Instantaneous pressure measurements on a spherical grain under threshold flow conditions

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The aim of this investigation was to experimentally examine the surface pressures and resulting forces on an individual sediment grain whose size is comparable to the scales of the turbulent channel flow in an effort to discern details of the flow/grain interaction. This was accomplished by measuring the pressure fluctuations on the surface of a coarse, fully exposed, spherical grain resting upon a bed of identical grains in open channel turbulent flow. This spherical particle was instrumented with low-range, high-frequency-response pressure transducers to measure the individual surface pressures simultaneously on its front, back, top and bottom. The local flow velocity was measured synchronously with a laser Doppler velocimeter. The flow and sediment are near threshold conditions for entrainment with the channel and particle Reynolds numbers varying between 31000–39000 and 330–440 respectively. The emphasis was on determining the characteristics of the flow field with the potential to dislodge a spherical grain under uniform flow conditions as well as in the wake of a circular cylinder placed spanwise across the flow in otherwise fully developed open channel flow. It is concluded that the streamwise velocity near the bed is most directly related to those force events (and associated individual surface pressure distributions) crucial for particle entrainment. The lift force was observed to momentarily reach values which can be consequential for particle stability, although it is poorly correlated with the fluctuating normal velocity component. Turbulence intensity near the bed, rather than being the causative factor for increased force fluctuations, was shown to be an indicator of changes in the average lift force experienced by the grain during the application of extreme drag forces, at least for this particular flow condition (the upstream, spanwise-mounted circular cylinder). This effect is known to alter the sediment transport rates significantly. The characteristics of the temporal durations of flow events about the local maxima in the stagnation pressure, drag and lift forces, using a conditional sampling method, revealed the prevalence of sweep-type near-bed flow events in generating favourable conditions for particle dislodgement, although the dominant feature is the positive streamwise velocity fluctuation, not the normal velocity component. The duration of such events was the highest in the fourth and first quadrants in the $u, w$ plane, inducing high impulses on the grain.

\textbf{Key words:} River dynamics, Sediment transport, Particle/fluid flow

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1. Introduction

Sediment transport by water flow is a complex stochastic phenomenon that determines the morphological development of river beds, estuaries, wetlands and coastal areas. The flow condition at which sporadic movement of bed sediment just begins to occur is referred to as the incipient or threshold condition. This condition defines the stability of movable beds. In channel flow, near threshold conditions, the time-averaged hydrodynamic forces are not large enough to cause entrainment of sediment grains. Under these conditions, however, movement of individual particles is still observed (Paintal 1971; Hofland 2005). In an effort to resolve this apparent paradox, many researchers have advocated that the cause of particle entrainment is the peak fluctuating hydrodynamic forces acting on the sediment bed as a result of turbulence (Kalinske 1947; Einstein & El-Samni 1949; Sutherland 1967; Heathershaw & Thorne 1985; Kirchner et al. 1990; Nelson et al. 1995; Sumer et al. 2003). On the other hand, more recent findings have provided evidence that not only the magnitude of the peak turbulent forces acting on individual grains but their durations as well have to be considered for determining the incipient conditions for a given bed material size and configuration (Diplas et al. 2008; Celik et al. 2010; Valyrakis et al. 2010).

Incipient motion models, regardless of the framework utilized (e.g. impulse, force or moment balance), require knowledge of the actual instantaneous local forces acting on the grains, their relation with near-bed turbulence patterns and their temporal variations for accurate predictions of the threshold of sediment movement from the bed. Einstein & El-Samni (1949) stated that two possible approaches could be used to obtain the hydrodynamic forces. One is to solve for the flow field over the bed surface and to employ statistical tools to calculate the turbulence-generated forces on the bed material. Although there are numerical models for solving the governing equations over a fully rough bed (Stoesser, Frohlich & Rodi 2007; Zeng et al. 2008; Derksen & Larsen 2011), full resolution of the forces at realistic Reynolds numbers is not yet achievable. The second approach is to measure directly the forces or pressures acting on individual bed particles. However, because of the experimental difficulties involved, such direct measurements are uncommon.

It is well known that the turbulent flow field at a particular location and the resulting forces acting on the particles are heavily influenced by the upstream and the local bed structure (Bushnell & McGinley 1989; Schmeectle & Nelson 2003; Hofland, Booij & Battjes 2005). It is also expected that the probability of entrainment of a mobile grain will change accordingly when the flow field is altered. Celik et al. (2010) showed that the frequency of bed particle entrainment at low mobility conditions is extremely sensitive to minute changes in flow parameters, such as the mean bed shear stress and also to the particle configuration (which pertains to the resistance to motion) under uniform flow conditions. A significant change in sediment movement rate was observed not only as a result of such manipulations in uniform flow conditions but for unsteady flow conditions as well. Nelson et al. (1995) and Sumer et al. (2003) reported a considerable increase in the bedload transport under unsteady flow conditions, where the flow field was altered using various methods. They attributed the enhanced bedload transport to the increased turbulence intensity near the bed.

Bed materials, natural and artificial, consisting of sediment of various sizes and shapes, have been used in many flume studies to identify the threshold of particle movement (Papanicolaou et al. 2002; Hofland et al. 2005; Smart & Habersack 2007; Paiement-Paradis, Marquis & Roy 2010) and its relation to instantaneous force
values obtained from the near-bed velocity measurements. Separate pressure or force measurements on rough beds, though rare, are also available in the literature (Hofland et al. 2005; Schmeeckle, Nelson & Shreve 2007; Detert, Nikora & Jirka 2010a; Dwivedi, Melville & Shamseldin 2010a; Dwivedi et al. 2011) providing information on the link between the flow turbulence and hydrodynamic forces. In their numerical model of bedload transport, Schmeeckle & Nelson (2003) tried to incorporate the complex interaction of flow with individual spherical grains of various sizes by taking into account the instantaneous drag force acting on each grain. They concluded that the typical parameterizations of mean drag and lift forces were useful for bedload estimations but not sufficient, particularly of the lift, to accurately represent the actual instantaneous forces acting on the grains. They also suggested that the pressure fluctuations due to localized vortices which are advected by the near-bed flow affect the instantaneous forces significantly.

At high Reynolds numbers, it is reasonable to consider that the instantaneous drag and lift forces result from the pressure distribution over the entire surface of the grain. Therefore, such information is directly relevant to the movement of bed material. Hofland et al. (2005), Smart & Habersack (2007), Detert et al. (2010a), Dwivedi et al. (2010a) experimentally explored the role of fluctuating pressures on particle mobility near threshold flow conditions. Hofland et al. (2005) argued that the drag force, estimated using the measured horizontal pressure difference acting on a cubic particle, was correlated with both streamwise and vertical components of the near-bed flow velocity. They also reported the correlation between the degree of particle exposure and the pressures measured on it and the occurrence of overall favourable conditions for particle movement during sweep events. Although they did not measure the actual vertical pressure difference, Hofland et al. (2005) showed that the streamwise velocity fluctuations of low frequency coincided with high-frequency lift force fluctuations. Dwivedi et al. (2010a) measured both horizontal and vertical pressure differences on a spherical grain under threshold flow conditions and suggested the importance of sweep events in generating concurrently very high drag and lift forces. Dwivedi et al. (2010a) obtained the net vertical pressure from the difference between the pressure measured at the top of the test grain and a pressure sensor within the porous medium under the grain.

In another study, Dwivedi et al. (2010b) used quasi-steady theory to predict the drag force spectra. This approach had been used before by van Radecke & Schulz-DuBois (1988), Schmeeckle & Nelson (2003), Hofland et al. (2005). Hofland et al. (2005) suggested that the particle movement was initiated by a strong positive lift force followed by a sweep-like event giving the final push (possibly by a peak in the form drag) to the particle. Cameron (2006) in his experimental investigation reported similar observations and also strong accelerations in streamwise velocity following hairpin vortices near the bed just before the initiation of particle movement. It should be noted that the findings of Hofland et al. (2005) and Cameron (2006) were obtained near threshold flow conditions. In another experimental study Detert et al. (2010a) observed hairpin vortex packages with the potential to produce low-pressure zones on the uppermost layer of the sediment bed, extending 2–4 \( d \) in the streamwise direction near the rough wall; \( d \) is the diameter of the roughness elements. Smart & Habersack (2007) argued that localized vortices and the resulting peak lift forces acting on individual bed materials were the main causes for particle entrainment. These findings are, in general, consistent with the results obtained from a large number of studies concerning smooth and rough wall pressure fluctuations (an extensive review is provided by Robinson 1991).
The body of research on incipient motion is now extensive and the more recent work is revealing the characteristics of the fluctuating force on individual grains for both embedded and highly exposed cases. The most recent experimental investigations have emphasized the fluctuating drag and lift forces (or pressure differences associated with drag and lift), the corresponding drag and lift coefficients, spectra, and the possible connection between these and near-bed flow dynamics. The latter is accomplished by both qualitative examination of the flow field and concomitant statistical analysis. However, it has not been definitely established if specific flow structures are principally responsible for large force fluctuations and the details of the turbulent flow interaction with an individual grain have not been thoroughly investigated. In particular, how is the pressure distribution on a grain surface related to the flow structures advecting past the grain? In the present investigation we address this by examining the individual surface pressure time histories as well as the corresponding resulting lift and drag, simultaneously with the upstream velocity time history. What are the temporal characteristics of high force fluctuations? This is investigated here by measuring the temporal durations of the more extreme force fluctuations, simultaneously with their magnitude. It is clear from recent research that flows with higher turbulence intensity lead to significantly higher entrainment (even if the mean bed shear stress is unchanged). Is the intensity a surrogate for some underlying more physical and fundamental flow/grain interaction? This question is addressed by measuring the surface pressure time histories, corresponding forces and flow velocity time series in a high-turbulent-intensity environment induced by a spanwise-mounted circular cylinder located upstream of the instrumented grain.

