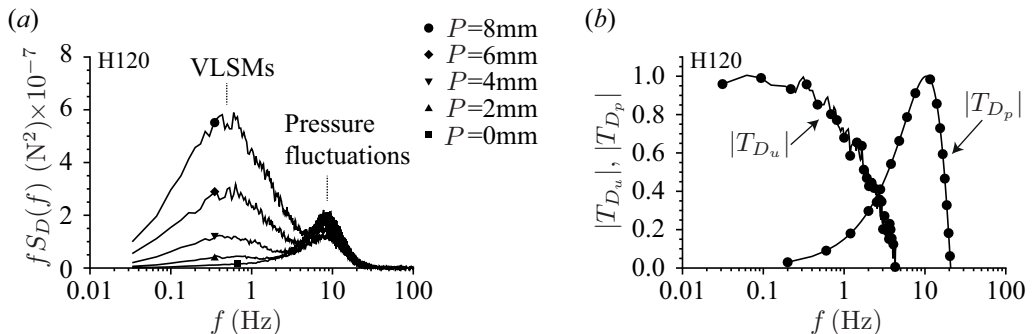


FIGURE 1. Pre-multiplied spectra of drag force fluctuations for different particle protrusions (a); and gain functions $|T_{D_u}|$ and $|T_{D_p}|$ (b).

80 incorporated into revised models coupling drag force fluctuations, velocity fluctuations,
 81 and pressure field fluctuations.

82 Assuming quasi-linearity in flow-particle interactions, low external noise, and negligible
 83 correlations between the local pressure and velocity fluctuations, it follows from the
 84 theory of random functions (e.g. Bendat & Piersol 2000) that the particle drag force
 85 spectra $S_D(f)$ can be approximated as a function of the fluid velocity spectra $S_u(f)$ and
 86 the fluid pressure spectra $S_p(f)$ at representative points near the particle as:

$$S_D(f) = \{\rho C_{D_u} A_u \bar{u}\}^2 |T_{D_u}(f)|^2 S_u(f) + \{C_{D_p} A_p\}^2 |T_{D_p}(f)|^2 S_p(f) \quad (1.1)$$

87 where ρ is the fluid density, C_{D_u} is a drag-velocity coefficient, A_u is exposed frontal
 88 area of the particle relevant to velocity fluctuations, \bar{u} is the mean streamwise velocity
 89 extracted from a point near the particle, $T_{D_u}(f)$ is the dimensionless drag-velocity
 90 frequency response function, C_{D_p} is a drag-pressure coefficient, A_p is the particle frontal
 91 area relevant to pressure fluctuations, and $T_{D_p}(f)$ is the dimensionless drag-pressure
 92 frequency response function. Equation 1.1 combines the leading-order terms contributing
 93 to the drag force spectra. In general, additional terms may be required to account for
 94 non-Gaussian velocity fluctuations, higher-order relationships between velocity and drag
 95 fluctuations (Dwivedi *et al.* 2010), correlations between pressure and velocity fluctuations
 96 (which are typically small due to the non-local property of pressure fluctuations, e.g.
 97 Tsinober 2001), and potentially other mechanisms contributing to the drag force. The
 98 reference location for the velocity and pressure signals should, in general, be not so close
 99 to the particle where the signals are modified by its presence (i.e., it should be outside
 100 the particle wake region) but not so far away from the particle for the correlation with
 101 the particle drag force to be lost. As a practical measure, Dwivedi *et al.* (2010) chose
 102 a reference point for the velocity field that maximised the correlation coefficient with
 103 the particle drag force. Cameron *et al.* (2019) adopted the same procedure which is
 104 also used here. The effective frontal areas A_u and A_p are not necessarily equivalent and
 105 reflect the respective distributions of velocity and pressure around the particle. The gain
 106 function $|T_{D_u}|$, i.e. the modulus of the complex valued frequency response function T_{D_u} ,
 107 is obtained from the velocity-drag cross-spectrum S_{uD} as:

$$|T_{D_u}| = \frac{1}{\rho C_{D_u} A_u \bar{u}} \frac{|S_{uD}|}{S_u} \quad (1.2)$$

108 with

$$S_{uD}(f) = \frac{1}{T} \int_0^T u(t_1) e^{i2\pi f t_1} dt_1 \int_0^T F_D(t_2) e^{-i2\pi f t_2} dt_2 \quad (1.3)$$

109 where $u(t_1)$ is the velocity time series, $F_D(t_2)$ is the drag force time series, T is the time
 110 span, and i is the imaginary unit. The function T_{D_u} reflects the averaging of small-scale
 111 velocity fluctuations over the spatial domain with volume comparable to the particle
 112 volume and is illustrated in figure 1(b) from the data presented in Cameron *et al.* (2019).
 113 The drag-pressure gain function $|T_{D_p}|$ is defined using the pressure-drag cross-spectrum
 114 S_{pD} as:

$$|T_{D_p}| = \frac{1}{C_{D_p} A_p} \frac{|S_{pD}|}{S_p} \quad (1.4)$$

115 with

$$S_{pD}(f) = \frac{1}{T} \int_0^T p(t_1) e^{i2\pi f t_1} dt_1 \int_0^T F_D(t_2) e^{-i2\pi f t_2} dt_2 \quad (1.5)$$

116 where $p(t_1)$ is the pressure time series. The function T_{D_p} acts as a differencing filter
 117 reflecting that the drag force is proportional to the pressure difference between up-
 118 stream and downstream particle faces. Data are not available yet to directly estimate
 119 $|T_{D_p}|$. Cameron *et al.* (2019), however, suggest that it is reasonably approximated by
 120 $|T_{D_p}| \approx \sin(\pi f D / u_c)$ which is plotted in figure 1(b), where u_c is the convection velocity
 121 of pressure fluctuations. Together, the gain functions T_{D_u} and T_{D_p} (figure 1) define the
 122 time scales of velocity and pressure fluctuations, respectively, that contribute to particle
 123 drag force and potentially entrainment.

124 Equation 1.1 can also be obtained by considering a time-domain parameterisation for
 125 the instantaneous drag force as:

$$F_D(t) = 0.5\rho C_{D_u} A_u [\dot{u}(t)]^2 + C_{D_p} A_p \Delta_p(t) \quad (1.6)$$

126 and following a derivation procedure similar to that used in Naudascher & Rockwell
 127 (1994) and (Dwivedi *et al.* 2010), where $\dot{u}(t)$ is the streamwise component of velocity near
 128 the particle after filtering to remove high frequency fluctuations that do not contribute
 129 to the drag force, and $\Delta_p(t)$ is the pressure difference in the flow above the particle at a
 130 streamwise separation equal to the particle diameter. Similar filtering of the streamwise
 131 velocity component has previously been proposed by Nelson *et al.* (1995) after identifying
 132 that low frequency velocity fluctuations were contributing a majority of the sediment
 133 transport. Such parametrisation of the drag force may be implemented in sediment
 134 transport models (e.g. Schmeeckle & Nelson 2003; Ancy *et al.* 2008; Ali & Dey 2016) to
 135 more accurately account for the scales of velocity fluctuations contributing to drag forces
 136 and incorporate the role of pressure spatial fluctuations. Insufficient data, however, are
 137 currently available to generalise the behaviour of A_u , A_p , C_{D_p} , C_{D_u} , $T_{D_u}(f)$, $T_{D_p}(f)$ and
 138 the pressure and velocity spectra ($S_p(f)$ and $S_u(f)$ respectively) over a range of flow-
 139 submergences (H/D where H is flow depth and D is particle diameter), particle Reynolds
 140 numbers ($D^+ = D u_* / \nu$ where u_* is shear velocity and ν is fluid kinematic viscosity),
 141 particle relative protrusions (P/D) and particle shapes.

