Accounting for the role of turbulent flow on particle dislodgement via a coupled quadrant analysis of velocity and pressure sequences

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Abstract Recent studies have demonstrated the importance of duration, in addition to magnitude, of energetic turbulent events on particle dislodgement under threshold of motion conditions. It is therefore proposed here that the use of turbulence sequences, instead of single instantaneous extreme events, is more appropriate for characterizing the role of fluctuating velocities and associated hydrodynamic forces on particle mobility. The validity of the proposed method is examined through the detailed analysis of directly measured velocity and pressure data sets. In an effort to relate the results of the conventional velocity quadrant analysis with the instantaneous pressure measurements, the concept of pressure quadrant analysis is introduced. The coupled sequences of the synchronous velocity and pressure quadrant events allow for a more complete description of the local turbulent flow characteristics, including the prevalent coherent structures, and more clear interpretation of their role on particle mobility. It is concluded here that large-scale sweep structures are capable of generating excessive and persistent force fluctuations which are predominantly responsible for the dynamic process of particle dislodgement. This result supports the impulse criterion as the proper way of accounting for the cumulative effect of coherent structures on particle movement.

Keywords: Initiation of particle motion; Coherent structure; Impulse criterion

1. Introduction

Evaluation of the effect of coherent structures on particle mobility remains a key challenge to researchers seeking to formulate models that are capable of accounting for the role of turbulent

flows on sediment transport under near-threshold conditions [1-4]. Among various approaches, the quadrant analysis has been extensively used to characterize the flow events associated with initiation of particle motion. Specifically, flow processes near sediment particles can be categorized into four velocity quadrant events: (1) Q_{1V} ($u' > 0, w' > 0$), (2) Q_{2V} ($u' < 0, w' > 0$), (3) Q_{3V} ($u' < 0, w' < 0$), and (4) Q_{4V} ($u' > 0, w' < 0$), where (u', w') are the streamwise and bed-normal velocity fluctuations, respectively, and the subscript “V” is used for velocity events. An extensive review of the quadrant method was recently provided by Wallace [5].

Particle suspension is frequently attributed to Q_{2V} (ejection) events due to their pronounced upward velocity [6-8]. Sediment transport as bedload, however, is commonly associated with Q_{4V} (sweep) or Q_{1V} (outward-interaction) events because of their particularly strong streamwise velocity [9-12].

A common consideration in previous research has been the importance of instantaneous flow velocity spikes detected around the instant of particle movement [13]. This consideration appears to be logical when initiation of particle motion occurs in a very short time, several tenths of a second [14, 15]. However, recent experimental evidence [16-19] has suggested that, for near-threshold conditions, only a small fraction (~10% for the experiments reported in [16, 17]) of the velocity spikes or their force realizations that exceed a theoretical critical value can actually dislodge the particle. The duration of velocity spikes has been highlighted because most of the particle dislodgements are attained by peak turbulent events of longer duration. Most of the short-lived spikes can only make the particle vibrate within its sitting bed pocket [16-19]. Here the term “particle dislodgement” is specifically referred to the process of removing a stationary particle permanently from its pocket.

The relevance of turbulence duration motivates this study to consider particle dislodgement as a result of velocity quadrant sequences, rather than a single velocity quadrant event. This perception agrees qualitatively with experimental observations describing the dynamic processes of particle dislodgment driven by coherent structures. For example, Hofland and Booij [20] suggested that a near-bed hairpin-vortex-system (HVS) can initially generate lift forces via small-scale ejections (Q_{2V}) to moderately elevate a particle. Subsequently, HVS can exert drag forces via large-scale sweeps (Q_{4V}) to dislodge this particle. Similar descriptions of the dislodging processes can be found in other references [15, 21-23].

Another challenge in predicting particle dislodgement is the reliability of flow velocity as a proxy for hydrodynamic forces exerted on sediment particles. The pioneering work of Einstein and El-Samni [24] emphasized the major influence of fluctuating pressures rather than velocities on the roughness elements. Direct pressure or force measurements performed on sediment particles have indicated an incomplete coupling between the velocity history and the synchronous pressure/force data record (e.g. [25, 26]). The fluctuations of near-particle velocity do not account fully and uniquely for the corresponding instantaneous fluid forces (e.g. [27, 28]). Researchers have tried to address this rather complicated instantaneous velocity/force correspondence through the use of a time-variant drag coefficient [9, 26]. The direct measurement of hydrodynamic pressures is therefore considered in this study for a proper examination of fluid forces.

The main objective of this paper is to provide a comprehensive perspective on particle dislodgement under a framework of turbulence sequences. Particular emphasis is placed on the periods of particle dislodging processes to underline the cumulative effects of causative turbulence sequences. To achieve this goal, the conventional velocity quadrant analysis is extended to incorporate the quadrant analysis of the associated pressure sequences. Also, a velocity filtering technique is employed here to improve the velocity measurements and, consequently, their coupling with the corresponding pressure records.

The rest of the paper is organized as follows. Section 2 presents the experiments used to obtain the velocity and pressure measurements. Section 3 describes the methods of data analysis. The results and interpretations are shown in section 4, a discussion in section 5, and a set of conclusions in section 6.

2. Experiment

The experiment was originally carried out by Celik *et al.* [9, 25] to evaluate particle mobility under near-threshold conditions. The main aspects of the experiment and related data collection programs are outlined here to keep the paper self-contained. Additional experimental details can be found in the above publications.

2.1. Physical model

A 14.4 m long and 0.6 m wide water recirculating flume tilted at a slope of 0.25% was used. The flume test section was covered with two layers of densely-packed single glass beads of diameter $D = 12.7$ mm. This setting allowed for the full development of turbulent flows under investigation. Table 1 shows pertinent parameters that characterize flow and boundary conditions. The glass-bead boundary was rendered hydraulically rough with a particle (shear) Reynolds number of 424 (defined in Table 1). Also, the ratio of flow depth to particle diameter reported here ($h/D = 5.9$) is typical of the depth-limited flows encountered in gravel-bed rivers [29, 30], enabling meaningful comparisons with field conditions.