The aim of this investigation is to experimentally examine the pressure distribution and resulting forces on an individual grain whose size is comparable to the scales of the turbulent flow in an effort to discern details of the flow/grain interaction and address these questions. This is accomplished by measuring the pressure fluctuations on the surface of a coarse spherical sediment grain resting upon a bed of identical grains in turbulent open channel flow. To examine the interaction between the flow and the surface pressures, the point-wise flow velocity is measured directly upstream of the grain and encoded simultaneously with the separate, local, surface pressure measurements. Because we are interested in fluctuating forces which could initiate sediment movement, the flow considered here is near the threshold condition for grain entrainment. We use two different flow configurations for this study: uniform, fully developed, open channel flow above a fully rough sediment bed, and in a separate series of experiments a circular cylinder (four different diameters are investigated) is mounted spanwise across the channel. These latter experiments were used to identify the role of externally imposed flow structures with enhanced flow turbulent intensity on the grain surface pressure characteristics and their influence on particle dislodgement.

The organization of this paper is as follows. In §2, we introduce in detail the experimental facility, the measurement methods employed here and their limitations. Section 3 presents the results. These are elaborated in five subsections. First, instantaneous pressure differences are used to determine the force fluctuations. Characteristics of the individual pressures that contribute to these forces are presented next. The third subsection focuses on identifying the deterministic and statistical relations between individual pressures and prevalent flow structures. To better understand the succession of peak lift and drag force events, ensemble-averaged samples conditioned about the peak events are considered here and an in-depth analysis of the duration of the impulsive force events concludes §3. Results
from the experiments with the spanwise-mounted circular cylinder are presented in each subsection along with those of the uniform flow results. All of these results are used to construct a model that describes the interaction between the flow characteristics and the erodible boundary and provides a more complete picture of the mechanism responsible for particle dislodgement under threshold conditions. Finally, the discussion and summary section, §4, reviews the overall findings of the present study.

2. Experiments

The experimental investigation was undertaken at the Baker Environmental Hydraulics Laboratory of Virginia Tech. A tilting flume, 14.4 m long, 0.6 m wide and 0.3 m deep, with Plexiglas sidewalls was used for the experiments. A Cartesian coordinate system \((x, y, z)\) where \(x\) is streamwise along the flume axis, \(y\) is spanwise across the flume, and \(z\) is perpendicular to the flume bottom was adopted in this study.

Three different reaches in the flume, characterized by different bed materials and/or grain sizes, were used. A top view sketch of these reaches is shown in figure 1. The first 10.4 m of the flume was covered with natural gravel \((d_{50} = 25 \text{ mm}, \text{where } d_{50} \text{ is the median sediment size})\). The next 1.5 m section was covered with three layers of glass beads with a diameter, \(d\), of 8 mm and a specific gravity of 2.54. The last 2.5 m reach near the flume exit was covered with two layers of 12.7 mm diameter glass beads (specific gravity 2.54). The thickness of material covering the flume bed was kept at an average level of 23 mm \((\pm 1 \text{ mm in the glass bead section and } \pm 3 \text{ mm at the natural gravel section})\) throughout the 14.4 m flume length. The bed slope was kept constant at 0.25\% throughout the experiments.

To avoid water surface drawdown near the flume exit and maintain uniform flow depth throughout the channel, steel rods with a diameter of 8 mm were placed at the downstream end of the flume (Balakrishnan 1997). The rods were mounted horizontally in rails installed near the tailgate structure. Flow discharge was controlled by a variable speed pump.

Pressure fluctuations on the surface of a spherical grain were measured using an in-house custom-designed fixture attached to the flume bed along its centreline. The fixture, located 1 m upstream from the flume exit and 3 m downstream of the transition between the natural sediment and well-packed bed of spherical beads, is an instrumented sphere, 12.7 mm in diameter, secured on top of three identical size base balls, arranged in a hexagonal densely packed structure, consistent with the surrounding bed grains (figure 2).
The fixture was designed, built and installed such that the tubing system for pressure measurements was completely hidden within the instrumented grain and supporting base structure as shown in figure 2(a). Solid brass spheres (deviation from spherical form: 0.005 mm, Small Parts Inc.) and brass tubes were fine-machined and used to construct the fixture. First, to form the instrumented sphere, a small spherical cap (3 mm height) was removed from one of the solid brass balls along a cutting plane (figure 2b). The interior of the remainder of the brass ball was machined out through this plane face. Pressure tap holes were drilled through the front (facing upstream), $p_1$, back, $p_2$, top, $p_3$, and bottom, $p_4$, of the instrumented sphere. The pairs $p_1$ and $p_2$, and $p_3$ and $p_4$, are opposite points through the centre of the sphere (i.e. antipodal points), so situated that a line drawn from one point to the other for each pair forms a straight line in the streamwise and vertical (stream-normal) directions respectively when the sphere is placed in the flume bed (figure 2c,d). The size of these holes matched the outer diameter of the brass tubing, which is 1.58 mm. The inner diameter of the brass tubing, and the pressure taps, is 1 mm. In addition, outlets with the same diameter as the outer diameter of the brass tubes were drilled through the points where the three supporting base brass balls would be in contact with the instrumented grain in a closely packed arrangement. Then the tubing was installed inside the instrumented grain (figure 2b). All four tubes for tap holes, $p_{1-4}$, exited the grain from the points where the supporting base grains were in contact with the instrumented particle.

With four tubes and only three supporting points, two of the tubes were passed through one contact point (see figure 2a,b). The interior of the instrumented grain (i.e. the gap between the tubes, see figure 2b) was filled with aluminum to support the tubes inside. A separate but precisely matching spherical cap was made and welded on to the plane face of the instrumented grain to complete the sphere. Tubes coming out of the pressure tap holes ($p_{1-4}$, figure 2b) were trimmed and the entire grain was smoothed for the final product to have a completely spherical outer surface as shown in figure 2(c).
The protruding tubes from under the instrumented grain passing through the contact points were passed through the interior of the supporting brass balls (figure 2a) through pre-machined holes. All four brass balls were then welded together at their natural contact points without introducing any blockage to the flow through the porous bed. The final design had one end of the brass tubing, the pressure taps (p1−4), flush with the surface of the instrumented sphere and the other end coming from underneath the supporting base spheres to be connected to the pressure transducers.

The configuration of the flume test section used here was identical to that of experiments described by Celik et al. (2010) that monitored the entrainment frequency of a mobile Teflon ball with a diameter of 12.7 mm, and a specific gravity of 2.3. Such simplified bed geometries, where a fully exposed spherical coarse grain is resting on densely packed identical size spheres have been used by other researchers in sediment transport research (Ling 1995; Papanicolaou et al. 2002; Cheng, Law & Lim 2003; Ancey et al. 2006).

2.1. Devices and methods used for experiments

We used four Honeywell Sensotec FP-2000 series gauge pressure transducers with a full-scale (FS) pressure range of 25.4 cm of water column (corresponding to 2450 N m$^{-2}$ and 5 V output), with 0.1% FS accuracy from a best-fit straight line for an operating temperature range between −40°C and 240°C, to measure the pressure fluctuations. Analogue voltage outputs from the pressure transducers were digitally sampled and recorded using a 16-bit data acquisition board (National Instruments – DAQPad-6015 with a SC-2345 series signal conditioning unit) and LabVIEW software. A resolution of 0.076 mV (0.038 N m$^{-2}$) is specified for the data acquisition board. Considering that the delay between each channel and the transfer time of a digital pressure signal from the data acquisition system to the computer was of the order of microseconds, there was negligible phase delay between the simultaneously measured pressure signals (p1−4).

Streamwise and vertical velocity components of the near-bed flow velocity, u and w respectively, were measured with a two-dimensional laser Doppler velocimeter (LDV) system operating in a direct back-scatter data acquisition mode. The ellipsoidal LDV measurement volume, with estimated dimensions of 100, 100 and 800 µm in the streamwise, vertical and spanwise directions respectively, was located one diameter upstream of the instrumented grain along its centreline. This location coincides with the x and z coordinates of the centre of the pressure taps in the front and back of the instrumented ball. A traverse system was used to systematically position the LDV measurement volume within the flume with an accuracy of 0.002 mm.

The LDV signal was digitally sampled and recorded using a TSI IFA 755 (burst correlator) signal analysis system. The error in the velocity measurements due to uncertainty in fringe spacing estimations was calculated to be no more than 1.5%. Average sampling frequencies for the flow velocity measurements varied between 250 and 700 Hz.

Separately measured pressure and velocity signals were synchronized as follows. A TSI DL-100 external input module, with a 16-bit analogue-to-digital converter and 50 kHz sampling frequency coupled and registered the analogue voltage output from one of the pressure transducers (p1) with valid LDV signals (u and w) during the signal acquisition process while the recording of pressure signals (p1−4) using the NI-DAQPad-6015 data acquisition board was performed in parallel. This arrangement enabled coupling the velocity and pressure signals (via p1) with a delay (due to the separate measurement chains) of less than 20 µs.
Flow depth measurements in the flume were obtained using metric rulers attached to the Plexiglas flume wall at several locations along the flume. The depth reported in this study was measured near the fixture at 2 min intervals over the 15 min sampling duration for each test. Other measurement locations were monitored during the tests to check the flow uniformity. The maximum error in an individual flow depth measurement was 0.5 mm. Average depth values over the sampling durations were used for the analysis. The next two sections describe the static calibration and dynamic performance tests of the pressure measurements.

2.2. Static calibration test
Pressure transducers were first calibrated under static loading conditions. This was achieved by recording the voltage output from each transducer under known static pressures using the 16-bit data acquisition board. The transducers were attached to the bottom of a Plexiglas box (25.4 cm × 25.4 cm × 30 cm) and the static calibration was performed over the range of 0 to 23.6 cm of water column by measuring the output voltage of the transducers corresponding to various water levels in the box. This box is shown in figure 3. Sampling rate and duration for individual static load tests were 250 Hz and 2 min respectively.