142 Fluctuating lift forces on particles have proven more difficult to analyse than drag
 143 forces with Schmeeckle *et al.* (2007) and Dwivedi *et al.* (2011b) reporting poor correlation
 144 with the local streamwise or vertical fluid velocity. Hofland & Booij (2004) on the other
 145 hand found a relation between the vertical velocity component and lift, but this result

is likely uniquely related to their flat-topped particle with a single pressure sensor to approximate the lift force. Considering spatial fluctuations in the pressure field rather than the velocity field, Smart & Habersack (2007) proposed that lift forces generated by pressure fluctuations often exceeded particle weight forces and could cause particle entrainment. This role of spatial pressure fluctuations suggests that a modified version of equation 1.1 may also be applicable to parameterise particle lift forces.

Overall, the indications of figures 1(a) and 1(b) and the analysis of Cameron *et al.* (2019) are that as VLSMs contribute significantly to particle drag forces, they should also directly contribute to particle entrainment, particularly at larger protrusions. This hypothesis will be tested in this study using particle image velocimetry (PIV) recordings of the flow field leading up to, during, and after the instant of the entrainment of single spherical particles.

1.3. Objectives

The first objective of the study is to explore the relationship between drag force fluctuations and particle entrainment which is a key component of sediment transport models (e.g. Einstein 1950; Ancy *et al.* 2008). While it is straightforward to define a threshold entrainment condition where drag and lift forces are balanced by the particle weight and friction with the bed, it is known that the destabilising forces need to persist for sufficient duration to completely displace a particle from its resting pocket (e.g. Diplas *et al.* 2008; Celik *et al.* 2010; Valyrakis *et al.* 2010; Maldonado & de Almeida 2019). The cited authors identify the force impulse, i.e. the product of force and duration, as the key parameter characterising particle entrainment. Their studies, however, largely relate to the conditions of maximum particle protrusion, with single spherical particles overlying a co-planar spherical particle bed. We will, in this study, explore the relationship between drag force fluctuations and entrainment at low and intermediate particle protrusions ($P < 0.5D$). To do this we will compare mean waiting-times until entrainment estimated from drag force time series with those obtained from single particle entrainment experiments. The waiting-time is defined as the elapsed time before a resting particle is entrained by the flow. For independent entrainment events, the waiting-time is expected to follow an exponential distribution (e.g. Cinlar 2013) characterised by a single parameter, the entrainment rate λ_t where λ_t^{-1} is the mean waiting-time. For a given flow condition, the mean waiting-time is a function of the particle protrusion with increasing P expected to correspond to decreasing λ_t^{-1} . We can define the protrusion corresponding to a particular mean waiting-time as $P_{\lambda^{-1}}(D^+, \rho_s/\rho, H/D)$, where ρ_s is the particle density and ρ is the fluid density. In this study we will establish and utilise $P_{\lambda^{-1}} = P_{60}$, i.e. the protrusion corresponding to a mean waiting-time of 60 seconds, by recording waiting times for single particles over a range of ρ_s/ρ and H/D with constant D^+ . This first objective provides new information regarding interrelations between fluctuating drag and entrainment events and also underpins the PIV entrainment experiments.

The second objective of this study is to explore the relationship between the velocity field and particle entrainment events. To do this we used stereoscopic particle image velocimetry to record the velocity fields during entrainment events over a range of ρ_s/ρ and H/D . These experiments were conducted with particle protrusions that resulted in a standardised 60 second mean waiting time with $P = P_{60}$ which is the outcome of the first objective. Similar experiments have been conducted in the past focussing on single particles to identify ‘coherent structures’ responsible for entrainment (e.g. Hofland & Booij 2004; Dwivedi *et al.* 2011a; Wu & Shih 2012) along with more general studies of mobile beds (Sutherland 1967; Séchet & Le Guennec 1999). No convincing evidence has emerged that there is a dominant ‘coherent structure’ responsible for entrainment except

195 for the general observation that entrainment is correlated with ‘sweep’ events (i.e. with
 196 the streamwise velocity fluctuation greater than zero, and the vertical velocity fluctuation
 197 negative) which might be associated with Adrian’s (2007) type hairpin vortices. Hofland
 198 & Booij (2004) identified that ‘sweep’ events allowed the flow to penetrate deeper into
 199 the bed increasing drag forces on a cube shaped particle, while, at the same time,
 200 producing negative lift forces due the downward directed flow. Similarly, Sutherland
 201 (1967) hypothesised eddies that disrupted the viscous sublayer and directly impinged
 202 on the particle surface to be responsible for entrainment. Séchet & Le Guennec (1999)
 203 in contrast claimed a more significant contribution of low speed ‘ejection’ events. These
 204 studies, however, pre-date the observations of VLSPs in OCFs (Cameron *et al.* 2017),
 205 and it is timely to re-investigate this matter with specially targeted experiments, i.e. with
 206 multiple measurement plane orientations and with extended fields of view.

207 The structure of the paper is as follows. In §2 we describe the flow conditions and
 208 equipment used for two types of experiments: firstly to establish the mean waiting-time
 209 until entrainment across different flow depths and particle densities; and secondly to
 210 reveal the velocity field at the time of entrainment. In §3 we present our experimental
 211 results and in the final section we summarise our main findings.

212 2. Experimental setup

213 Experiments were conducted in the Aberdeen Open-Channel Facility (AOCF) using
 214 the same flow and bed conditions as in Cameron *et al.* (2017) and Cameron *et al.* (2019).
 215 The bed was made of a single layer of 16 mm diameter (D) glass spheres in a hexagonally
 216 close-packed arrangement. The flow depth (H) varied between 30 mm and 120 mm (table
 217 1) while adjusting the bed slope (S_0) to keep the shear velocity $u_* = \sqrt{gHS_0}$ constant,
 218 where g is acceleration due to gravity. The roughness Reynolds number $D^+ = Du_*/\nu$ was
 219 605 indicating fully-rough bed conditions. The flows were steady, uniform, and the large
 220 flow width to depth ratio ($B/H > 10$) ensured that the central region of the flow away
 221 from the sidewalls was fairly two-dimensional and generally free of secondary currents
 222 (Cameron *et al.* 2017). Target experiments for this study were conducted using flow
 223 conditions H030, H070, and H120 (table 1). The H050 and H095 flow parameters are
 224 retained in table 1 as we will re-use in our analysis some of the data from Cameron *et al.*
 225 (2017) and Cameron *et al.* (2019).