For bed mobility considerations, the present experiment was designed for a dimensionless shear stress (Θ) about one-tenth the critical value obtained from the Shields diagram [31] (Table 1). As a result, extensively mobilized bed condition is not present in this work. However, sporadic dislodgement is possible for highly protruding particles resting on top of the glass-bead layers [26, 32]. At this stage of very low and highly intermittent bedload transport, the role of energetic near-bed turbulence on particle dislodgement is particularly important [13]. To better understand this role, a simplified arrangement of a single, highly exposed test particle is employed here so that no other protruding particle affects the flow physics upstream of the test particle (Fig. 1). The wakes separated from the upstream base beads are considered as a part of local flow fluctuations.

Table 1 Experimental flow and boundary conditions

h	U	u_*	Fr	Re	R_*	$\frac{\Theta}{\Theta_{cr}}$	$\bar{u}$	$\bar{w}$	σ_u	σ_w	$\overline{\Delta P_x}$	$\overline{\Delta P_z}$	$\bar{\tau}$	τ_η
cm	cm/s	cm/s	-	-	-	-	cm/s		cm/s		N/m ²		s	
7.5	45.0	3.34	0.52	34,000	424	0.12	22.9	-1.45	6.72	3.59	33.9	-1.61	0.185	0.016

h = flow depth

U = area-averaged flow velocity

u_* = bed shear velocity = $\sqrt{\tau_0/\rho}$; τ_0 = mean bed shear stress; ρ = density of water

Fr = Froude number = $U/\sqrt{gh}$

Re = flow Reynolds number = Uh/ν ; ν = kinematic viscosity of water

R_* = particle (or shear) Reynolds number = u_*D/ν ; D = particle diameter

Θ = Shields stress = $\tau_0/[\rho g(S_G - 1)D]$; S_G = specific gravity of particle;

Θ_{cr} = critical Shields stress = 0.056 from the Shields diagram

$(\bar{u}, \bar{w})$ = long-term average of the near-particle streamwise and bed-normal flow velocities (u, w)

(σ_u, σ_w) = standard deviation of u and w respectively
 $(\overline{\Delta P_x}, \overline{\Delta P_z})$ = long-term average of the streamwise and bed-normal net pressures ($\Delta P_x, \Delta P_z$)
 $\bar{\tau}$ = local integral time-scale = $\int_0^\infty R_{uu}(t - \tau) d\tau$; R_{uu} = autocorrelation function of u ; τ = time shift
 τ_η = local Kolmogorov time-scale = $\sqrt{\nu/\epsilon}$; ϵ = dissipation rate of local turbulence kinetic energy [33, 34]

2.2. Velocity/Pressure measurements

The near-particle flow velocity and associated hydrodynamic pressures were measured to quantify the influence of coherent structures upon single-particle mobility. At the flume centerline, a 12.7 mm spherical test particle was permanently placed on top of the two-layer glass beads throughout the experiment. This highly (87%) exposed test particle was instrumented with four piezoelectric transducers located on the front (P_1), back (P_2), top (P_3) and bottom (P_4) to measure the in-situ instantaneous surface pressures (Fig. 1a). These measurements allowed for the net pressure record in the streamwise ($\Delta P_x = P_1 - P_2$) and bed-normal ($\Delta P_z = P_4 - P_3$) directions to be calculated. The drag and lift forces can be approximated by the obtained net pressures (Fig. 1b). A two-component Laser Doppler Velocimetry (LDV) was used to obtain the streamwise (u) and bed-normal (w) velocity records. The location of velocity measurements is along the centerline and one particle diameter upstream of the test particle (Fig. 1a), consistent with similar studies reported in the literature [15, 26].

The output signals of simultaneous velocity and pressure measurements were collected via a multichannel signal processor. The pressure transducers operated at a constant sampling rate of 250 Hz. However, the LDV sampling rate varied over time between 250 and 700 Hz, depending on the instantaneous concentration of seeding particles within the measuring control volume. Since the LDV data were nonuniformly sampled, the spline interpolation procedure was used to resample the data at a constant rate of 700 Hz without overfitting. The resulting uniform LDV data was resampled again at 250 Hz to obtain a one-to-one synchronized data set of velocity and pressure realizations. Antialiasing filters were used in the above resampling processes.

Compared to the local Kolmogorov time-scale of 0.016 s (Table 1), the sampling rate of velocity and pressure records (250 Hz, i.e. time-resolution of 0.004 s) was sufficiently high to resolve boundary turbulence characteristics. The duration of the data collection program for this experiment was 15 min. When compared to the local integral time-scale of 0.185 s (Table 1), this

period proved to be sufficiently long to secure stationary statistics of the hydrodynamics measurements.

Fig. 1 Schematics of (a) particle arrangement and locations of LDV and pressure transducers (P_1 to P_4), and (b) force diagram of the test sphere. The LDV sampling volume has dimensions of $100 \mu\text{m}$ (streamwise) $\times$ $100 \mu\text{m}$ (bed-normal) $\times$ $800 \mu\text{m}$ (spanwise). The drag (F_D) and lift (F_L) forces are estimated by $F_D = \Delta P_x A_x$ and $F_L = \Delta P_z A_z$, respectively. A_x and A_z are the projected areas of the spherical particle perpendicular to the streamwise and bed-normal directions, respectively. F_G is the submerged particle weight and F_N is the contact force. r is the distance between the center of the rolling sphere and the axis of rotation, α is the bed slope, and θ is the angle between r and the horizontal plane.