The pressure transducers we used exhibited an initial (zero gauge pressure) offset voltage. These inherent DC offset voltages were measured for each transducer before each static calibration and before each flume test. A representative DC offset level for a transducer (transducer 2 used for $p_2$) is shown in figure 4. The static calibration revealed a linear response with static calibration factors (mV cm$^{-1}$ of water column) for all transducers. Figure 4 gives the calibration data and the best-fit line. Compared to the results obtained from all the pressure transducers, this data set exhibits the maximum deviation from the best-fit straight line. The maximum residual error for transducer 2 was found to be 7.5 mV (0.38 mm of water column or 3.72 N m$^{-2}$)
which is 50% higher than the value of 5 mV reported in the transducer specification sheets (see inset in figure 4).

A change in the stagnation pressure of 3.72 N m$^{-2}$ corresponds to a 4% increase in the incident flow velocity. Experiments with various sizes of spherical mobile particles indicated that the flow velocity, measured one particle diameter upstream of the grain, may increase by more than 100% at the instants just prior to particle movement (Balakrishnan 1997). In addition, the vertical pressure difference that is necessary to overcome the submerged weight, $W_s$, of a 12.7 mm diameter Teflon grain is 108 N m$^{-2}$ (the critical pressure, from here on denoted by $\Delta p_{\text{crit}}$). This value (3.72 N m$^{-2}$) is 3.4% of $\Delta p_{\text{crit}}$ and 0.6% of the typical gauge pressure reading. More importantly, the standard error of the estimate from the regression analysis was found to be 1.05 N m$^{-2}$ and is considered to be the uncertainty for an individual pressure measurement in this study.

2.3. Dynamic performance test

We employed various brass tubing arrangements in our pressure measurement set-up to connect the pressure taps and transducers as shown in figure 2(a–c). Therefore, a dynamic performance test was necessary to evaluate the distortion, if any, in the pressure signal due to length of the tubes and bends. According to Yoshida, Tamura & Kurita (2001) the effect of bends in a tubing line on the pressure signal is negligible if the effective cross-sectional area of the tube at the bend zone is more than 50% of the original area of the straight tube. To avoid excessive crimping of the brass tubing we used a commercial tube bender. Although the length of tubing used between the pressure taps and the transducer sensing elements (one per sensor) varied slightly between taps, the overall length of the tubing did not exceed 10 cm.

A dynamic performance set-up similar to that reported by Yoshida et al. (2001) was used to test our transducers and the tubing system. The Plexiglas static calibration box

![Figure 4. Voltage output of the transducer with respect to the static load in terms of water column ($h$) above the transducers’ sensing element: data shown with cross symbols for transducer 2. The equation at the top represents the best-fit line. The inset is a magnification of the data point with maximum residual error (the open circle represents the value predicted by the best-fit-line equation). The horizontal line at the lower left corner shows the DC offset voltage level for this transducer.](image)
was modified and utilized for the dynamic performance tests (figure 3). This time we used a 25.4 cm diameter subwoofer and an amplifier to generate a fluctuating pressure field in the sealed box. The input to the subwoofer was white noise, generated by the MATLAB software (The MathWorks Inc.). The fixture was placed in the calibration box with a water level of 3.8 cm. To isolate the transducers from the vibrating Plexiglas box and test bench, the transducers were mounted on a separate supporting structure (see figure 3) that was fixed to the lab floor without any connection to the calibration test platform. Flexible Teflon tubing was used to securely attach the transducers to the brass tubes as shown in figure 3 to further reduce any vibration effects. The same arrangement was also used in the flume tests.

The top pressure tap ($p_3$) and corresponding transducer were used as the control for comparing the performance of the others. The bottom pressure tap ($p_4$) and connecting tubing were judged to be most susceptible to frequency distortion due to the necessary tight bend radius of the tubing designed within the instrumented fixture (figure 2a) and the length of the tubing. Since it was not possible to introduce a calibrated input pressure signal to the testing box, the signal from $p_3$ was used as the input (undistorted signal) and $p_4$ was treated as the output. The goal here with the dynamic performance tests was not to determine the frequency response of the transducers but rather to quantify the influence of tubing within the instrumented fixture on the measured pressure signals. That is, the calibration data provided by the manufacturer (indicating a flat frequency response up to 300 Hz) was used for all four transducers.

Nezu & Nakagawa (1993) suggest that the maximum response frequency, $f_{\text{max}}$, for turbulence measurements in channel flow should be at least as high as $(50/\pi)(U/h)$ in order to resolve flow structures down to the viscous sub-range. Here, $U$ is the cross-sectionally averaged velocity and $h$ is the flow depth (see table 1 for $U$ and $h$ values). $U$ was calculated from measurements of the volumetric flow rate, $Q$, via an air/water U-tube manometer connected to a Venturi meter in the inlet pipe line underneath the flume.

For the flow conditions used in our tests, the frequency up to which a flat response is required was obtained using Nezu & Nakagawa’s (1993) assumption and found to vary between 62 and 95 Hz. Approximate length scales of the flow structures that can be detected at such sampling frequencies are larger than 4.7–5.7 mm ($\approx U/f_{\text{max}}$). Given that the test particle diameter is 12.7 mm and the forces induced by flow structures smaller than the particle size are not significant (Schmeeckle et al. 2007), these length scales are large enough to estimate the important force fluctuations.

In order to determine the limitations in the pressure measurements due to tube bends, and the actual value of the maximum response frequency of the tubing system, the dynamic performance tests were performed using the test rig shown in figure 3. We used a sampling frequency of 1000 Hz and a sampling duration of 2 min in these tests. Subsequently, the transfer function between the two pressure signals measured at the top and bottom of the grain was estimated and the amplitude and phase plots (Bode plot) between the two signals are given in figure 5. It is indicated that the tubing effect is negligible up to at least 100 Hz, which satisfies Nezu & Nakagawa’s (1993) criterion.

2.4. Flume facility and pressure transducer interaction

Prior to the flume tests, a separate investigation was carried out to detect the natural frequency of the flume as well as the effect of flume pump operation on the pressure signals. Two Endevco, Isotron Model 50, single axis accelerometers (with 2–4000 Hz
frequency range, and a sensitivity of 50 mV g\(^{-1}\), where g is the acceleration due to gravity) were attached to the flume walls, one near the test section where the instrumented fixture was located, and the other 2 m upstream of the test section. The vibration levels in both spanwise and vertical directions were recorded by changing the orientation of the accelerometers for a variety of flume operating conditions. The results from this investigation indicate that the flume has a natural frequency of around 100 Hz (when there is no pump and flow activity). A second research flume located in the same room was found to have a similar natural frequency which might be an indication of a structural natural frequency.

The effect of the flume vibration due to the pump and the flow on the pressure signals was also investigated and found to be negligible as long as the transducers were fixed firmly but separate from the flume structure. This was confirmed by comparing simultaneous DC voltage readings (while the flume was running) obtained

| Run | \( U \) (m s\(^{-1}\)) | \( h \) (cm) | \( Re_\ast \) |
|-----|-----------------|--------|--------|
| A1  | 0.47            | 8.1    | 438    |
| A2  | 0.45            | 7.5    | 424    |
| A3  | 0.43            | 8.2    | 413    |
| A4  | 0.41            | 7.9    | 398    |
| A5  | 0.42            | 8.3    | 385    |
| A6  | 0.40            | 8.6    | 377    |
| A7  | 0.41            | 9.1    | 372    |
| A8  | 0.39            | 8.7    | 364    |
| A9  | 0.35            | 8.9    | 330    |
| UC  | 0.42            | 9.1    | 399    |

Table 1. Summary of the flow conditions. Note that the last row presents the undisturbed flow condition parameters for cylinder tests (UC) without the cylinder.
from a pressure transducer which was attached to a fixture separate from the flume to that of another transducer which was attached to the flume wall.

2.5. Summary of experiments

Experiments were performed using the bed configuration shown in figure 2 under (i) uniform flow conditions and (ii) in the wake of a cylinder positioned spanwise across the flow and located upstream of the particle. The following experimental procedure was repeated for each flow condition, after allowing the flume to run for an extended length of time prior to any measurements to establish stationary conditions. First, the point-wise flow velocity located one grain diameter upstream of the instrumented grain and along its centreline, and the four pressure signals were recorded simultaneously for the 15 min test duration. The sampling rate for the LDV and pressure signals was 250 Hz. At the completion of the run, velocity profile measurements from the bed surface to within 25 mm of the free surface were obtained, one diameter upstream of the target grain, via LDV. These profiles were then used to determine the friction velocity, \( u_* \), using the Clauser method (Song, Graf & Lemmin 1994).

Individual pressure signals were checked for drift after each run. The drift was found to be negligible in all cases. Based on the results from the investigations of measurement uncertainties presented earlier, all the pressure data from flume tests were first digitally filtered with a ninth-order Butterworth low-pass filter with a cut-off frequency of 90 Hz. This cut-off frequency is below the flume facility natural frequency of approximately 100 Hz, reported earlier.

The unevenly sampled LDV signal was linearly interpolated and re-sampled at 250 Hz to obtain pairs of synchronized pressure and velocity signals. Statistics of the (original) unevenly sampled and re-sampled velocity signals were compared and the influence of re-sampling on the velocity data statistics was found to be insignificant.