226 For this study we have performed two types of experiments: (1) waiting-time exper-
 227 iments to address the first objective (§1.3), and (2) synchronous stereoscopic particle
 228 image velocimetry (PIV) with entrainment of a single mobile particle to achieve the
 229 second objective. These are described below.

230 2.1. Waiting-time experiments

231 In order to measure the distribution of waiting-times until entrainment of individual
 232 particles, we constructed a computer-controlled device to automatically place a sphere
 233 onto the bed of the flume, record the time until it was entrained by the flow, and then load
 234 a new sphere. The time of entrainment of the target particle was determined by a fibre-
 235 coupled photo diode beneath the target sphere which indicated increased light intensity
 236 when the sphere was not present. The optical fibre was mounted inside a 1 mm diameter
 237 vertically-orientated steel tube which could be height adjusted to control the protrusion of
 238 the particle between $P=0$ (co-planar) and $P=0.5D$. For a given flow condition, the mean
 239 waiting-time is expected to decrease with increasing particle protrusion. We chose a target
 240 mean waiting-time of 60 s and performed experiments to establish the particle protrusion
 241 corresponding to this mean waiting-time (i.e. P_{60}). The 60 s period is somewhat arbitrary,

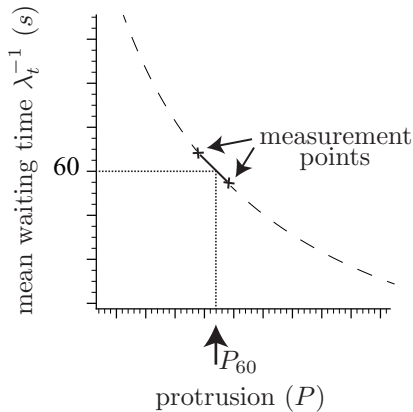


FIGURE 2. Illustration of how the protrusion P_{60} corresponding to a mean waiting time between entrainments of 60s is obtained.

242 but it needed to be long enough that it was possible to place the particle in a stable
 243 position on the bed, and short enough to allow a sufficient number of entrainment events
 244 to be captured.

245 Experiments were performed with spheres made of Nylon (‘N’) with a density of 1.12
 246 g/cm^3 and Delrin (‘D’) with a density of 1.38 g/cm^3 . We recorded the waiting-times for
 247 500 entrainment events with a protrusion resulting in a mean waiting-time of between
 248 40s and 60s and 500 events with a protrusion resulting in a mean waiting-time between
 249 60s and 80s. The protrusion for 60s mean waiting-time (P_{60}) was then calculated by
 250 linear interpolation of the mean waiting-time versus P curve (e.g. figure 2). Uncertainty
 251 in the estimation of P_{60} using this method was approximately ± 0.1 mm. This procedure
 252 was repeated for ‘N’ and ‘D’ spheres with flow conditions H030, H070, and H120 (table
 253 1).

2.2. Particle image velocimetry with a single mobile particle

255 To assess the flow structure at the instant of particle entrainment we have used
 256 stereoscopic PIV in two planes, ‘cross-flow’ and ‘streamwise’ (figure 3a). The ‘cross-flow’
 257 plane extended 320 mm in the transverse direction and was centred at the mid-point of
 258 the flume cross-section. The ‘streamwise’ plane extended 340 mm upstream of the target
 259 particle and 200 mm downstream, i.e. covering a total streamwise extent of 540 mm. Both
 260 configurations covered the flow region from the roughness tops to the water surface. The
 261 ‘cross-flow’ plane PIV configuration is equivalent to that reported in detail in Cameron
 262 *et al.* (2017) and Cameron *et al.* (2019). To setup the ‘streamwise’ plane we have re-
 263 orientated the light sheet to enter the water around 1 m downstream of the measurement
 264 area via an immersed 20 mm prism. The four cameras used for the ‘cross-flow’ plane
 265 were split into two groups of two cameras, with one group covering the upstream 270 mm
 266 and the other group covering the downstream 270 mm with a small overlap between
 267 the measuring regions of each group. The PIV processing algorithms and parameters
 268 were the same as those used in Cameron *et al.* (2017) and Cameron *et al.* (2019). For
 269 the ‘streamwise’ plane, the two subregions were combined in post-processing to create a
 270 seamless 540 mm wide measuring region.

271 We used the ‘cross-flow’ and ‘streamwise’ configurations to record 25 entrainment
 272 events for each of the ‘N’ and ‘D’ particles at their respective P_{60} protrusion with
 273 flow conditions H030, H070, and H120. In total we recorded 150 entrainment events
 274 with the ‘cross-flow’ configuration and 150 entrainment events with the ‘streamwise’

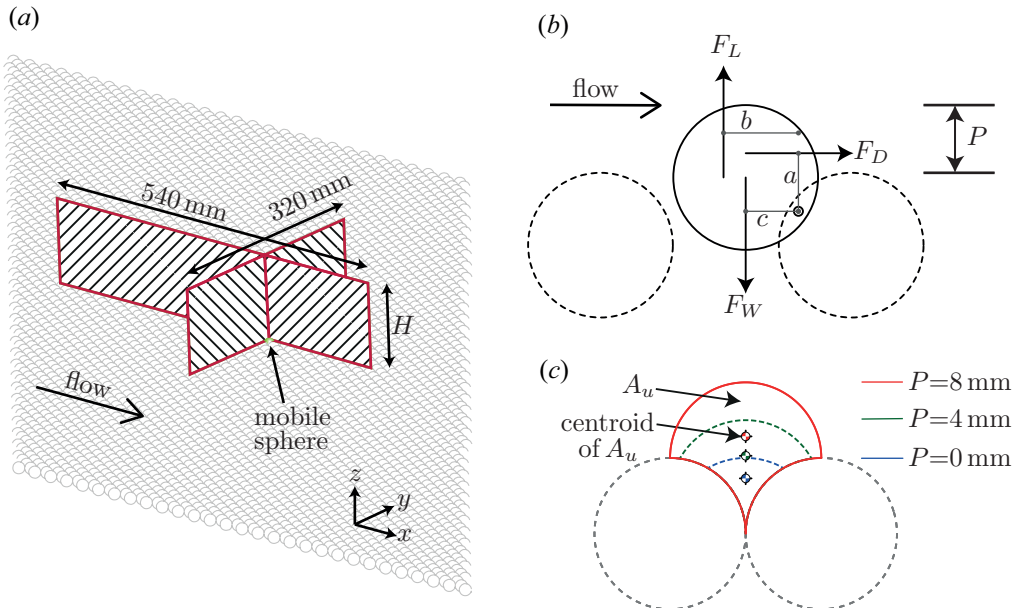


FIGURE 3. Transverse and streamwise PIV measurement planes relative to mobile sphere (a); forces and force lever arms acting on a sphere (b); and frontal area and centre of area for different particle protrusions (c).