2.3. Time-lag correction

Despite the synchronization of LDV and pressure transducers, a shift in time is expected among the signals recorded at different locations when responding to a propagating flow event. This type of time-lag is commonly examined via Taylor's "frozen turbulence" hypothesis and an appropriate convective velocity [35]. In contrast to typical considerations of the local time-averaged flow velocity as the convective speed, more recent research has indicated that the near-bed turbulence would propagate downstream at a speed higher than the local mean flow [35]. It is therefore reasonable to assume that the convective speed is case-specific and that it depends on the dynamics of coherent structures.

This study considers the conditional average of local flow velocities during the periods of particle dislodgement as the convective speed for the causal coherent structures. The periods of particle dislodgement are identified by a numerical model (section 3.3). The obtained convective speeds can yield the time-lag between the LDV and frontal transducer P_1 , which varies around a mean value of 0.040 s among different coherent structures. As for the time-lag between P_1 and the other transducers, the cross-correlation functions of P_1 - P_2 and P_1 - P_3 signals indicate that P_3 is behind P_1 by 0.008 s and that P_2 is behind P_1 by 0.028 s. No noticeable time-lag can be found between P_3 and P_4 signals. Correcting the aforementioned time-lag among signals can enhance the reliability of associating rapidly fluctuating turbulence with hydrodynamic impact on the particle.

2.4. Velocity and pressure coupling

Fig. 2 shows a representative section of the synchronous velocity and net pressure records used here. The dominant streamwise velocity u and downstream net pressure ΔP_x overall trends are in reasonable agreement. However, a detailed comparison identifies occasional high-frequency velocity fluctuations (superimposed on the major trend) that are not captured in the corresponding net pressure records. These small fluctuations are modulated, or low-pass filtered out, by the test particle and seem to be inconsequential as far as particle mobility is concerned. In this regard, prior experimental evidence has suggested that turbulence structures smaller than the particle size produce no substantial effect on particle mobility [26]. Furthermore, full particle dislodgement is probably accomplished by flow structures as large as at least twice the particle size [14]. Given these indications, it is appropriate to remove the high-frequency velocity signals for revealing the most impactful coherent structures.

Another reason for post-processing the velocity signals is to reduce inconsequential velocity spikes or plunges (red arrows in Fig. 2a). These velocity deviations cause no considerable change in pressure (Fig. 2b), yet leave ample room for misinterpretation of local hydrodynamics due to their prominence among the surrounding velocities. A despiking process is therefore necessary.

The high-frequency velocity fluctuations and inconsequential spikes are removed by appropriate low-pass filters (section 3.1). The consequent improvement is examined by referring to the corresponding net pressure record. Overall, the direct pressure measurements are used to probe the applied hydrodynamic conditions related to particle dislodgement and, moreover, to

help enhance the veracity of flow physics analysis. This approach is preferable, especially when identifying an appropriate location for obtaining velocity measurements to more accurately determine the fluid forces acting on a sediment particle remains a controversial point [24-26].

Fig. 2 Representative time series of (a) instantaneous local velocity and (b) corresponding net pressure records. The long-term average values (Table 1) are presented by horizontal lines. The red arrows indicate inconsequential u -velocity spikes and plunges that barely have an impact on the net pressure response.

3. Methods of data analysis

3.1. Velocity filtering technique

In attempts to remove minor turbulence events, velocity filtering techniques usually employ arbitrary criteria. For instance, the threshold “hole size H ” used in the conventional quadrant analysis covers a variety of values, typically ranging from 0 to 8, with even higher values having been reported in the literature [36, 37], where H is defined by $|u'w'| \geq H(\sigma_u\sigma_w)$. This hole-size-filter detects the bursting events of particularly large instantaneous Reynolds stresses ($-\rho u'w'$) [5].

By contrast, the present focus is on the magnitude of the streamwise velocity, a relatively good predictor of particle dislodgement as compared to the instantaneous or time-averaged Reynolds stress [10, 11]. To remove inconsequential coherent structures that are smaller than the

particle diameter, digital low-pass filters with a cutoff frequency of $f = \bar{u}/D$ are used here to process velocity data. Less attention is focused on the w -velocity component due to its insignificant role on dislodgement of a highly protruding particle [9, 25].

Fig. 3a exemplifies a section of the post-processed velocity u_{pp} record contrasted with the original u data. The velocities are expressed as pressure predictors for a comparison with the net pressure ΔP_x (Fig. 3b). It is noticed that a striking velocity spike (red arrow) has been attenuated by the filter to a more modest level below the threshold $\Delta P_{x_{cr}}$ for initiation of particle rolling. This spike removal prevents overestimation of hydrodynamic impact because the applied ΔP_x does not exceed $\Delta P_{x_{cr}}$ during the same period of time. Inconsequential small velocity variations that obscure coupling between velocity and pressure are also eliminated. Nevertheless, despite the above improvements, the velocity remains essentially a surrogate measure of hydrodynamic forces (Fig. 3).

Among several typical filters such as Chebyshev, Butterworth, and Elliptic, a 6th-order Butterworth filter is chosen for the present experimental setting. It effectively reduces the probability of hydrodynamically inconsequential u -velocity spikes by 30%, compared to 22% reduction by Chebyshev and 25% by Elliptic. Although the other two filters seem to be able to achieve similar performance, their extra parameters (i.e. ripple factor and selectivity factor) need to be finely tuned to optimize the stopband and passband conditions for particular signals. In order to avoid such arbitrariness, the Butterworth filter is used for general applications.

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253 3.2. Pressure quadrant

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Fig. 3 Representative time series of (a) the original u - and post-processed u_{pp} -velocity and (b) the direct measurements of ΔP_x . The velocities are expressed as pressure predictors $(0.5\rho\overline{C_D})u^2$, with the mean drag coefficient $\overline{C_D} = 1.28$ obtained by Celik *et al.* [9] for the same experiment. A 6th-order Butterworth filter with a cutoff frequency of 17 Hz is used to remove high-frequency velocity fluctuations including the short-lived spikes and plunges. The cutoff scale (maroon arrow) corresponds to the size of the test particle.