2.5.1. Experiments under uniform flow conditions

We conducted flume experiments under nine different uniform flow conditions. Table 1 gives a summary of the flow conditions tested. Presented parameters are \( U \), \( h \), and particle Reynolds number, \( Re_* = u_* d / \nu \), where \( \nu \) is the kinematic viscosity of water. These experiments matched the threshold conditions used in tests by Celik et al. (2010) for a Teflon ball at different levels of particle entrainment frequency. The turbulence intensity (TI) given by \( u'_r m s / \bar{u} \) was measured to be near 0.27 for all uniform flow experiments; here \( u'_r m s \) is the root mean square (r.m.s.) of the turbulent velocity fluctuations, \( u' \), where the prime denotes the fluctuating component obtained by Reynolds decomposition, and \( \bar{u} \) is the time average value of \( u \) measured near the instrumented grain via the LDV system (an overbar denotes time average of a parameter over the entire sampling duration). The integral length scale was estimated to be about twice the diameter of the test grain (estimated from the Eulerian integral time scale via the autocorrelation function of the streamwise velocity signal) and it did not vary in any appreciable way between the uniform flow cases.

2.5.2. Experiments in the wake of a cylinder

Bluff body wake flows are of interest in many branches of physics and engineering and have been studied extensively (see Williamson 1996 for a detailed review). The wake flow downstream of the bluff body is characterized by higher turbulence intensities and larger pressure fluctuations acting on the wall. In many practical river engineering applications, flow is altered due to presence of hydraulic structures. These conditions lead to a significant increase in sediment movement and result in
scour near these hydraulic structures in rivers and waterways (Sumer et al. 2003; Radspinner et al. 2010). Flow around and past pipelines, bridge piers and other in-stream structures are some examples. The purpose of the tests considered here was to examine if, and more precisely the way in which, the presence of a cylinder might influence the fluctuations of pressures acting on the instrumented grain in such high-turbulence-intensity, unsteady, wake flows.

The cylinder was placed horizontally and in a direction perpendicular to the flow, extending across the entire flume width upstream of the test section. Four different sized PVC pipes with diameters, $D$, of 33.4, 26.7, 21.9 and 12.7 mm were used, labelled D1–D4. Figure 6 shows the bed conditions with the cylinder. $X$ is the distance between the centre of the instrumented test grain and centreline of the cylinder in the streamwise direction, and $e$ is the distance between the bed (top of the spheres in the uppermost layer) and the cylinder; $e$ was set equal to $D$ for all four cylinder diameters to avoid suppression of the vortex shedding due to rough bed proximity (Sumer & Fredsoe 2006). $X$ was chosen to be $2.5D + 1.5d$ as this location was where the highest turbulence intensity (obtained from near-bed velocity measurements) was observed in preliminary flume tests. The presence of the cylinder in the flow increased the turbulence intensity at a location one diameter upstream of the instrumented particle (LDV measurement point shown in figure 6) by 35%, 51%, 57% and 14% for $D$ values of 33.4, 26.7, 21.9 and 12.7 mm respectively, compared to undisturbed flow condition tests (designated UC). The last row in table 1 summarizes the undisturbed flow conditions under which the cylinder tests were performed.

3. Results: analysis and interpretation

The results are presented in five subsections. The first three focus on the instantaneous forces, individual pressures and flow velocities while the last two focus on the flow events with high magnitudes and sufficient durations with a potential to completely dislodge a grain. The horizontal and vertical differences of the pressures ($p_1 - p_2$ and $p_4 - p_3$ respectively) as shown in figure 2 are referred to as drag and lift forces acting on the particle from here on for both instantaneous and conditionally sampled values.

3.1. Force magnitude results

Time series and probability density functions of surface pressure differences and fluctuating forces on submerged ‘grains’ have been reported by a number of research groups, particularly within the last few years. We contribute to those results in
this subsection through an investigation of the statistical relationships between the instantaneous lift and drag forces and the fluctuating upstream velocity components as well as the cross-correlation between the drag and lift forces themselves. Of particular interest is the role of the fluctuating normal component of velocity, \( w \), in determining these forces. Four time series were used for this purpose, \([p_1 - p_2](t)\) (i.e. drag), \([p_4 - p_3](t)\) (i.e. lift), \( u(t) \), and \( w(t) \).

Cross-correlation functions (CCF) were used to investigate the statistical similarities between two time series. The correlation coefficient at time lag \( \Delta t \), \( R_{ab}(\Delta t) \) between any two variables, \( a \) and \( b \) is given by:

\[
R_{ab}(\Delta t) = \frac{\sum \left( (a(t) - \bar{a})(b(t + \Delta t) - \bar{b}) \right)}{(N - 1)\sqrt{\sum (a(t) - \bar{a})^2} \sqrt{\sum (b(t + \Delta t) - \bar{b})^2}}
\]  

where \( N \) is the number of pairs of data \((a,b)\). A positive \( \Delta t \) in (3.1) implies that \( b \) values were measured at time \( \Delta t \) later than that of \( a \).

Figure 7 shows plots of CCFs between the flow velocity components and the drag force. Plots of CCFs between the flow velocity components and the lift force are given in figure 8. Similar patterns were observed in all uniform flow and cylinder test data, and therefore the statements made below apply to all. The strong and well-known dependence of the instantaneous drag force on \( u \) is apparent. On the other hand, there is a weak negative correlation between drag and \( w \). The instantaneous lift force is also positively correlated with \( u \) but the correlation is weaker \((R = 0.37, \text{figure 8})\) and there is also a weak negative correlation with \( w \). These findings in general do not support the models occasionally employed for the incipient motion criterion, where the instantaneous lift is functionally related to the square of the instantaneous wall-normal velocity component.

Figure 9 shows the CCF between the instantaneous drag and lift forces. The peak correlation is positive and relatively high, establishing a consistent statistical pattern between high drag and positive lift fluctuations. The strong correlations between fluctuations in \( u \) with drag and lift separately, and between lift and drag, suggest that for highly exposed grains as investigated in this study, positive fluctuations in drag
and lift are most strongly associated with the streamwise velocity. This is consistent with the bedload transport investigations of Heathershaw & Thorne (1985) and Nelson et al. (1995) in which strong correlations between fluctuations in downstream bedload and the streamwise velocity were observed. The relatively weak correlations with the wall-normal component, $w$, suggest that $w$ is not necessarily associated with the generation of the lift or drag fluctuations (again for such highly exposed grains), but rather that $u$ is most relevant and the weak correlation of the forces with $w$ is due to the negative correlation between $u$ and $w$ in the wall layer. That is, the relevant feature of sweeps for grain entrainment is the streamwise velocity, and the role of $w$ is largely incidental rather than fundamental.

The highest positive correlation between the fluctuating drag and lift forces in figure 9 occurs at $\Delta t = -0.012$ s ($R = 0.45$) with lift occurring prior to drag. However, a strong second relative maximum occurs at $\Delta t = +0.060$ s ($R = 0.42$) with
The histograms of the instantaneous lift force normalized with the critical pressure from runs UC and D1 (top, 3; bottom, 4).

Figure 10. The histograms of the instantaneous lift force normalized with the critical pressure from runs UC and D1 (top, 3; bottom, 4).

Lift following drag. The underlying pressure pattern responsible for this bimodal CCF is examined in §3.4 through conditional sampling and may be relevant to conditions favouring grain entrainment.

As stated previously, the CCFs are similar for both the uniform channel flow experiments and the experiments in the wake of a spanwise-mounted cylinder. The vortex shedding from the cylinder does affect the character of the CCFs but the general trends and conclusions are similar to those discussed above. However, the distribution of the lift is dramatically shifted when the cylinder is present. This is revealed in figure 10, where the histogram of the instantaneous lift force, \((p_4 - p_3 - \gamma \Delta z)/\Delta p_{\text{crit}}\) is shown for both the uniform channel flow without the cylinder, UC, and D1, the channel flow with the 33.4 mm diameter cylinder. Note that the vertical pressure difference excludes the hydrostatic pressure difference between the locations of \(p_4\) (bottom) and \(p_3\) (top, \(\gamma \Delta z\), where \(\gamma\) is the specific weight of water and \(\Delta z \approx d = 12.7\) mm) to eliminate the buoyancy effect. The lift is non-dimensionalized using \(\Delta p_{\text{crit}}\). We note that the time-average lift, taken over the entire duration of each run, varied among the uniform channel experiments from \(+0.5\%\) to \(-1.5\%\) of \(\Delta p_{\text{crit}}\) (series A1–A9, UC), but the instantaneous lift was observed on rare occasions reach as much as \(50\%\) of \(\Delta p_{\text{crit}}\). With the cylinder present, the mean lift increased significantly while the distribution is largely unchanged, with the result that fluctuations in the lift in the presence of the cylinder can reach \(80\%\) of \(\Delta p_{\text{crit}}\) (for the 33.4 mm diameter cylinder). As the diameter of the cylinder is reduced the lift distribution shifts toward the left in figure 10. Of course the high instantaneous lift episodes represent favourable conditions for grain movement as the effective submerged weight is reduced (reduced threshold of motion), perhaps in the presence of momentarily larger drag. Furthermore, the increase in the mean lift in the cylinder wake can dramatically affect the threshold of motion and greatly enhance the potential of grain entrainment (Celik et al. 2010). Thus, although the global characterization of the flow in the wake of the cylinder is one of dramatically higher turbulent intensity (not unlike the flow conditions studied by Nelson et al. 1995 and Sumer et al. 2003), the fluid dynamical effect is one of increased mean lift with fluctuations in the lift reaching nearly \(80\%\) of the critical level.

The drag and lift forces presented in this subsection were obtained from the time series of the separately but simultaneously measured instantaneous surface pressures.

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In the next subsection we examine the behaviour of these individual pressures, their statistical relation to one another and to the upstream flow velocity components. Correlations reveal time lags between peak correlations that are indicative of advecting pressure fields and are relevant to the forces exerted on the grain, their duration, and the potential to dislodge the grain.