RUN	H (mm)	Q (m ³ /s)	U (m/s)	S_0	u_* (m/s)	R	H^+	D^+	H/D	B/H	Fr
H030	30.1	0.0153	0.431	0.00600	0.042	11700	1140	605	1.9	39.2	0.79
H050	50.3	0.0275	0.463	0.00360	0.042	21000	1900	605	3.1	23.5	0.66
H070	70.5	0.0404	0.486	0.00257	0.042	30800	2670	605	4.4	16.7	0.58
H095	94.9	0.0569	0.508	0.00189	0.042	43400	3590	605	5.9	12.4	0.53
H120	120.1	0.0745	0.526	0.00150	0.042	56900	4540	605	7.5	9.8	0.48

TABLE 1. Flow conditions for the experiments. H is flow depth above the roughness tops, $B=1180$ mm is channel width, $D=16$ mm is particle diameter, Q is flowrate, S_0 is bed surface slope, $U=Q/BH$ is the bulk velocity, $u_*=\sqrt{gHS_0}$ is shear velocity, $R=UH/\nu$ is the bulk Reynolds number, $Fr=U/\sqrt{gH}$ is the Froude number, the + superscript denotes normalization with the viscous length scale ν/u_* , ν is fluid kinematic viscosity, and g is acceleration due to gravity.

275 configuration. The recording duration covered the 30 s prior to the entrainment time and
 276 5 s afterwards. The sampling frequency was 100 Hz, 50 Hz, and 32 Hz for H030, H070, and
 277 H120, respectively. Additionally, we used the ‘streamwise’ configuration with a fixed coplanar
 278 bed and a recording duration of 10 minutes to measure directly the wavenumber
 279 velocity spectra for the H030, H070, and H120 flows. This data are reported in §3.1.

280 3. Results

281

3.1. Background flow statistics

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283

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As reported in Cameron *et al.* (2017), the double-averaged (in time and in space) streamwise velocity $\langle \bar{u} \rangle$ for the studied flow conditions exhibits a logarithmic scaling range for elevations $0.5D < z < 0.5H$, despite the small relative submergence (H/D). The

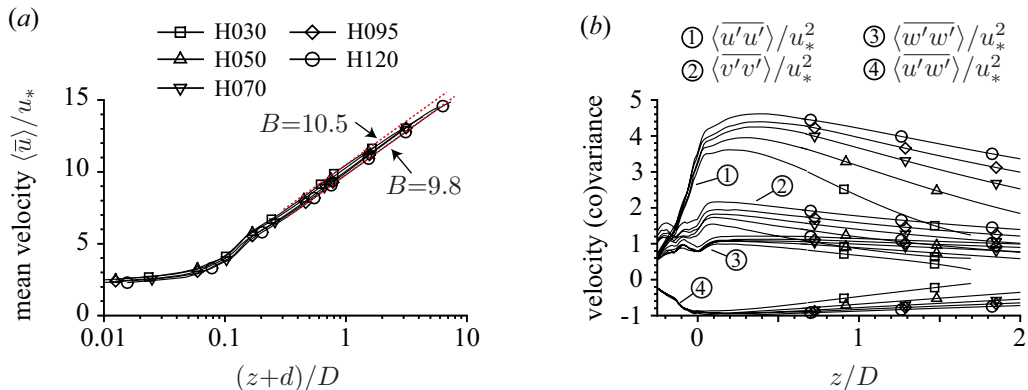


FIGURE 4. Mean velocity (a) and velocity variance (b). The roughness tops are at $z=0$ while the dashed lines in (a) are the log law with $\kappa=0.38$, $d=1.7$ mm and offset B as indicated, u' , v' , and w' are streamwise, transverse, and vertical velocity fluctuations, respectively. Angular brackets define spatial averaging and overbar defines time averaging.

285 von Kàrmàn constant κ was found to be 0.38 with a zero-plane displacement $d \approx 1.7$ mm,
 286 i.e., the ‘virtual bed’ is just below the roughness tops which are at $z=0$. Both the von
 287 Kàrmàn constant and the zero-plane displacement appeared to be only very weakly
 288 dependent on the relative submergence. Figure 4(a) shows that the additive term B in
 289 the logarithmic law

$$\frac{\langle \bar{u} \rangle}{u_*} = \frac{1}{\kappa} \ln \left(\frac{z+d}{D} \right) + B \quad (3.1)$$

290 increases from $B=9.8$ for H120 to $B=10.5$ for H030 as the relative submergence H/D
 291 decreases from 7.5 to 1.9 (table 1). Above $0.5H$, the velocity distributions deviate only
 292 slightly from the log law and are pseudo-logarithmic through most of the flow depth.
 293 Towards the bed, the velocity gradient increases and reaches a maximum near the
 294 roughness tops.

295 Second-order statistics (figure 4b) reveal a clear effect of decreasing streamwise velocity
 296 variance with decreasing relative submergence. We demonstrated in Cameron *et al.* (2019)
 297 that below the roughness tops the velocity variances tend to collapse as a function of z/D
 298 whereas in the outer flow the profiles converge if expressed as a function of z/H . Just
 299 above the roughness tops neither scaling holds and the velocity variances are a function of
 300 H/D . Higher-order statistics, two-point correlation functions and pre-multiplied spectra
 301 for these flow conditions are reported in Cameron *et al.* (2017).

302 The ‘streamwise’ plane PIV measurements described in §2.2 permit estimates of
 303 velocity spectra directly in the wave-number domain, compared to the approximation
 304 of applying Taylor’s hypothesis to frequency domain measurements in Cameron *et al.*
 305 (2017). Therefore it is worth re-examining velocity spectra with this new data, particu-
 306 larly given its relationship to the drag force spectra (i.e. equation 1.1). The PIV window
 307 size is not sufficiently large to directly resolve VLSMs. However, the directly-measured
 308 wavenumber spectra extend to higher wavenumbers ($k=2\pi/\lambda$, where λ is wavelength)
 309 compared to the frequency domain based estimates. Figures 5 and 6 therefore report
 310 hybrid spectra, via frequency domain using Cameron *et al.*’s (2017) data for $k < 50 \text{ m}^{-1}$
 311 and direct wavenumber spectra estimates using newly collected data for $k > 50 \text{ m}^{-1}$.

312 Near-bed streamwise velocity spectra S_u are expected to collapse across two ranges
 313 of the normalised wavenumbers (kz) with $S_u \propto (kz)^{-1}$ for the ‘-1’ scale range and
 314 $S_u \propto (kz)^{-5/3}$ for inertial subrange scales (e.g. Perry *et al.* 1987; Raupach *et al.* 1991;