In an effort to enhance our understanding about the time-resolved characteristics of the local flow hydrodynamics and their impact on particle mobility obtained through the traditional velocity quadrant approach, a quadrant-based analysis of the net pressures applied upon the test particle is considered here. Similar to velocity, the net pressure can be categorized into four pressure quadrant events: (1) Q_{1P} ($\Delta P'_x > 0, \Delta P'_z > 0$), (2) Q_{2P} ($\Delta P'_x < 0, \Delta P'_z > 0$), (3) Q_{3P} ($\Delta P'_x < 0, \Delta P'_z < 0$), and (4) Q_{4P} ($\Delta P'_x > 0, \Delta P'_z < 0$), where $(\Delta P'_x, \Delta P'_z)$ are the fluctuations of the streamwise and bed-normal net pressures, respectively, and the subscript “P” is used for pressure events. Fig. 4 illustrates the proposed pressure quadrant plane.

The pressure quadrant approach based on direct pressure measurements can provide an integrated examination of the instantaneous drag and lift forces. For instance, Q_{1P} reflects a trend

of increasing drag and lift forces when compared to the mean hydrodynamics. It can be regarded as a force fluctuation towards the downstream-upward direction “↗”. On the other hand, Q_{4P} represents a trend of increasing drag force, but decreasing lift force, which gives a force fluctuation towards the downstream-downward direction “↘”. This indication about the direction of force fluctuation is similar to that of velocity quadrants which characterize the direction of velocity fluctuation. Relating the pressure quadrant to the velocity quadrant can give insights about the role of particular flow processes on the instantaneous applied forces.

Fig. 4 also shows the thresholds for initiation of particle movement and possible motion modes. The suspension threshold $\Delta P'_{z_{cr}}$ (subscript “cr” indicates the critical value) is determined by considering a force balance in the vertical direction: the bed-normal pressure fluctuation $\Delta P'_z$ needs to generate sufficient lift force to overcome the submerged particle weight. The rolling threshold $\Delta P'_{x_{cr}}$ is calculated by moment balance (Appendix A): the streamwise pressure fluctuation $\Delta P'_x$ should produce sufficient moment to overcome the resisting moment due to gravity. The threshold $\Delta P'_{x_{cr}}$ varies linearly with $\Delta P'_z$ (Fig. 4) because the bed-normal pressure can influence the apparent particle weight. Particle sliding sometimes accompanies particle rolling if the friction between the particle surface and bed has been overcome. For a situation where $\Delta P'_x$ is quite large and $\Delta P'_z$ is close to the suspension threshold, the flow can induce saltation.

Need to keep in mind that full particle dislodgement typically takes more than a single quadrant event to be completed. A causal pressure sequence spanning over different quadrant domains is likely to occur under highly fluctuating flow conditions. In such cases, the final motion mode should depend on the cumulative effect of various pressure quadrants. The zones of rolling, saltation, and suspension are specified here only for identifying the pressure requirements in contributing to different motion types.

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290 **Fig. 4** Representative pressure quadrant plane presented in the unit of N/m^2 . The origin of the
 291 quadrant plane corresponds to the time-averaged net pressures $(\overline{\Delta P'_x}, \overline{\Delta P'_z})$ (Table 1). The particle
 292 rolling and suspension thresholds, $\Delta P'_{xcr}$ and $\Delta P'_{zcr}$, respectively, are determined for the present
 293 particle configuration. $\Delta P'_{xcr}$ is marked by a solid-blue line and $\Delta P'_{zcr}$ is marked by a dashed-red
 294 line.

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296 3.3. Simulating particle dislodgement

297 A trade-off of the direct pressure measurement is that the instrumented particle needs to be held
 298 in place throughout the experiment [22, 27]. Identifying particle movement, hence, relies on a
 299 numerical simulation. This study uses a perfect-rolling model, reported by Schmeeckle and
 300 Nelson [38], to predict particle dislodgement (Appendix A). Specifically, the angular
 301 displacement of the particle is calculated by considering the instantaneous moment induced by
 302 fluid forces that can be approximated by the net pressure measurements (Fig. 1b). The rolling
 303 trajectory is established over time until reaching the topmost of the bed pocket. Selection of the
 304 rolling mode is warranted because of the results obtained during mobile-particle experiments
 305 conducted by Celik *et al.* [16] under nearly identical hydrodynamic conditions.

306 Although this numerical approach has already been used to predict incipient rolling [19, 38-
 307 40], the particular advantage here is access to the directly measured net pressures. This allows

for more accurate detection of excessive fluid forces that surpass the rolling threshold, as contrasted to the force predictions made by nearby velocity measurements [38] or by theoretical approximation based on the law of the wall [40].

A total of 105 particle dislodgements are identified throughout the 15-min data record via the perfect-rolling simulation. This result is in very close agreement with the 104 dislodgements detected by Celik *et al.* [16] over a 15-min period in the mobile particle experiment, which constitutes a replicate of the fixed particle one. This agreement provides a great deal of confidence regarding the use of velocity/pressure data obtained from the static case to describe the general particle dislodgement characteristics. However, the detailed velocity/pressure conditions for a static and a mobile particle are not expected to be the same during the dislodgement process. This is not a serious limitation considering that each particle dislodgement is different, controlled by a unique combination of pressure and velocity conditions. A representative case of the rolling simulation is detailed in section 3.4 to emphasize the dynamic process of particle dislodgement.

3.4. Time-resolved rolling trajectory

The use of continuous simulation enables the calculation of a time-resolved rolling trajectory and underlines the dynamic nature of particle dislodgement. Fig. 5 exemplifies a simulated dislodgement accomplished by several turbulence sequences. The hydrodynamic impact is reflected in the dominant net pressure fluctuation $\Delta P'_x$. The bed-normal fluctuation $\Delta P'_z$ is factored into the critical value $\Delta P'_{x_{cr}}$ by allowing a time-variant threshold value (Fig. 5a). Specifically, an upward-directed pressure fluctuation ($\Delta P'_z > 0$) lowers $\Delta P'_{x_{cr}}$ by decreasing the submerged particle weight and vice versa. The particle location is represented by φ , the ratio of angular displacement to the angle of repose (Fig. 5b). A negative φ indicates a location upstream of the resting pocket.