### 3.2. Characteristics of the surface pressures

First we report the frequency distributions of the separate surface pressures. These distributions are qualitatively consistent with those reported by others (§1). The distributions of all four pressure signals were skewed as shown in the histograms of individual pressures, \( p_1-4 \), from run A2 in figure 11. It is shown that \( p_1 \) was positively skewed with skewness values varying between 0.74 and 0.83 for all runs performed under uniform flow conditions (A1–A9 and UC). This is in agreement with the findings of Hofland & Battjes (2006). The other three pressure signals were negatively skewed with skewness values consistently near \(-0.39, -0.36 \) and \(-0.33 \) for \( p_2, p_3 \) and \( p_4 \) respectively. Kurtosis values for the pressure signals \( p_2 \) and \( p_3 \) were near 3.1 which is close to the expected value for a normal distribution, while they were 3.7 and 3.8 for \( p_1 \) and \( p_4 \) showing a deviation from a normal distribution due to moderate tails for these two pressure signals. Maximum pressure variations (i.e. \( p'_{\text{max}} \) and \( p'_{\text{min}} \)) were observed to be 4.5 and 6.8 times the r.m.s. of fluctuations, \( p'_{\text{rms}} \) for \( p_1 \) and \( p_4 \) respectively. These findings imply that both \( p_1 \) and \( p_4 \), front and bottom, include in their tail region extreme values which can play a role in particle dislodgement by contributing to the very high-magnitude drag and lift forces reported previously.

The magnitude of the fluctuations in \( p_2, p_3 \) and \( p_4 \) are low compared to \( p_1 \). Among the former three, \( p_3 \) (top) exhibits the highest degree of fluctuations relative to \( p_2 \) (back) and \( p_4 \) (bottom) for both the uniform and cylinder wake flows. That is, \( p'_{\text{rms}} \) of \( p_1 \) was consistently larger than those of \( p_2, p_3 \), and \( p_4 \) by factors of 4, 3 and 5 respectively for the uniform flow conditions tested. The ratio of r.m.s. pressure fluctuations to the bed shear stress, \( \tau_0 \), with respect to particle Reynolds number is given in figure 12 for the nine uniform flow conditions (see also table 1). Shear stress values were calculated using \( \rho u^2 \), where \( \rho \) is the density of water. An average value of 3 for \( p'_{\text{rms}}/\tau_0 \) is reported in the literature for rough walls (Smart & Habersack 2007; Vollmer & Kleinhans 2007). In our experiments, we obtained values close to 3 only for \( p_2 \) and \( p_4 \) (back and bottom pressures respectively). For \( p_1 \) and \( p_3 \) this ratio

![Figure 11](image-url)
was near 18 and 7 respectively. Therefore \( p_1 \) and \( p_3 \) are expected to make the major contributions to the fluctuations of pressure forces acting on the grain. The very high values of \( p'_{rms}/\tau_0 \) for \( p_1 \) and \( p_3 \) also indicate the inadequacy of the approaches based on temporally and spatially averaged bed shear stress in describing the full range of flow-induced pressures and forces acting on fully exposed bed material.

It is expected that the increased turbulence intensity which occurs with the introduction of the spanwise-mounted circular cylinder would result in increases in the surface pressure fluctuations. This in fact was observed, although the time-average levels of the separate surface pressures were unchanged from those of the uniform flow case, UC. However, as anticipated, \( p'_{rms} \) values of all four pressures increased in the presence of the cylinder by a factor of 2 for all cylinder diameters tested. As shown in the previous subsection, these fluctuations cause lift force to attain instantaneously very high values and dramatic increases in bedload activity (Celik et al. 2010).

The ratios \( p'_{rms}/\tau_0 \) provide overall trends, but without any indication of the timing of the occurrence of the peak pressures at the various locations around the test particle. To better capture the statistical relationships among the surface pressures, we use the continuously and simultaneously recorded pressure time series to determine CCFs between pressure pairs. These records and the resulting cross-correlations between pressure pairs are presented next. The relative timing of occurrence of the four pressure contributions will allow a better understanding of the mechanisms responsible for particle dislodgement. It will also facilitate the development a connection between particle movement and relevant flow structures. Figure 13(a–f) shows the CCFs between individual pressures as a function of time lag. As the data from all runs under uniform flow conditions (A1–A9 and UC) exhibit similar behaviours, we present plots of CCFs between pressures from run A2 only.

The pressures \( p_1, p_2 \) and \( p_3 \) (front, back, and top) are well correlated with each other (figure 13a–c). In particular, a very significant correlation \((\sim 0.6, \Delta t = -30 \text{ ms})\) is obtained between the pressures on the top and back of the grain (figure 13c). This suggests that the flow processes causing high pressure fluctuations on top of the particle, via a Bernoulli effect for example, might also be responsible for similar pressure fluctuations at the rear of the sphere, at a slightly later instant (negative time lag). Considering the relatively high positive correlation between these pressures,
Figure 13. Cross-correlation functions between: (a) $p_1$ and $p_2$, (b) $p_1$ and $p_3$, (c) $p_2$ and $p_3$, (d) $p_1$ and $p_4$, (e) $p_2$ and $p_4$, and (f) $p_3$ and $p_4$, all from run A2 (front, 1; back, 2; top, 3; bottom, 4).

A decrease in pressure at the top of the grain is statistically consistent with a corresponding decrease in the base pressure (behind the grain). This finding explains the positive correlation between the drag and lift forces shown in figure 9. The time lag for maximum correlation is of the order of the mean advection velocity of the flow. Negative correlations shown in figure 13(a, b) are indicative of cases where an increase in $p_1$, stagnation pressure, in the front (with increase in streamwise velocity fluctuation) is observed before a decrease in the pressures on the top and back of the grain. The time lags associated with peak correlation between the front stagnation pressure and those on the top and in the base region (the rear of the grain) support the notion that the pressure distribution over the grain is influenced by advection of flow regions or structures, at least for flows such as this where the scales of the flow are comparable to the grain size.

Curiously, figure 13(e, f) shows that $p_2$ and $p_3$ which are highly correlated with $p_1$ are also correlated with $p_4$, although these correlations are not as strong as those shown in figure 13(a, b). On the other hand, there is little or no correlation between $p_1$ and $p_4$ (figure 13(d)). Smart & Habersack (2007) reported comparable findings between the pressures measured on top of a roughness element and within the natural gravel pore directly below. A possible explanation for this phenomenon is that the fluctuations of $p_1$ are dependent upon the structures of near-bed turbulent flow and the characteristic signature of these flow structures is filtered or suppressed in the pore flow underneath the particle where $p_4$ is measured.

Another observation is that the CCFs involving the pressure behind or on top of the grain exhibit two dominant peaks (i.e. figure 13a, b, f). The time lag between the peaks...
is of the order of 100 ms. Using Taylor’s hypothesis, this duration, together with the time-average near-bed velocity gives a length scale about twice the particle diameter. These length and time scales are too small to be linked to the largest eddies in the channel which are several times the flow depth in size in the streamwise direction (Shvidchenko & Pender 2001). On the other hand, the time lag between the peaks is too large to be associated with higher frequency particle-scale or smaller flow structures generated via vortex shedding by the roughness elements upstream of the grain or by the grain itself. Schmeeckle et al. (2007) argued that the particle-scale structures associated with the vortex shedding generated by the upstream grains do not influence the instantaneous forces acting on the test grain. In order to better explain the origin of the two relative maxima in the CCFs between the surface pressures, the CCF between lift and drag, as well as the time lag between the maxima, and their relevance to grain entrainment, we examine next the separate pressure time series with the simultaneously measured flow velocity time series.

3.3. Statistical relations between pressures and near-bed flow velocity

We first illustrate the qualitative relation between the velocity and pressure signals by showing the representative time histories of $u$, $w$ and the simultaneously measured pressures from run A2 in figure 14 and from the cylinder test with $D = 33.4$ mm in figure 15. A strong similarity in the temporal variations between $u$ and $p_1$ is observed in both figures 14 and 15. This is expected as $p_1$ is located at the stagnation point, and so anticipated to be closely related to $u^2$. In figure 14, a negative correlation is apparent between $p_1$ (as well as $u$, as will be shown later) and the pressure on top of the grain, $p_3$, and the pressure on the back of the grain, $p_2$, consistent with the results shown in figures 13(b) and 13(a) respectively. The time lag associated with
this negative correlation is large compared to the integral scale and is of the order of \( h/U (\sim 200 \text{ ms}) \). This negative correlation is however not evident in the cylinder tests (figure 15). A better assessment of the correlations is made using the CCFs.

Figure 16 presents the CCFs between \( u \) and the pressure signals for uniform flow conditions. The CCFs between \( w \) and the pressures for uniform flow conditions are shown in figure 17. According to the CCFs with respect to time lags shown in figure 16, \( p_2 \) and \( p_3 \) are negatively correlated with \( u \) while, as expected, \( p_1 \) has a strong positive correlation with \( u \). This finding is consistent with the negative correlation between \( p_1 \) and \( p_2 \) as well as \( p_1 \) and \( p_3 \) presented earlier (figure 13). Although the time lag for peak correlation between corresponding pressure fluctuations is relevant, these results suggest that a positive streamwise velocity fluctuation (\( u' > 0 \)) is associated with a positive fluctuation in the drag force and probably a concurrent positive lift fluctuation. It is emphasized however that time lag between the respective pressures will affect this general observation.

Figure 17 reveals a negative correlation between \( w \) and \( p_1 \); \( p_2 \) is also dependent, albeit weakly compared to \( p_1 \), on the vertical velocity (positive correlation). This indicates that, noting the positive correlation between \( u \) and \( p_1 \), during a sweep-like event (\( u' > 0, w' < 0 \)) when \( w \) is towards the bed and \( u \) is high, \( p_1 \) also has high values. This is accompanied by a decrease in \( p_2 \), the pressure on the back of the grain, together with the changes in \( p_1 \), implying a high drag force. When \( u \) is low and \( w \) is positive (ejection-like event with \( u' < 0, w' > 0 \)) there is a decrease in \( p_1 \) and an increase in \( p_2 \) (as a result of which, a lower value of drag force is expected). Note that the variability in time lags between the traces of a flow event and its effect on different pressure ports is not considered here (which is elaborated at the end of this subsection). As shown in figure 17, \( p_3 \) is also weakly correlated with \( w \).
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Figure 16. CCFs between $u$ and the pressures from run A2. The circle shows the second peaks in the CCFs (front, 1; back, 2; top, 3; bottom, 4).