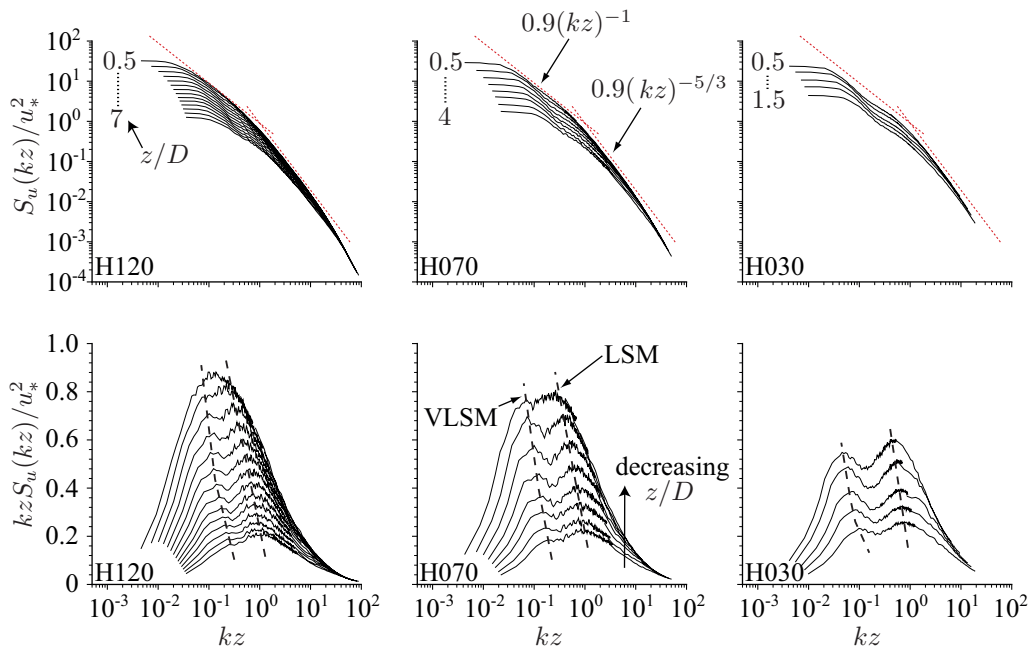


FIGURE 5. Auto-spectra (top row) and pre-multiplied auto-spectra (bottom row) of streamwise velocity fluctuations at different elevations. Red dashed lines are the scaling ranges of Nikora & Goring (2000).

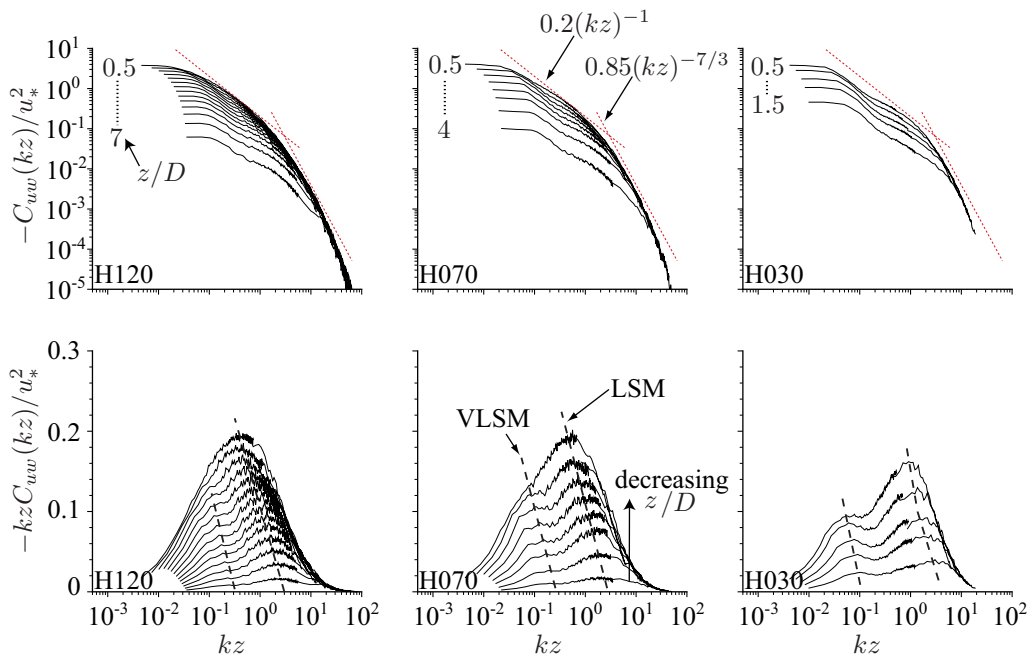


FIGURE 6. Co-spectra (top row) and pre-multiplied co-spectra (bottom row) of streamwise-vertical velocity fluctuations at different elevations. Red dashed lines are the scaling ranges of Nikora & Goring (2000).

315 Nikora & Goring 2000). Similarly, the co-spectra $-C_{uw}$ are expected to exhibit analogous
 316 ranges where $-C_{uw} \propto (kz)^{-1}$ and $-C_{uw} \propto (kz)^{-7/3}$. Figures 5 and 6 suggest that for the
 317 studied flows the Reynolds number is not high enough to support an extended inertial
 318 subrange, while the small relative submergence restricts the extent of the ‘-1’ range.
 319 Nevertheless, for H120 our data approach the $\propto kz^{-1}$ trend reported in Nikora & Goring
 320 (2000) for high Reynolds number field experiments ($R=200\,000 - 780\,000$) which is
 321 marked by dashed lines in figures 5 and 6. For H070 and H030 the measured spectra
 322 and co-spectra drop below the Nikora & Goring (2000) trend in the ‘-1’ range consistent
 323 with the submergence effect identified for the streamwise velocity variance. The kink
 324 in the spectra at low wavenumbers due to VLMSs becomes clearer with decreasing
 325 submergence and the pre-multiplied spectra $kzS_u(kz)$ reveal the expected bi-modal
 326 shape. It is interesting to note in the H120 case that near-bed ‘-1’ scaling appears
 327 to co-exist with VLMSs in the higher flow layers. This corresponds to the apparent
 328 bifurcation in spectra $kS_u(k)/u_* = f(\lambda/H, z/H)$ reported in Cameron *et al.* (2017) and
 329 also seen in figure 5 where the pre-multiplied spectra transitions from having a single
 330 peak near the bed to a bi-modal shape at larger elevations. For all flows, the measured
 331 spectra are somewhat below the Nikora & Goring (2000) trend for the inertial range
 332 in high-Re open channel flow. This may result from the lower Reynolds number of our
 333 laboratory experiments. It is interesting to note from the pre-multiplied spectra (figure
 334 5 and 6) that VLMSs contribute substantially (approaching 40%) to the streamwise
 335 velocity variance, but slightly less to the Reynolds stress (approximately 30%). Below
 336 $0.5D$ the velocity variance is spatially heterogeneous and dominated by wake regions
 337 behind individual roughness elements (e.g. Cameron *et al.* 2019). Velocity spectra in
 338 the range of $z < 0.5D$ are therefore highly dependent on the roughness geometry, and it
 339 is unlikely that any universal scaling of the spectra for this range of elevations can be
 340 defined.

341

3.2. Mean waiting-time

342 The protrusion corresponding to a mean waiting-time until entrainment of 60 s (i.e.
 343 P_{60}) is plotted against the flow depth for the Nylon ‘N’ and Delrin ‘D’ spheres in figure 7
 344 (circle and square symbols, respectively). As described in §2.1, P_{60} for each configuration
 345 was estimated based on 1000 timed entrainment events. The ‘N’ spheres were found
 346 to entrain with a protrusion of ≈ 2 mm while the higher density ‘D’ spheres required
 347 protrusions of 6–7 mm. For both sphere materials, particles have higher stability at lower
 348 submergences and thus require larger protrusions to entrain at the same rate as at larger
 349 depths. This is consistent with the observation that the near-bed streamwise velocity
 350 variance and the drag force variance decrease as the flow depth is reduced (Cameron
 351 *et al.* 2019).