In Fig. 5 an incomplete particle dislodgement is launched by the first excess pressure sequence (labeled as “A”), leading to reverse rolling towards the bed pocket (decreasing φ) and subsequent vibration within the pocket. The vibration is characterized by a very short period of slightly negative φ (red arrow). Another failed attempt of particle dislodgement “B” is captured at a later point in time, but it barely reveals within-pocket vibration. Two consecutive excess

pressure sequences, “C₁” and “C₂”, cause continuous rolling towards downstream and eventually complete the particle dislodgement process.

During the dislodging process “C”, a significant drop in $\Delta P'_{x_{cr}}$ results mostly from the fast reducing particle resistance $F_g \cos(\theta)$ as θ changes with particle location. The angle θ increases from 0.4π at the original resting site to nearly $\pi/2$ at the topmost location (Fig. 1b), where the counteracting moment resisting particle rolling becomes almost zero. Consequently, the greatly lowered threshold facilitates forward particle movement for the excess sequence “C₂”, even though “C₂” is less energetic than the preceding sequence “C₁”. Based on this dynamic dislodgement scenario, a time-sequence approach is well suited for the proper consideration of the successive destabilizing turbulence events.

Fig. 5 Representative time series of (a) net pressure fluctuation $\Delta P'_x$ and (b) resulting rolling progress expressed by the ratio ϕ of angular displacement to the angle of repose. The rolling threshold $\Delta P'_{x_{cr}}$ varies with $\Delta P'_z$ over time and drops significantly when the particle is moderately displaced. The red arrow indicates a short period of vibration after an incomplete dislodgement.

3.5. Ensemble-average analysis

In addition to the essential moving fluid parcels that directly impart momentum on particles (e.g. excess pressure sequences shown in Fig. 5b), the prevalent characteristics of the related large-scale coherent structures are examined here. This is pursued via an ensemble-average analysis performed over the entire 105 particle dislodgement cases. The period of ensemble-averaging processes is selected as 3.0 s, more than 15 times the integral time-scale of 0.185 s, to account for the effects of macro-turbulence. The number of dislodgement replicates considered here is sufficiently large to secure statistically stationary results (Appendix B).

3.6. Quadrant probability

The temporal records of velocity and pressure quadrants are of particular interest. The most frequently encountered quadrant events are highlighted throughout the ensemble-averaged time series to characterize coherent structures. For comparison purposes, the probability $F_i(t)$ of finding the flow at quadrant i at a given time t can be defined by

$$F_i(t) = \frac{n_i(t)}{\sum_{j=1}^4 n_j(t)} ; \text{ for } i = 1, 2, 3, 4, \quad (1)$$

where n_i is the number of i -th quadrant realizations.

4. Results

The velocity and pressure (quadrant) sequences associated with particle dislodgement are presented here to verify the proposed turbulence sequence approach. The overall statistics of causative quadrant events, including the ensemble-averaged time series, provides characteristics of relevant coherent structures. For presentation purposes, a new time scale t_E is used here so that different dislodgement cases can be compared easily by designating the instant of initiation of particle movement at $t_E = 0$. Particle dislodgement is completed at $t_E = T_D$, with T_D the duration of the dislodging process.

4.1. Case studies

Two different dislodgement cases are considered here (Fig. 6). Case 1 is characterized by a major velocity lobe having high magnitude and short duration (Fig. 6a). Case 2 exhibits the opposite trend (Fig. 6b), where the fluid parcel is less energetic but relatively extended as compared to Case 1. Also, Case 2 shows abundant high-frequency velocity fluctuations,

indicating a highly unsteady condition which likely stems from the interactions between coherent structures and background turbulence. The velocity filter is quite useful for removing inconsequential events under such unsteady conditions (blue arrows). In both cases, the post-processed velocities are in better agreement with the synchronous pressures (Fig. 6 insets), compared to the original velocity records.

As expected, velocity quadrant signatures are subjected to some minor changes after performing the filtering process. For the entire 15-min measurement period (225,000 realizations), the maximum change in probability (or fractions) among all four quadrant categories is $< 2\%$. However, a somewhat considerable quadrant variation can be noted at a smaller time-scale such as the dislodgement duration T_D . For example, Case 2 has a probability change as high as 11% in favor of Q_{4V} (Fig. 6d). The highly unsteady flow of Case 2 appears to be sensitive to velocity filtering, contrasted to Case 1 with a minor 2% change (Fig. 6c). In addition to the probability, the magnitude of velocity quadrants is modified to a more modest level.

Fig. 6 Temporal records of original velocity u and post-processed velocity u_{pp} for (a) Case 1 and (b) Case 2. The velocity traces during the period of particle dislodgement are highlighted by

red lines, and their quadrant signatures are presented in (c) and (d) for Cases 1 and 2, respectively. The corresponding ΔP_x traces are plotted in the insets of (a) and (b) for comparison purposes. The scale right next to the ΔP_x traces represents a magnitude of 100 N/m^2 .

4.2. Sequential velocity quadrants

In Cases 1 and 2 the Q_{4V} and Q_{1V} events related to particle dislodgement are shown in Figs. 6c and 6d. Their sequence characteristics are further demonstrated in Fig. 7 to emphasize the time-variant nature of the causal turbulence. A complete dislodgement takes the full length of the quadrant sequences exhibited therein to be achieved. To improve clarity, quadrant events are marked differently based on their association with the first ($t_E = 0 \sim 0.5 T_D$) or second half ($t_E = 0.5 T_D \sim T_D$) of the dislodgement periods. The trace (or direction) of quadrant transitions is indicated by single-arrow lines.