Figure 17. CCFs between $w$ and the pressures from run A2. The circle shows the double peaks in CCFs (front, 1; back, 2; top, 3; bottom, 4).

(positive correlation). These correlations, together, support the conclusion that pressure fluctuations conducive to grain entrainment are correlated with fourth-quadrant flow events; however, the relatively weak correlations with the wall-normal component, $w$, also suggest that the pressures (and resulting forces) are not functionally related to $w$. That is, the correlation with $w$ is induced through its negative correlation with $u$. Lastly, the pressure on the bottom of the grain, $p_4$, is uncorrelated with either $u$ or $w$, which is in agreement with results shown in figure 13.

To better understand the succession of peak lift and drag force events, the time lags between these events, and certain trends in the near-bed flow velocity accompanying
these peak forces, analysis of the ensemble-averaged samples conditioned about the peak events are presented next.

3.4. Conditionally sampled peak pressure and force events

Conditional sampling of pressure has often been utilized before to characterize peak pressure events acting on rough and smooth walls and their relation to the near-bed flow structures (Johansson, Her & Haritonidis 1987; Laadhari, Morel & Alcaraz 1994; Detert, Weitbrecht & Jirka 2010b). For this purpose, we employed a peak detection method which is based on the $p_1$ signal. This is justified because the peak events in $p_1$ are more relevant to particle entrainment for the fully exposed particle configuration studied here (Diplas et al. 2008). Local peaks in the pressure signal with positive fluctuations higher than $H$ times the r.m.s. of the pressure fluctuations (i.e. $p' > H p'_{rms}$) were detected, where $H$ is a threshold value. In this study, results for $H = 2$ will be presented as this level provides a general impression about the magnitude of low-frequency peak events while allowing inclusion of a reasonable portion of the $p_1$ signal in the analysis. Prior to the analysis, the pressure data were low-pass filtered (ninth-order Butterworth) at 125 Hz (half of the Nyquist frequency) in order to smooth the shape of the peaks and reveal the underlying temporal variations. The magnitude of the positive pressure peaks in the filtered $p_1$ signal, with $p' > H p'_{rms}$, together with their time of occurrence were detected. Figure 18 illustrates the detected peaks in $p_1$ using the data from A2. Table 2 summarizes the results from the peak detection analysis.

For the given threshold value, the number of detected peaks did not vary significantly with the change in the flow strength for the uniform flow condition cases. The presence of the cylinder induced a slight increase in the average peak magnitudes for $D = 33.4$ mm and a small decrease for the other three pipe diameters. The magnitude of the detected peaks in the $p_1$ signal showed a positively skewed distribution with a heavy tail. The skewness values were between 1.1 and 1.5 for all runs, including the cylinder tests. This is due to the strong dependence of the $p_1$ on $u^2$. The probability density function (p.d.f.) of the detected peaks for runs UC and D1 (with $H = 2$) together with their normalized histogram are given in figure 19(a,b).
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**Figure 19.** p.d.f. of the detected peak magnitudes in $p_1$ ($H = 2$): (a) data from UC, (b) data from cylinder test with $D = 33.4$ mm. Both normalized histograms and theoretical p.d.f.s are presented. p.d.f. is a Johnson SB distribution, $p$-value: 0.52 for (a) and 0.65 for (b).

| $H = 2$ |   |   |
|---------|---|---|
| Run     | No. of peaks per s | Ensemble-average peak magnitude (N m$^{-2}$) |
| A1      | 1.4 | 801.14 |
| A2      | 1.4 | 759.73 |
| A3      | 1.4 | 844.39 |
| A4      | 1.3 | 816.60 |
| A5      | 1.3 | 862.17 |
| A6      | 1.3 | 886.77 |
| A7      | 1.3 | 892.05 |
| A8      | 1.3 | 898.43 |
| A9      | 1.3 | 837.61 |
| UC      | 1.4 | 891.48 |
| D1      | 1.5 | 909.11 |
| D2      | 1.3 | 879.69 |
| D3      | 1.6 | 854.88 |
| D4      | 1.7 | 858.35 |

|   | TI | D (mm) |
|---|----|--------|
| D1 | 0.37 | 33.4 |
| D2 | 0.41 | 26.7 |
| D3 | 0.43 | 21.9 |
| D4 | 0.31 | 12.7 |

**Table 2.** Summary of the results from peak detection analysis (for $p_1$). Turbulence intensity, TI, for uniform flow experiments was 0.27. The last four rows present the tests with the cylinders.

In order to examine the other pressure signals as well as near-bed flow velocity components associated with the peaks in $p_1$ signal, the following procedure was implemented: 200 ms long pressure ($p_{2-4}$) and velocity ($u$ and $w$) waveforms were conditionally sampled by means of centring these 200 ms long windows on the instants of detected peaks in $p_1$ for each run (e.g. a window covering 100 ms before and 100 ms after each positive $p_1$ peak). Subsequently, the ensemble average of these conditionally sampled waveforms was calculated (indicated by a superscript $+$, e.g. $p^+$). The number of peaks per second, presented in table 2, also represents the number of conditionally sampled waveforms used here to obtain the ensemble-average waveforms.
Figure 20. Ensemble-averaged waveforms of conditionally sampled pressures ($p_1$–$p_4$) and velocities ($u$ and $w$) from top to bottom (a)–(f), based on the detected positive peaks in the $p_1$ signal; $t = 0$ is the instant when the peaks in $p_1$ were detected. Data from run A2 were used and the ensemble-average values are based on the 1296 detected peaks. Time-average $w$ is shown with dashed horizontal line in (f). Threshold level, $H = 2$. Estimated uncertainty is of the order of 0.2 N m$^{-2}$. (Front, 1; back, 2; top, 3; bottom, 4.)

The representative patterns for the ensemble conditioned average pressures and the flow velocities (from run A2) are shown in figure 20. Individual pressure waveforms (corresponding to a single peak in $p_1$) were observed to be within 15% of $\Delta p_{\text{crit}}$. Note that the estimated uncertainty in the ensemble-averaged pressure variations is on the order of 0.2 N m$^{-2}$. The trends exhibited here for run A2 are representative of the results obtained from all the uniform flow tests.

The duration of the pressure peaks in $p_1$ is roughly 40 ms while the events in the flow velocities exhibit a longer duration, 3 to 4 times the pressure peak durations (figure 20a). This is inconsistent with the quasi-steady theory which is based on similar behaviours of pressures/forces and velocities at the same frequencies. Considering a 40 ms timespan for the peak in $p_1$ (figure 20a) and the frequency of occurrence given in table 2, the peak events which were detected using $H = 2$ occurred during approximately 6% of the total sampling time. This is in accord with the value obtained by Johansson et al. (1987) using an $H$ value of 2.5.

The relative maximum of $p_1^+$ (front) coincides with accelerations in $u^+$ and decelerations in $w^+$ (figure 20), consistent with sweep events with significant temporal duration. The ensemble-average $p_3^+$ (top) waveform shows a greater range in magnitude compared to $p_2^+$ (back) and $p_4^+$ (bottom). In addition, multiple relative maxima and minima in $p_2^+$, $p_3^+$ and $p_4^+$ were observed consistently in all uniform
flow cases. This behaviour helps to explain the presence of two relative maxima (or minima) observed in the CCF plots earlier (see figure 13). For instance, a relative minimum occurred in $p_3^+$ before the maximum in $p_1^+$ (figure 20c). Then the positive peak in $p_1^+$ was followed by relative minima in both $p_2^+$ and $p_4^+$, as well as a minimum in $p_3^+$. It was shown earlier in figures 13 and 16 that $p_4$ is not correlated with $p_1$ or flow velocity components. Figure 20 does not suggest a correlation between the waveform of $p_4^+$ with the other pressures or flow velocity components and the range of variation of the conditioned-average $p_4^+$ is exceptionally small. Nevertheless these relatively low-magnitude peaks in $p_4$ consistently occur around the peaks in $p_1$ for all of the uniform flow cases. It is plausible that the decrease $p_3$ (as observed in figure 20) just prior to an increase in the stagnation pressure on the front of the grain could be attributed to the vortices within coherent structures, downstream of the sweep events, creating low-pressure zones at their cores which then pass over the grain (Jackson 1976; Schmeecle et al. 2007; Smart & Habersack 2007), followed by a sweep event with a strong increase in stagnation pressure and reduced pressure on the top of the grain. Vortex shedding from the grain itself during such an interaction may also play a role in these pressure patterns (Kalinske 1947; Hofland et al. 2005).

Representative patterns for the ensemble-average pressures and the flow velocities from the cylinder test with $D = 33.4$ mm are shown in figure 21. Qualitatively similar
patterns were observed for the data with different diameter cylinders. For the tests
with the spanwise cylinder, the waveforms of \( p_3^+ \) do not exhibit multiple (and out-of-phase) relative minima and maxima over the 200 ms window as were observed in the uniform flow case. A strong drop in \( p_3^+ \) takes place at about the same time as the peak in \( p_1^+ \) initiates, which is followed by a positive peak in \( p_1^+ \) and then in \( p_3^+ \).