352 The P_{60} versus H curve can also be estimated using the 90 minute duration drag force
 353 time series for fixed particles from Cameron *et al.* (2019) which cover the parameter space
 354 $P=0-8$ mm and $H=30-120$ mm. To do this, we solve the moment balance equation for
 355 near horizontal beds $aF_{Dc} + bF_{Lc} - cF_W = 0$ (figure 3b) for F_{Dc} and count the number
 356 of independent events in the time series with recorded force greater than F_{Dc} , subject
 357 to a minimum event duration t_c (figure 7b). Here F_{Dc} is the critical drag force on the
 358 particle, F_{Lc} is the critical lift force, $F_W = g(\rho_s - \rho)\pi D^3/6$ is the immersed weight force,
 359 a is the drag force lever arm, b is the lift force lever, and c is the weight lever. Lift
 360 force measurements are not available for these conditions so we set $F_{Lc} = 0$. The lever
 361 arms a and c were calculated such that F_{Dc} and F_W passed through the frontal area
 362 centroid (figure 3c) and the volumetric centre of the particle, respectively. The result of
 363 this procedure is the surface of mean waiting-time in the plane (P, H) for a given t_c and

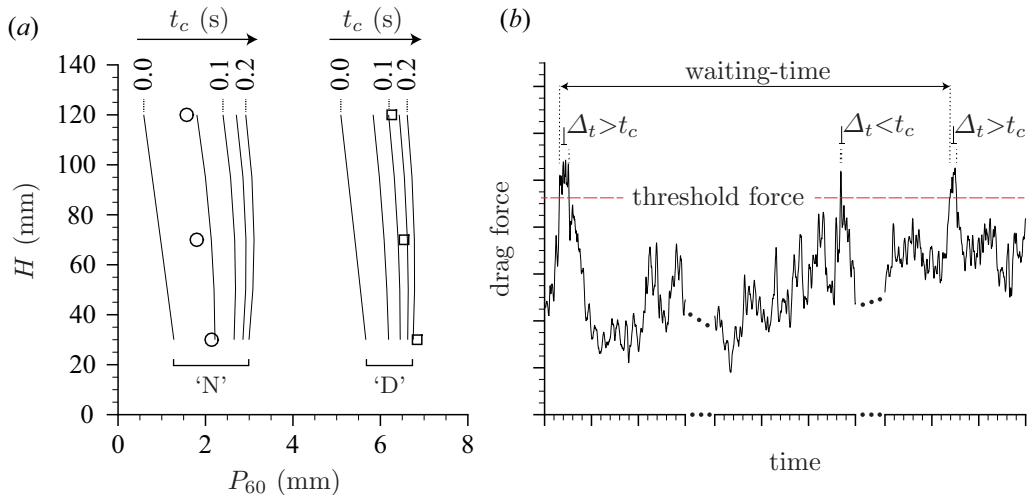


FIGURE 7. (a) Protrusion (P_{60}) corresponding to an entrainment rate of $1/60$ s for Nylon ‘N’ and Delrin ‘D’ spheres for different flow depths (symbols). Solid lines in (a) are P_{60} inferred from drag force time series where entrainment events are defined as shown in (b) by the drag force exceeding a threshold force for a duration (Δt) exceeding a critical duration (t_c). Drag force time series data were taken from Cameron *et al.* (2019).

364 ρ_s . It is then straight-forward to extract the contour of 60 s mean waiting-time which is
 365 shown in figure 7. We have chosen to use a minimum event duration threshold t_c in this
 366 analysis instead of a minimum force impulse threshold (e.g. Celik *et al.* 2010) because
 367 physical values of t_c are easier to interpret in the context of turbulence scales, i.e., figures
 368 1, 5, and 6.

369 It is immediately clear that for a minimum event duration threshold equal to zero
 370 (i.e. $t_c=0$), P_{60} is underestimated compared to the single particle entrainment data, even
 371 without considering potential contributions from the lift force. For ‘N’ spheres, the single
 372 particle entrainment data correspond to t_c of approximately 0.05s, while for ‘D’ spheres
 373 the required event duration is around 0.1-0.2s. It seems reasonable that the ‘N’ spheres
 374 entrain with shorter event durations, as due to their lower density they can accelerate
 375 faster in response to an unbalanced force and therefore fully entrain in a shorter time.
 376 Although figure 7 indicates that the critical event duration t_c increases with decreasing
 377 submergence, i.e from 0.1s for H120 to 0.2s for H030 with ‘D’ spheres, it is not clear
 378 why. It may be the result of submergence effects on turbulence scales and energy (figure
 379 5) or the potential role of the lift force which was neglected in this analysis.

380 3.3. Ensemble average flow field

381 Ensemble average velocity fluctuation fields at the time of particle entrainment were
 382 estimated as

$$\hat{u}_i' = \frac{1}{N} \sum_{n=1}^N u_{i_n}(x, y, z, t=t_n) - \bar{u}(x, y, z) \quad (3.2)$$

383 where $u_{i_n}(x, y, z, t)$ is the velocity field for the n th repeated experiment, t_n is the time
 384 corresponding to the start of particle motion in the n th ensemble and $N=25$ is the number
 385 of repeated experiments for each flow condition and particle protrusion. Averaging in
 386 this way preserves flow features that are common across repeated entrainment events
 387 while suppressing random deviations from the common pattern. It is important to note
 388 that the ensemble average of velocity fluctuation fields sampled at random times (i.e.