Generally, the original velocity quadrants display erratic transitions between successive events (Figs. 7a and 7b). Although a very rough trend can be identified, the convoluted quadrant traces make the flow physics difficult to interpret meaningfully. The impactful flow processes are obscured by such unsteadiness due to the interactions with local turbulence, particularly for Case 2 (Fig. 7b).

The velocity filter effectively improves the velocity quadrant sequences by removing outliers and provides smoother transitions between successive points (Figs. 7c and 7d). In Fig. 7c the filtered quadrant trace clearly exhibits a short period of intensifying downward velocity fluctuations (temporarily enlarged negative w') in the beginning and then a strengthening flow in the direction of “ $\searrow$ ”. This trend indicates a progressively advancing coherent structure that is characterized mainly by strong sweeps (Q_{4V}). The brief appearance of outward-interactions (Q_{1V}) supports the above statement. According to Hofland *et al.* [27] using Particle Image Velocimetry (PIV) mapping techniques, Q_{1V} appears briefly near a protruding particle right before the flow field is dominated by Q_{4V} of the coherent structure.

The more complex local flows of Case 2 can be regarded as a generalized version of Case 1. In Fig. 7d the entire quadrant trace consists of several intensifying-weakening cycles regarding

u' magnitude, suggesting a series of distinct fluid parcels flowing past the test particle. As a result, the particle experiences consecutive hydrodynamic impacts of highly variable magnitude.

Fig. 7 Quadrant sequences of Cases 1 and 2 respectively: (a) and (b) present the original velocity quadrant traces; (c) and (d) present the post-processed velocity quadrant traces; (e) and (f) show the causal pressure quadrant traces. The blue broken lines in (e) and (f) represent the critical pressure fluctuation $\Delta P'_{x_{cr}}$ for initiation of particle rolling.

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437 4.3. Sequential pressure quadrants

438 The hydrodynamic impact of Cases 1 and 2 is presented more conclusively by pressure quadrant
439 sequences than by velocity quadrant sequences (Figs. 7e and 7f). In the rolling process, the test
440 particle experiences mostly the pressure fluctuations characterized by Q_{1P} , indicating a trend of
441 increasing drag and lift forces (“↗”). The resultant force either almost monotonically increases
442 (Fig. 7e) or somewhat regularly fluctuates over time (Fig. 7f), based on the complexity of the
443 approaching coherent structures. The force variations can also be perceived via the dominant ΔP_x
444 contribution shown in the insets of Figs. 6a and 6b.

445 The temporal patterns of pressure quadrant sequences are more congruent with the post-
446 processed velocity quadrant sequences than with the original ones (Fig. 7c → 7e and Fig. 7d →
447 7f). Even so, the improved velocity quadrant realizations cannot reflect particle mobility
448 completely due to the following two reasons.

449 Firstly, it is not easy to define a unique threshold velocity quadrant that can correspond to the
450 critical pressure quadrant ($\Delta P'_{x_{cr}}$). The very first event of pressure quadrant sequences is close to
451 the deterministic threshold $\Delta P'_{x_{cr}}$ (red circles in Figs. 7e and 7f), whereas the first velocity
452 quadrant event varies considerably between Cases 1 and 2 (Figs. 7c and 7d). The varying
453 incipient velocity quadrant highlights the difficulty of identifying a single characteristic velocity
454 to predict particle motion. Therefore, the traditional incipient velocity method is not suitable for
455 the near-threshold conditions considered here.

456 Secondly, velocity fluctuations are not entirely consistent with pressure fluctuations regarding
457 both the resultant direction and magnitude. The upward pressure fluctuations (Q_{1P}) are
458 associated with not only the upward velocity fluctuations (Q_{1V}) but also the downward velocity
459 fluctuations (Q_{4V}). Also, the increasing/decreasing magnitude of pressure quadrants is not
460 closely reflected by the trend of velocity quadrants (e.g. $t_E = 0 \sim 0.5 T_D$ in Fig. 6c compared with
461 Fig. 6e). As a result, the approaches based on velocity fluctuations in estimating particle mobility,
462 such as Reynolds stress methods, can be compromised by such velocity-pressure incongruence.

463 Overall, pressure quadrant sequences can accurately characterize the consecutively applied
464 fluid forces, while velocity quadrant sequences can reveal the relevant flow processes. Used in

tandem, these quadrant types can provide a better understanding about cause and effect relation between hydrodynamic processes, including coherent structures, and particle movement.

4.4. Statistics of causal quadrant sequences

As shown in Fig. 7, the period of residence in individual quadrant domains changes considerably throughout the entire quadrant sequences and among different cases. Fig. 8 provides visualization of the associated temporal fractions to demonstrate the domain transitions. Cases 1 and 2, along with three other dislodgement cases (3-5), are exemplified here.

In Fig. 8a the velocity quadrant sequences of Cases 1 to 4 can all be categorized as the same sequence type of $\{Q_{4V}, Q_{1V}, Q_{4V}\}$, solely based on the order of appearance of the quadrant types. Similarly, in Case 5 the flow processes can be characterized by the sequence of $\{Q_{4V}, Q_{1V}\}$. This simplified characterization is mainly intended to capture the overall process qualitatively, thus ignoring that the temporal fraction related to each quadrant domain is quite different. The duration aspect of quadrant sequences remains important as far as particle dislodgement is concerned.

In Fig. 8b the pressure quadrant sequences are categorized in the same manner. Furthermore, very short residence in a quadrant domain ($<5\%$ of T_D) is neglected to highlight the most impactful quadrant groups. For instance, Q_{4P} in Cases 2 and 3 (red arrows) is negligible. As a result, the consecutive hydrodynamic impact of Cases 1 and 2 is characterized by a pressure quadrant sequence residing exclusively within $\{Q_{1P}\}$, and that of Cases 3 to 5 is reflected by $\{Q_{1P}, Q_{4P}, Q_{1P}\}$.