Considering the location of the pressure measurement points, the signature of a certain flow structure moving downstream near the grain is first expected to be observed in \( p_1 \) and then in \( p_3 \) and finally in \( p_2 \). Unlike the uniform flow case, the cylinder test results follow this order as can be seen by the instants of peaks occurring in \( p_1^+ \), \( p_2^+ \) and \( p_3^+ \). Unlike the uniform flow interaction (figure 20) this sequence of pressure events supports the notion of flow structures travelling downstream and inducing a pressure signature as they move past and over the grain. But, as with the uniform flow cases, the flow velocity patterns again suggest a connection between high-speed fluid motion towards the bed (a sweep-like event with significant duration) and the positive peak in \( p_1^+ \).

The horizontal and vertical differences of the ensemble average of conditionally sampled pressures (\( p_1^+ - p_2^+ \) and \( p_3^+ - p_3^+ \) respectively), indicative of drag and lift forces respectively, were also obtained and are given in figure 22 for the uniform flow series (data from runs UC, A1 and A9). Note that the vertical pressure difference excludes the hydrostatic pressure difference between the locations of \( p_2 \) (bottom) and \( p_3 \) (top), \( \gamma \Delta z \), where \( \gamma \) is the specific weight of water and \( \Delta z = d = 12.7 \text{ mm} \), to eliminate the buoyancy effect. That is, the lift force estimated in this fashion will be compared to the submerged weight of a 12.7 mm, Teflon grain (i.e. \( \Delta p_{crit} \)). The waveforms from runs A1 and A9 were also included along with the undisturbed flow condition for the cylinder tests (UC) to represent the upper and lower limits of the pressure gradients respectively for uniform flow conditions.
The vertical pressure difference in figure 22 indicates an average upward lift, \( \sim 4\% \) of the critical pressure difference, \( \Delta P_{\text{crit}} \), over the 200 ms window centred on the peaks in drag force. The contribution of \( p_3^+ \) to this average positive vertical pressure difference is 65\%. A peak occurs in the vertical pressure difference (\( \sim \)lift force) 5 to 10 ms before the peak in the horizontal pressure difference (\( \sim \)drag force) and is dominated by \( p_3^+ \) (out of phase with \( p_1^+ \)). The second peak in the lift force, again essentially caused by a drop in \( p_3^+ \), is observed \( \sim 65 \) ms after the peak in drag and 73 ms after the peak in \( u^+ \). The latter delay indicates a convection velocity of \( \sim 10u_* \), comparable to findings reported in the literature (Laadhari et al. 1994). Both of these peaks in \( p_3^+ \) (figure 22) correspond to \( \sim 6\% \) of \( \Delta P_{\text{crit}} \), sufficient to momentarily reduce the threshold level for particle entrainment and potentially aid in dislodgement. These two separate lift events, one before and one following a strong drag event (conditioned upon peak drag force events), are consistent with the two strong relative maxima in the drag–lift CCF shown in figure 9. While the positive lift contributions are dominated by \( p_3^+ \) (top), the valleys in lift force (for example the instants at \(-0.050 \) and \(+0.030 \) ms in figure 22), by contrast, are caused by drops in \( p_4^+ \). The peak in drag force, dominated on the average by positive contributions from \( p_1^+ (118\%) \) accompanied by negative contributions from \( p_2^+ (-18\%) \), coincides with the acceleration in \( u^+ \) and also with deceleration in \( w^+ \). The second peak in the lift which occurs after the peak in the drag (dominated by \( p_3^+ \), see figures 16 and 22 for CCFs between \( p_1 \) and the flow velocities) is also consistent with the acceleration in \( u^+ \) and deceleration in \( w^+ \) (this is assuming a constant convection speed, \( 10u_* \), and the distance which the flow structure has to travel to have influence at the location of \( p_3^+ \)). Nevertheless, it is not reasonable to link the aforementioned first peak in the lift force (figure 22b) to the same effect, because it occurs before the peak in the drag force and at about the same time as the peak in \( u^+ \). Therefore, it is unlikely that the cause of this first peak in the lift force is associated with the acceleration in flow towards the bed. While the measurements in this study do not indicate a definite source for this phenomenon, interactions of vortices with the grain, particularly at the interface (shear layer) of low- and high-speed fluid streaks near the bed, might be creating low-pressure zones and eventually a strong drop in \( p_3^+ \) and an upward lift force. Such vortices were observed by Cameron (2006) and Detert et al. (2010b) to occur near the bed downstream of sweep events. This interpretation is also consistent with the findings of Hofland (2005), Schmeckle et al. (2007), Smart & Habersack (2007).

Figure 23 presents the waveforms of \( (p_1^+ - p_2^+) \) and \( (p_4^+ - p_3^+ - \gamma \Delta z) \) from the cylinder test with \( D = 33.4 \) mm. Similarly to the results from the uniform flow case, peaks in the lift force are observed to occur before and after the peak in the drag. But, unlike the uniform flow case, the first peak in the lift shown in figure 23 is a result of a steady drop in the pressure on top of the grain (see figure 21), coinciding with a commensurate steady increase in the bottom pressure occurring just before the peak in drag force occurs.

The same behaviour in the lift forces for both uniform and cylinder wake flows caused by slightly different pressure patterns in \( p_3^+ \) and \( p_4^+ \) indicates that this might be particular to the geometry used here. The presence of the cylinder does not increase the relative magnitude of the peaks in drag and lift forces but causes a significant increase in the average lift \( \langle p_4^+ - p_3^+ - \gamma \Delta z \rangle \) force during the 200 ms window centred on the peaks in drag force (Angle brackets denote averaging over the specified duration and will later be used to indicate averaging over the peak pressure duration, \( T \)). It is calculated that the overall lift acting on the grain during
Figure 23. The waveforms of the ensemble average of the conditionally sampled (a) horizontal and (b) vertical pressure gradients; $t = 0$ is the instant when the peaks in $p_1$ were detected. Data from cylinder tests with $D = 33.4$ mm were used. Threshold level, $H = 2$. Estimated uncertainty is of the order of 0.2 N m$^{-2}$. (Front, 1; back, 2; top, 3; bottom, 4.)

The observation window is 27% of $\Delta p_{crit}$ (a nearly 7-fold increase compared to uniform flow conditions) and the peaks in the lift can reach up to 32% of $\Delta p_{crit}$. The shift in the average lift force during peaks in drag is most likely associated with increased flow velocities (due to the presence of the cylinder) generating a permanent low-pressure zone over the uppermost layer of the bed via a Bernoulli effect as suggested by Brayshaw, Frostick & Reid (1983). Such relatively small changes in the effective weight of the particle have been shown to be responsible for significant changes in the particle entrainment frequency by Celik et al. (2010). The reason for the significant increase in the bedload activity with minute increase in the turbulence level as Nelson et al. (1995) and Sumer et al. (2003) observed can also be attributed to the modification of the average lift force during extreme drag forces by the flow structures in the cylinder wake which makes the particles effectively lighter. That is, turbulence intensity constitutes an indicator of changes in the lift force experienced by the grain during the application of extreme drag forces.

The previous results were obtained by using the extreme drag force fluctuations as the conditioning criterion. We also examined the forces and velocity patterns, this time using the extreme lift forces as the conditioning criterion. The peak detection method (with $H = 2$) was applied to the instantaneous lift force $(p_4 - p_3 - \gamma \Delta z)$ to detect the patterns of flow velocities and drag forces associated with extreme positive lift events. In figure 24, the ensemble-average lift force, $(p_4 - p_3 - \gamma \Delta z)^+$, is given together with accompanying (ensemble-average) conditionally sampled drag force, $(p_1 - p_2)^+$, $u^+$ and $w^+$ for run UC. The figure shows that the relative peak in the lift force, $\sim 10\%$ of $\Delta p_{crit}$ (figure 23a) coincides with sweep-like conditions, but the acceleration in $u^+$ and deceleration in $w^+$ are not as strong as they were in figure 20(e,f). There are very small variations (10 N m$^{-2}$) in the drag force $\sim 65$ ms before and 15 ms after the extreme lift event.
The magnitude of instantaneous pressure and force peaks presented above has been advocated in the literature to be the relevant parameter for particle entrainment (see for example Hofland et al. 2005; Schmeeckle et al. 2007). Yet, Diplas et al. (2008) and Celik et al. (2010) provided evidence that not every peak in the force magnitude, even when exceeding the threshold value, results in particle entrainment. They demonstrated that the force duration, $T$, of peak events is as important as the force magnitude. The next subsection is devoted to the identification and statistical characteristics of the duration of the peak drag force events (impulse concept, Diplas et al. 2008) and their relations with the lift force and flow structures.

### 3.5. Force duration results

The earlier part of this work dealt with the statistical characteristics of instantaneous pressure magnitude measurements. As such, each measurement exceeding a critical/threshold value was identified as an extreme event capable of contributing to the dislodgement of the test grain (figure 18). In the present subsection, the focus is on both the magnitude and duration of extreme events. To account for both aspects
of such events, the instantaneous pressure measurements are connected to represent a continuous record (see figure 25 for $p_1$). The resulting curve, together with the criterion of $p_1 > 2p'_{rms}$ ($H = 2$), are used to identify the instant of occurrence and duration, $T$, of an extreme/peak event (figure 25). Subsequently, the time-averaged $p_1$ values, $\langle p_1 \rangle$, over $T$ can be computed for each peak event. As a result, the two right-most pressure peaks shown in figure 25 are parts of a single impulse event according to the present detection scheme, while the earlier method will count them as two separate events.

Implementing this procedure for each run results in a series of random peak pressure events, associated $\langle p_1 \rangle$, and durations, $T$ (figure 25). The identified peaks were associated with the other pressures and flow velocity components through the time of occurrence of the peaks in $p_1$. In order to account for the phase delay between the flow velocity and pressure signals due to the distance between the pressure measurement points and the location of the LDV measurement volume, the flow velocity records were shifted forward by the lag time obtained at the rise point in the cross-correlation function between $u$ and $p_1$ (figure 16). In this way, the near-bed flow events and the pressures they generate on the particle were matched in time before the event duration analysis was performed. More specifically, all pressure signals were synchronized with $u$–$w$ pairs by using a single time delay that was obtained between $u$ and $p_1$, which is the strongest and the most relevant relation for the bed configuration studied here. Subsequently, each peak in $p_1$ was associated with an event-averaged $p_2$, $p_3$, $p_4$, $u$ and $w$ over the peak duration.