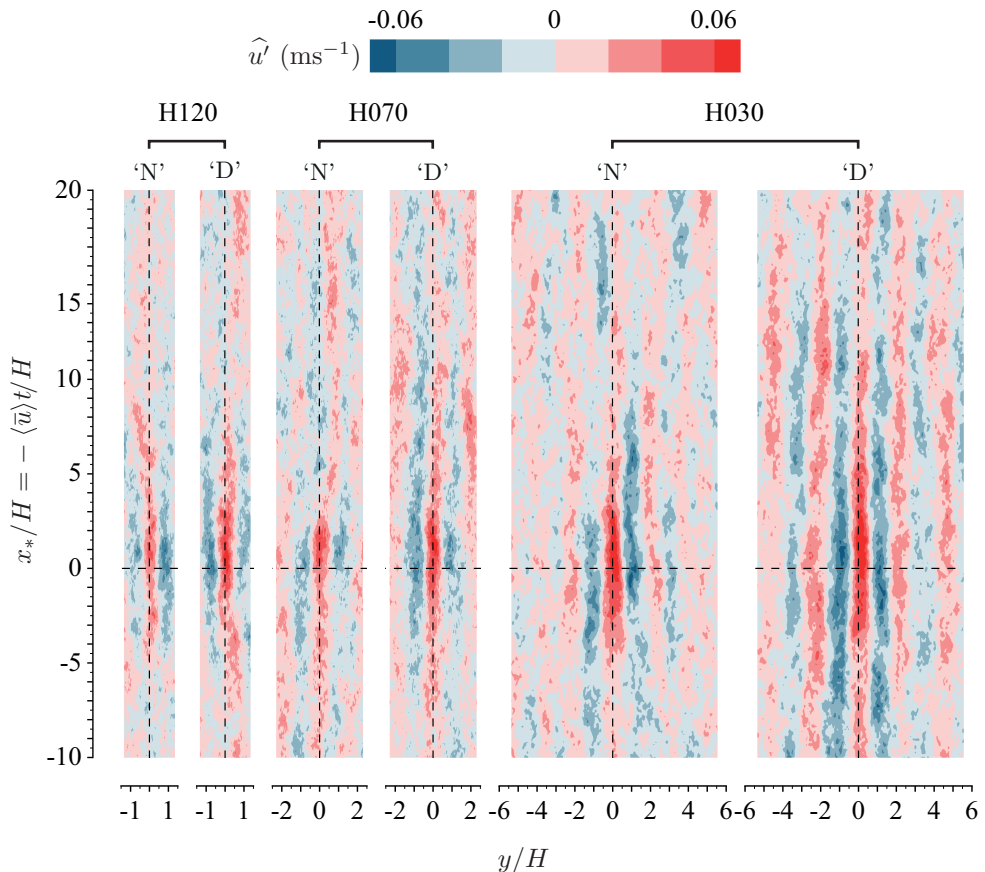


FIGURE 8. Ensemble average of streamwise velocity fluctuation at $z/H=0.5$ at time of entrainment. Mobile particle is at $x_*/H=0$, $y/H=0$.

389 replacing t_n in equation 3.2 with a random time coordinate) converges to zero. Therefore,
 390 non-zero values of \widehat{u}'_i can be interpreted as the flow structures associated with (or
 391 causing) particle entrainment. Such ensemble averaged flow fields are reported in figures
 392 8 to 10 for the $i=1$ streamwise component. The ‘cross-flow’ (figure 9) and ‘streamwise’
 393 (figure 10) planes were recorded directly, however, the bed-parallel plane (figure 8) is a
 394 reconstruction from velocity time series before and after entrainment using a convection
 395 velocity equal to $\langle \bar{u} \rangle(z)$. The ensemble average fields were calculated from 25 recorded
 396 entrainment events at the P_{60} protrusion for each flow condition and particle density.
 397 Due to the relatively small number of events contributing to the ensemble average,
 398 some patchiness is evident in the \widehat{u}' contours. Nevertheless, the elongated streaks of
 399 alternating high and low momentum fluid with $2H$ transverse period (figure 8) clearly
 400 indicate that VLSMs are the key contributor to the ensemble average. Compared to the
 401 instantaneous velocity fluctuation fields reported in Cameron *et al.* (2017), the \widehat{u}' fields
 402 are smoother and the meandering characteristic of the VLSMs is suppressed due to the
 403 ensemble averaging. The alternating streaks for the high protrusion Delrin (‘D’) particles
 404 appear to be better defined compared to the low protrusion Nylon (‘N’) cases. This effect
 405 may reflect the observation that VLSMs contribute less to the particle drag force (and
 406 therefore entrainment) as the protrusion is reduced (figure 1a) and the higher frequency

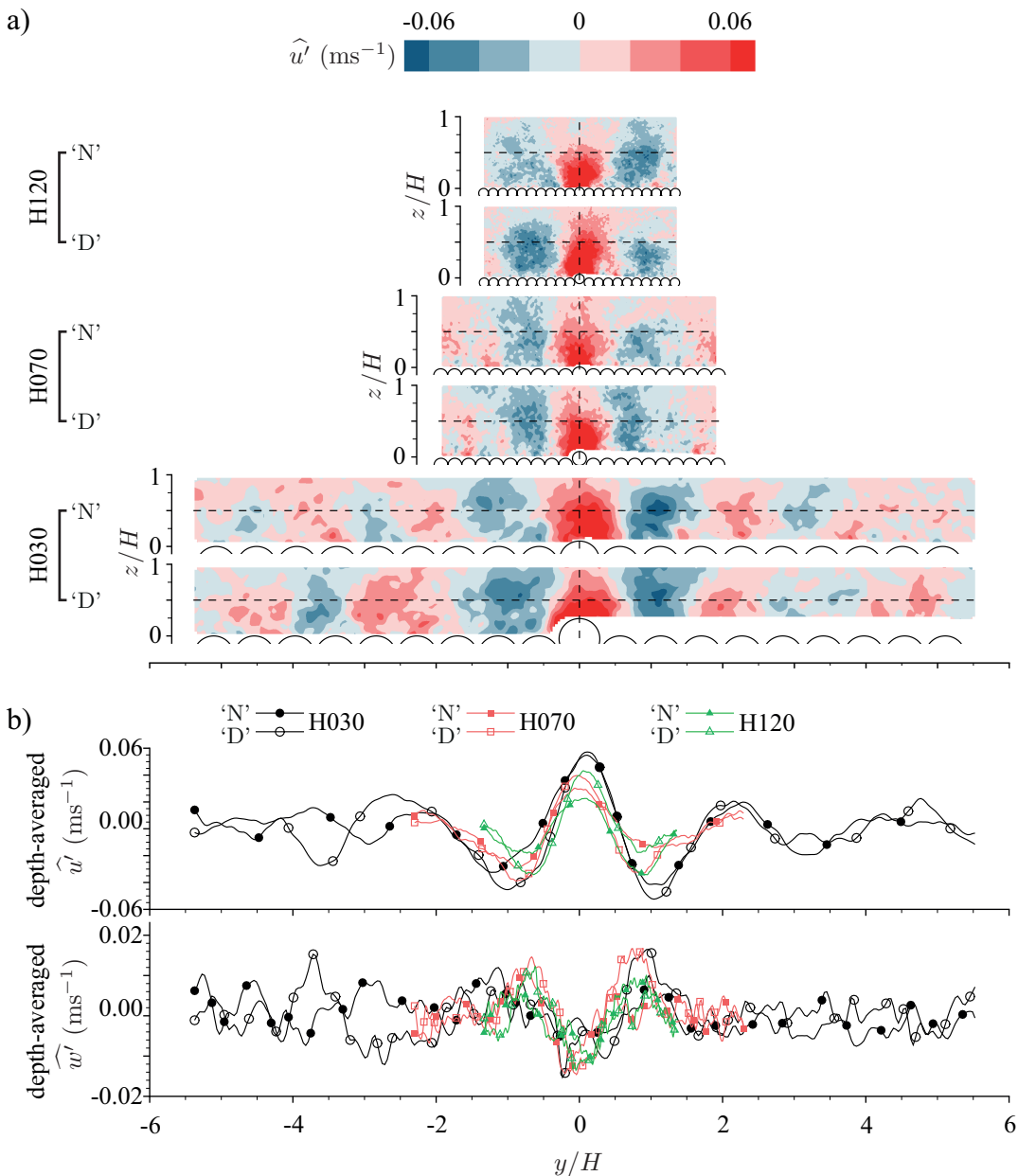


FIGURE 9. Ensemble average of streamwise velocity fluctuation in the transverse plane at time of entrainment (a), and depth averaged velocity fluctuation at time of entrainment (b).

407 pressure fluctuations due to the passage of smaller scale structures become relatively
 408 more important (Cameron *et al.* 2019).