Examining the entire 105 dislodgement cases under the above method yields the overall occurrence probability of the causal quadrant sequences (Fig. 9). Fig. 9a shows that most of particle dislodgements ($\sim 80\%$) are completed during the equally frequent flow sequences of $\{Q_{4V}, Q_{1V}, Q_{4V}\}$ and $\{Q_{1V}, Q_{4V}\}$. The causative hydrodynamics appears sequentially as $\{Q_{1P}, Q_{4P}, Q_{1P}\}$ or exhibits consistent $\{Q_{1P}\}$ all the time. These characteristic quadrant sequences are more representative of the particle dislodging process than the results obtained through the conventional single quadrant method.

Fig. 8 Visualization of residence time in different (a) velocity quadrant domains and (b) pressure quadrant domains. The residence time is normalized by the dislodgement duration, which is specified in (b) for individual cases.

Fig. 9 The occurrence probability of various sequence types: (a) velocity quadrant sequences and (b) pressure quadrant sequences

4.5. Ensemble-averaged temporal records

So far the essential hydrodynamic conditions that directly cause particle dislodgement have been described comprehensively. A broader perspective on the relevant coherent structures is then presented via the 3.0 s temporal records of ensemble-averaged variables. The resultant velocity, pressure, and corresponding probability of their quadrant signatures are of particular interest (Fig. 10). In this ensemble averaging process, the time interval considered for grouping data is 0.04 s (Appendix B), accounting for 10 data readings from each registered dislodgement. Therefore, each ensemble-averaged value lumps a total of 1050 velocity/pressure readings.

In Fig. 10, the characteristic quantities exhibit an asymmetrical, large-scale pattern spanning roughly over 2.0 s ($t_E = -0.5 \sim 1.5$ s). This flow pattern (structure) is characterized by abruptly increasing velocity and pressure signals (Figs. 10a and 10b), which exceed the threshold of

incipient rolling conditions at $t_E = 0$ s and reach their peak values at $t_E \approx 0.1$ s. These signals last for sufficiently long time to complete the dislodgement. Succeeding the particularly strong spike is a weak, yet long-lasting, wake that smoothly approaches the long-term average level. During this flow process, the dominant velocity quadrant Q_{4V} and pressure quadrant Q_{1P} (Figs. 10c and 10d) bear strong resemblance to those documented in the velocity and pressure traces (Figs. 10a and 10b). It is worth mentioning that all of the 105 dislodgements were completed at a later time, $0.128 \text{ s} \leq T_D \leq 0.480 \text{ s}$, than the instant the peak velocity and net pressure values occurred (see Fig. 10).

Overall, the ensemble-averaged records indicate an evident coherent structure deviating from the mean flow. This Q_{4V} dominant structure very likely belongs to the lower portion of near-bed span-wise vortices that have been extensively identified by PIV and similar visualization techniques [22, 41, 42]. When this Q_{4V} structure appears near the sediment particle, the applied net pressures (corresponding to quadrant Q_{1P}) increase the probability of particle dislodgement.

Fig. 10 Ensemble averaged traces: (a) the resultant velocity $V = (u^2 + w^2)^{0.5}$ with corresponding angle $\theta_V = \tan^{-1}(w/u)$, (b) the resultant net pressure $\Delta P = (\Delta P_x^2 + \Delta P_z^2)^{0.5}$ with corresponding angle $\theta_P = \tan^{-1}(\Delta P_z/\Delta P_x)$, and (c) and (d) the probability of velocity and

pressure quadrants, respectively. The long-term average quantities are presented by horizontal lines.

5. Discussion

For more than a century significant efforts have been made to clearly identify and quantitatively determine the critical conditions for particle movement. The temporally and spatially averaged flow parameters have been widely used for engineering applications [43]. Subsequently, a better understanding of turbulent flows allowed for a time-resolved analysis of flow physics near threshold conditions. Considering the random and intermittent nature of sediment movement that prevails near-threshold conditions, it is reasonable, as a first step, to highlight the importance of the extreme instantaneous quantities in highly fluctuating flow fields. The probabilistic properties of peak instantaneous forces or their velocity equivalents are of particular interest.

However, the peak magnitude of fluid forces alone is inadequate to capture the full process of particle dislodgement (e.g. Fig. 5a). From an energy perspective, the applied force needs to last for a sufficiently long period of time in order to perform the required mechanical work to move the particle for a certain distance. To account for the relevance of force duration, Diplas *et al.* [17, 44] proposed using hydrodynamic impulse (force magnitude times its duration) as a more comprehensive criterion to predict particle dislodgement. The dislodgement attributed to the instantaneous peak force, in fact, can be regarded as a special case of impulse concept, where an extremely large force only requires a very short period of time to impart the necessary momentum for particle dislodgement. For near-threshold conditions, such scenarios, though physically possible, are expected to be very rare. A modest force scenario, moderately exceeding the initiation of motion criterion, requires a longer duration to convey the same impulse as that conveyed by the extremely large force. The latter case is expected to be more representative of the flow events resulting in particle dislodging processes. As it has already been pointed out in recent studies, given the highly unsteady nature of the hydrodynamic forces, it is more appropriate to characterize particle threshold conditions via the concept of minimum impulse or energy rather than minimum force [9, 14, 17, 25].

Fig. 11 shows the rate of impulse transfer made by two different turbulent processes mentioned previously. The applied impulse is computed by multiplying the varying resultant force by its corresponding duration. In Fig. 11 the variable β indicates the ratio of the cumulative impulse at any given t_E to the total impulse amount required for particle dislodgement ($\beta = 1$). The slope of β curves reflects how fast the flow can impart momentum onto the particle via impulse and thus how quickly it can dislodge it. As expected, the stronger turbulent flow event of Case 1 attains dislodgement ($\beta = 1$) more quickly compared to the less energetic flow of Case 2. This result confirms the veracity of impulse as a consistent criterion to predict particle dislodgement even when subjected to different hydrodynamics.