The distribution of peak durations in $p_1$ are heavily and positively skewed (figure 26) and is described well by the extreme value distributions: Wakeby ($p$-value = 0.99), General extreme value ($p$-value = 0.86), and three-parameter log-normal ($p$-value = 0.67). The most extreme durations in uniform flow cases (based on $H = 2$) exceeded 500 ms.

Each of the peak event characteristics, duration $T$, $\langle p_1 \rangle$, $\langle p_2 \rangle$ and $\langle p_3 \rangle$ is plotted against the corresponding $\langle u \rangle$ and $\langle w \rangle$ measurements in figures 27(a–27d), respectively. The surface plots indicate that events lasting longer than 100 ms with magnitudes well over the threshold level occur predominately in the high-$u$ and negative-$w$ region (not

![Figure 25. (Colour online) Representative time series of (filtered) $p_1$ from run A2. The detected local peaks with $p' > 2p'_{rms}$ are shown with solid circles. Time-average $p_1$ is specified with the horizontal solid line. The widths of the shaded rectangular areas indicate the detected event durations, $T$, while the heights indicate the average $p_1$ over duration $T$, $\langle p_1 \rangle$. The vertical dashed lines show the time of occurrence of events for the duration analysis.](image)
necessarily with the most extreme values) implying association with sweep-like events. Such events also occur occasionally in the region of outward interactions ($u' > 0$ and $w' > 0$). A precise relation between the magnitude and duration in peak $p_1$ events is not apparent, although events with extremely high durations were generally not associated with the highest event magnitudes. This can be seen by matching the high values of duration and magnitude on the identical $\langle u \rangle$–$\langle w \rangle$ plane in figures 27(a) and 27(b). Note that all of the event magnitudes seen in these figures are above the threshold value of $p_1$. Plots of $\langle p_2 \rangle$ and $\langle p_3 \rangle$ concurrent with the peak events in $p_1$, $\langle p_1 \rangle$, are shown in figures 27(c) and 27(d) respectively. Consistently with the results obtained from the CCF analysis presented earlier (figure 13), peak $p_1$ values are typically associated with lower $p_2$ and $p_3$ values.

The magnitude of $p_4$ does not show any particular correlation with peak magnitudes or with duration in $p_1$. In agreement though with the results reported by Dwivedi et al. (2010a, 2011), we found high $p_4$ magnitudes occurring during the passage of sweep-like events (figure 28a). We note, however, that no correlation was obtained in general between $p_4$ and $\langle w \rangle$. A joint histogram of the $\langle u \rangle$ and $\langle w \rangle$ pairs is presented in figure 28(b) to provide information about the frequency of occurrence of events shown in figures 28(a) and 27(a–d).

A feature observed during all of the uniform flow tests was that the high-duration region in the sweep events yields angles of attack (inclination angle of the velocity fluctuations from the horizontal plane) between 7° and 19° (obtained using the data of figure 28b). Keshavarzi & Gheisi (2006) reported high sediment activity occurring with angles of attack near the upper limit reported here. The peak events did not occur during ejection- ($u' < 0$ and $w' > 0$) and inward-interaction-like events ($u' < 0$ and $w' < 0$). The distribution of pressure magnitudes and duration (based on $p_1$) on the $\langle u \rangle$–$\langle w \rangle$ plane, in relation to the impulse-based incipient motion model, implies that the sweep- and outward-interaction-like events near the bed are effective in particle dislodgement. A similar conclusion has also been reported earlier by Heathershaw & Thorne (1985) and Nelson et al. (1995) and more recently by Cameron (2006). The dominance of these two near-bed events in particle removal has often been attributed to the frequent high streamwise velocities and resulting high drag forces. However, results of the

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**Figure 26.** Histogram of the 478 event peak durations detected in $p_1$ ($H = 2$). Data from UC were used.
Figure 27. Surface plots of (a) the peak event durations, (b) magnitude of $\langle p_1 \rangle$, (c) magnitude of $\langle p_2 \rangle$, (d) magnitude of $\langle p_3 \rangle$, on the $\langle u \rangle$--$\langle w \rangle$ plane. Data from run UC were used and 478 events with finite durations are represented. Colour bars represent the duration (a) and magnitude (b–d) of pressure peaks. Note that the same colormap was used for different scales in the subplots. Horizontal and vertical dashed lines indicate the time-average $u$ and $w$ values over the entire test duration respectively. Data from run UC were used (front, 1; back, 2; top, 3; bottom, 4).

Present study emphasize that the occurrence of high event durations along with high magnitudes (for $p_1$), i.e. high impulse magnitudes, during the sweep- and outward-interaction-type events is equally important in identifying the actual physical processes leading to higher sediment transport rates.
Characterization of drag events with both high duration and magnitude and the concurrent associated lift forces is essential for developing better incipient motion models. In order to explore the coupling between the peak drag force magnitudes and corresponding durations with the lift forces occurring during these peak events, the duration detection method was applied to $p_1 - p_2$ with $H = 2$. The duration of events based on drag force magnitude and their frequency of occurrence are given in figures 29(a) and 29(b) respectively on the drag–lift plane for the uniform flow condition test, UC. Note that these force and duration patterns are for a fully exposed grain and our assessments pertain to rolling motion. Extreme events with relatively high durations (e.g. $>100$ ms), and high drag and lift forces were observed, although very rarely (figure 29b). In addition, there were events occurring more frequently than the extreme events, with durations between 50 and 100 ms, and positive lift and high drag force magnitudes. The most frequent events however were characterized by shorter durations (50 ms or less). These events also imparted near-zero lift forces and relatively low drag force magnitudes to the test particle compared to the extreme event durations. Similar arguments are also valid for the cylinder test case only this time the average lift force is positive with significantly high magnitudes.

4. Discussion and summary

Because of the highly fluctuating nature of turbulent flows, the magnitude of high instantaneous streamwise velocity or even the magnitude of the corresponding instantaneous drag forces occurring during the passage of the energetic flow structures are insufficient to completely describe the flow characteristics required for the full dislodgement of a sediment particle. Under such flow conditions, both the force magnitude and its duration play an equally important role in triggering particle
Figure 29. Surface plots of (a) the durations of the drag force signal on the drag–lift plane, and (b) a two-dimensional histogram of the drag and lift. The colour bars in (a) show the event durations and in (b) represents the number of counts for the two-dimensional histogram. Data from run UC were used.

dislodgement. Impulse, which captures both attributes of a highly fluctuating force capable of inducing a change of momentum, is therefore the more suitable parameter for developing a universally valid particle dislodgement criterion. The fact that the particle entrainment is far more likely to occur during first- and fourth-quadrant events, the latter being more frequent, is due to the combination of high force magnitude (caused by positive $u$ fluctuations) and sufficient duration associated with these events.

A criterion for grain dislodgement based upon impulse is achieved through the existence and identification of a critical impulse level (for a given bed and mobile grain size and density), as detailed in Celik (2011). This is illustrated here using the data in this investigation from the uniform flow experiment, designated UC, and for the cylinder experiment, designated D1, as shown in figure 30. In this figure, and using the drag contribution induced by $p_1 - p_2$ only, the fractions of all impulse events are shown as a function of the dimensionless impulse carried by the extreme drag events. We remark that an impulse-generating event does not occur unless the pressure-induced drag exceeds a minimum level just sufficient to initiate some motion of the grain. This requires a different threshold level of $H$ to be determined, consistent with the minimum pressure difference to initiate motion. The resulting impulses vary over a wide range from very low values incapable of fully dislodging the grain, to rare but high impulse levels (above the critical impulse) which are sufficient for full grain entrainment. To better illustrate the fraction of all impulses that exceed this critical impulse level, the impulse in figure 30 is non-dimensionalized by the critical impulse needed to fully dislodge a 12.5 mm diameter Teflon sphere resting upon a base of identical diameter spheres, as determined in Celik et al. (2010) and based
upon the drag force alone. To determine the impulse associated with each extreme event, the threshold level for $H$, consistent with the minimum value of $(p_1 - p_2)$ to just induce grain movement, was determined and found to be $H = 1.62$ for the UC case and 0.80 for D1. The impulse for each event is obtained by identifying all those events for which the ratio of $p_1 - p_2$ to $(p_1 - p_2)'$, the r.m.s. level of $(p_1 - p_2)$, exceeds the appropriate $H$ threshold and multiplying the event average $\langle p_1 - p_2 \rangle$ level for each such event by its respective duration. In the figure all those events with $I/I_{\text{crit}} \geq 1.0$ would result in full grain dislodgement. It is clear that for flows near critical, only a small fraction of all relevant events are capable of fully entraining the grain. The majority of events are capable of moving the grain but not fully dislodging it from its resting pocket in the bed, as they have insufficient impulse, $I/I_{\text{crit}} < 1.0$. It is also apparent from figure 30 that the fraction of events for $I/I_{\text{crit}} \geq 1.0$ is higher in the presence of the upstream cylinder, indicative of a much higher dislodgement rate for this case.

The results of figure 30 did not include the effect of lift; however, the results of the present investigation demonstrate consistent positive lift force peaks occurring before and after the peak events in the drag force. These patterns were even more pronounced during the cylinder experiments. The resulting increase in the lift force provides more favourable conditions for particle dislodgement and higher overall entrainment rates and should be included in any impulse-based criterion for entrainment.

In summary, the dominance of sweep and, to a lesser extent, outward interaction events in particle dislodgement is due to the frequent occurrence of high-magnitude impulse events during the fourth (most common) and first quadrants and the coincident increase in many cases of the lift forces.

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