409 Figure 9(a) indicates that the VLSMs occupy near the entire flow depth from the
 410 roughness tops to the water surface such that the transverse periodicity of the velocity
 411 fluctuation is preserved after depth averaging (figure 9b). Figure 9b indicates that the
 412 transverse wavelength of the fluctuations is close to $2H$ for H030, but narrows slightly as
 413 the flow depth is increased to H120. A similar shortening of the transverse wavelength of

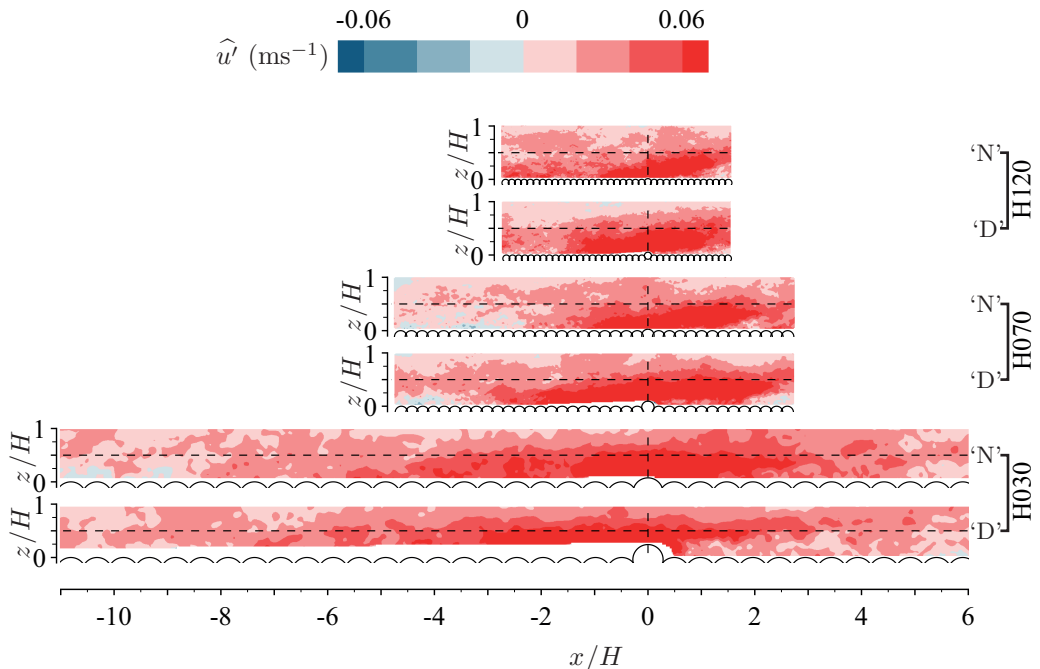


FIGURE 10. Ensemble average of streamwise velocity fluctuation in the streamwise plane at time of entrainment. Flow is from left to right.

414 VLSMs with increasing relative submergence was also noted in Cameron *et al.* (2017), but
 415 the origin of the effect is not yet known. Figure 9(b) also shows the depth average of the
 416 ensemble averaged vertical velocity fluctuation. Although the vertical velocity component
 417 is quite small and therefore not as well resolved in the ensemble average as the streamwise
 418 velocity component, a clear downflow region aligned with particle is seen, with upflow
 419 regions to the sides aligned with the zones of low streamwise momentum. This result
 420 is consistent with the depth-scale counter-rotating vortical structure of VLSMs (e.g.
 421 Hutchins & Marusic 2007; Cameron *et al.* 2017).

422 Figure 10 shows that the \hat{u}' contours are inclined with respect to the bed. This
 423 inclination likely results from the mean shear stretching the flow features as they evolve.
 424 At the instant of entrainment the target particle is immersed in the high velocity region
 425 of the VLSM where the drag force is maximised. For H030 the VLSMs appear longer in
 426 terms of flow depths compared to H070 and H120 consistent with the scaling noted in
 427 Cameron *et al.* (2017).

428 The role of VLSMs in the particle entrainment process identified in figures 8 to
 429 10 is consistent with previous indications (Cameron *et al.* 2019) that they contribute
 430 significantly to drag force fluctuations. In general, we can identify two reasons why
 431 very large scale structures are favoured. Firstly, the contribution of small-scale velocity
 432 fluctuations to the drag force are suppressed by averaging over the spatial domain
 433 with volume comparable to the particle volume. This is described by the gain function
 434 $|T_{D_u}|$ (equation 1.1, figure 1b). Secondly, the minimum force event duration (t_c) to
 435 completely entrain a particle acts as an additional filter, suppressing the contribution
 436 of higher frequency drag force fluctuations. For example, with a t_c of 0.1-0.2s for ‘D’
 437 particles (figure 7), the ≈ 10 Hz drag force fluctuations (figure 1a) that relate to pressure
 438 spatial fluctuations in the overlying turbulent flow, likely contribute very little to particle

439 entrainment. For the ‘N’ spheres, however, with a t_c of ≈ 0.05 s, and reduced sensitivity
440 of the drag force to VLSMs at the lower protrusion (figure 1a), the ≈ 10 Hz pressure
441 spatial fluctuations may play a more important role. Further data are required, with
442 direct measurements of turbulent pressure fluctuations to confirm their contribution to
443 particle entrainment.

444 3.4. *Instantaneous flow field*

445 In addition to the ensemble average velocity fluctuation fields, we have explored the
446 instantaneous fields for each of the 300 recorded entrainment events for evidence of
447 smaller scale ‘coherent structures’ contributing to entrainment. At the studied Reynolds
448 numbers, however, the instantaneous fields appear as a random collection of vortices
449 with different scales and orientations. It appears unlikely that any particular structure of
450 analytical value relevant to sediment transport could be extracted. This, however, might
451 be reviewed when high resolution volumetric data become available.

452 4. Conclusions

453 The ensemble average of velocity fields corresponding to the instant of particle en-
454 trainment demonstrate that sediment transport is strongly linked to VLSMs in the flow.
455 In particular, entrainment of single spherical particles occurs when the high momentum
456 region of a VLSM overlays a particle. Pressure spatial fluctuations which lead to a ≈ 10 Hz
457 peak in pre-multiplied drag force spectra may also contribute to particle entrainment.
458 This is particularly true for particles with small protrusion which have reduced exposure
459 to the VLSMs. The contribution of small-scale velocity fluctuations is suppressed by a
460 spatial averaging effect associated with the particle size. Furthermore, drag and lift force
461 fluctuations need to persist for sufficient duration to completely entrain a particle from
462 its resting cavity. This minimum event duration limits the contribution of high frequency
463 force fluctuations to the entrainment process. A relative submergence effect is seen in
464 entrainment rate data which indicates that particle stability increases with decreasing
465 flow depth under constant shear velocity conditions. This effect is also seen in the drag
466 force variance and likely relates to suppression of the large scale turbulence due to the
467 limited separation between flow depth and roughness length scales. Further data are
468 required to extend these observations to a wider range of relative flow submergence and
469 particle Reynolds number, and to ascertain the potential role of particle lift forces which
470 is still unclear.

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478 Declaration of Interests

479 The authors report no conflict of interest.

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