Fig. 11 also reveals different stages in the dislodging process based on the slope change. Case 1 has a mild slope initially and a rapidly increasing slope in the later stages. The rapidly increasing slope results from the combined effect of the surge in force magnitude (Fig. 6a inset) and coincident decrease in the threshold value (similar to that shown in Fig. 5a, event “C”), thus boosting momentum transfer significantly. This case underlines an accelerating process of dislodgement once the particle has been partially mobilized. In the sense of threshold of motion, the initial phase of fluid force magnitude relative to particle resistive forces can be most critical in determining particle mobility. Such considerations may explain why many researchers are inclined to regard particle dislodgement as a matter of force magnitude or moment balance of the instantaneously applied forces [45], and refer to the peak forces as the sole cause of particle dislodgement. On the contrary, Case 2 shows that the consecutive hydrodynamic impact, including the peak events, contribute to the overall development of particle dislodgement (Fig. 11). This process should be better characterized by the turbulence sequences and their respective durations than by the single instantaneous quantities.

Fig. 11 The rate of impulse transfer associated with turbulent processes of Cases 1 and 2.

6. Conclusions

The overarching goal of this study is to gain a better understanding of the pertinent hydrodynamic processes leading to particle dislodgement under near threshold of motion conditions. To accomplish this objective, this study demonstrates the utility of the following three concepts: 1) use of quadrant sequences instead of individual quadrant points, 2) use of pressure quadrant method as a more reliable approach for identifying threshold conditions, and 3) coupling of velocity and pressure quadrant sequences to better resolve prevailing flow characteristics and associated coherent structures responsible for particle movement. This sequence-based approach highlights the importance of turbulence event duration and the dynamic process of particle dislodgement.

Statistical analysis of 105 dislodgement events, which are determined analytically, indicates the velocity quadrant sequences of $\{Q_{4V}, Q_{1V}, Q_{4V}\}$ and $\{Q_{1V}, Q_{4V}\}$ as the most frequent flow processes present during the periods of dislodgement. The causative impact upon particle dislodgement is attributed to consecutive $\{Q_{1P}, Q_{4P}, Q_{1P}\}$ or consistent $\{Q_{1P}\}$ sequences. As for the relevant coherent structures, ensemble-average analysis identifies large-scale flow patterns characterized by sustained Q_{4V} events. The associated hydrodynamic effects are reflected by pertinent Q_{1P} over time. This result suggests that large-scale sweeps can generate excessive and persistent force fluctuations, which, in turn, promote conditions favorable for particle dislodgement.

Overall, the turbulence sequence methods presented here can resolve dynamic processes of particle dislodgement more appropriately than the typical considerations of single instantaneous parameters. Furthermore, they support the impulse criterion as the proper way of accounting for the cumulative effect of coherent structures on the mobility of a particle.

Appendix A: Perfect-rolling simulation

The schematic of the forces applied on the test particle is shown in Fig. 1b. The equations of motion used to simulate the trajectory of a perfect-rolling spherical particle are based on Schmeeckle and Nelson [38]:

$$r \left(\frac{7}{5} \rho_s + C_m \rho \right) \Gamma \frac{d^2 \theta}{dt^2} = F_D \sin(\theta - \alpha) + F_L \cos(\theta - \alpha) - F_G \cos(\theta), \quad (\text{A.1})$$

$$r(\rho_s + C_m \rho) \Gamma \left(\frac{d\theta}{dt} \right)^2 + F_N = F_L \sin(\theta - \alpha) - F_D \cos(\theta - \alpha) - F_G \sin(\theta), \quad (\text{A.2})$$

where ρ_s is the density of sphere, C_m is the added mass coefficient, and Γ is the sphere volume.

During the rolling process the applied forces are expected to change due to the varying relative speed between the flow and moving particle. The modulated drag force F_{Dm} can be determined as follows:

$$F_{Dm} = F_D (1 - u_p/u)^2, \quad (\text{A.3})$$

where u_p is the streamwise component of particle speed. The mean particle speed (1.84 cm/s) reported here is 5.1% of the mobilizing flow velocity, causing 10% reduction in the drag force. However, the increasing degree of particle exposure (A_D), from 87% to 98%, compensates for the above force reduction. The consequent force variation is negligible ($\sim 2\%$). Also ignored are the modulations of the lift force and ambient flow velocity for the reason of simplicity.

During the 15-min pressure record, permanent particle displacement beyond the pivot point occurs intermittently at a mean frequency of 7.0 dislodgements/min. This result exhibits an error $< 1\%$ compared to the mobile-particle experiments performed by Celik *et al.* [16] under practically identical hydrodynamic conditions. The periods of these particle dislodgements range

from 0.128 to 0.480 s with a mean value of ~ 0.2 s. Reasonable agreement is found in comparisons with other experimental results using particles of similar size [14, 15].

Appendix B: Convergence tests

Convergence tests are performed in advance to determine an appropriate temporal-resolution for the ensemble-average analysis with limited number of dislodgement replicates. The target variables are ensemble-averaged with N replicates over a time interval Δt , which is assigned values ranging from 0.004 to 1.0 s. Based on the variable convergence, the temporal-resolution of $\Delta t = 0.04$ s can maximize the turbulence-resolving capacity while maintaining stationary statistics with $N < 100$ replicates. Fig. B.1 shows the convergence of u -velocity and quadrant types Q_{4V} and Q_{1V} using the above resolution. The degree of u variation is progressively reduced and the standard deviation is $< 2\%$ of the mean velocity at $N = 90$ (Fig. B.1a). The velocity quadrants can converge even faster than u -velocity (Fig. B.1b). With the same time-resolution, the pressure data yield very similar results in the convergence tests (not presented).

Fig. B.1 Convergence test for the ensemble-average analysis: (a) u -velocity and (b) dominant velocity quadrants Q_{4V} and Q_{1V} .

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