J. Hydrol. Hydromech., 61, 2013, 3, 202–207
DOI: 10.2478/johh-2013-0026

Numerical study of near-bed turbulence structures influence on the initiation of saltating grains movement

Robert J. Bialik

Institute of Geophysics, Polish Academy of Sciences, Ks. Janusza 64, 01-452 Warsaw, Poland. E-mail: rbialik@igf.edu.pl

Abstract: The focus of this paper is on the analysis of the influence of near-bed turbulence structures with the inclusion of existing coherent structures on the entrainment of saltating particles in a water stream from the Lagrangian perspective. The interactions between turbulence structures and initiation of particles movement is the key for better understanding of the physics of sediment transport and particles behaviour. These aims are addressed by use of a 3D relevant model of spherical saltating particles, in which a special procedure has been designed to produce coherent structures. In this method, the spectra of turbulent kinetic energy, consisting of four ranges, are used to generate the time series of turbulent velocities in the streamwise, vertical and transversal directions. Numerical results suggest that the initiation of sediment movement is strongly correlated to positive streamwise velocity fluctuations and as such, supports earlier laboratory experimental and field observations, showing that the sweeps and outward interactions play a crucial role in the initiation of saltating particles' movement.

Keywords: Entrainment; Numerical simulations; Saltation; Sediment transport; Turbulence structures.

INTRODUCTION

The movement of sediment particles in the form of saltation is strongly affected by the flow conditions, especially at the moment when they start to move. One of the most popular views on the incipient motion of particles is that the entrainment of gravel, as well as that of sand grains, is caused by the interactions between particles and coherent structures often associated with the so-called bursting process. The quadrant analysis technique is usually used to identify these structures. This analysis is applied to discriminate important instantaneous Reynolds stress or covariance terms and four regions (quadrants) may be detected; firstly, depending on the signs of the streamwise (u') and vertical (w') velocity fluctuations and then, by checking fractional Reynolds stress belonging to those particular regions (e.g., Czernuszenko and Rowiński, 2008; Lu and Willmarth, 1973; Nezu and Nakagawa, 1993). Thus, outward interactions (Q_1) are sought when ($u' > 0$, $w' > 0$), ejections (Q_2) when ($u' < 0$, $w' > 0$), inward interactions (Q_3) when ($u' < 0$, $w' < 0$) and sweeps (Q_4) when ($u' > 0$, $w' < 0$). The bursting process, which is composed of quasi-cyclic ejections and sweeps of fluid parcels, is suspected of dominating entrainment and sediment transport. Many laboratory measurements and field observations show that the initiation of sediment movement is correlated with fluctuations in streamwise velocity (e.g., Drake et al., 1988; Heathershaw and Thorne, 1985; Nelson et al., 1995; Papanicolaou et al., 2001; Schmeeckle and Nelson, 2003; Thorne et al., 1989; Wiberg and Smith, 1985 and Williams et al., 1989). This suggests that the outward interactions and sweeps are most important in the process of sediment entrainment. Heathershaw and Thorne (1985) observed that the vertical velocity fluctuation is also important for the initiation of particle movement, because the positive value of this velocity component indicates additional lift force. They speculated that this type of velocity fluctuation is related to outward interactions that govern the sediment entrainment. Drake et al. (1988) noticed that gravel entrainment is associated with frequent and random sweep events. Thorne et al. (1989) also reported that the sweeps and outward interactions control the sediment entrainment. Nelson et al. (1995) gave a very good account of the role of the near-bed turbulence structures in the initiation of particle movement. They observed that individual sweeps and outward interactions move sediment far more than do the ejections and inward interactions. Moreover, they reported that when the outward interactions increase compared with other events, the sediment flux increases although the bed shear stress decreases. Wu and Jiang (2007) noticed that the earlier suggestions made by Nelson et al. (1995) are not valid for all sediment mixtures. They showed that while sweeps are always dominant, outward interactions and ejections depend on the different sorting of sediment. In addition, Diplas et al. (2008) and Valyrakis et al. (2010) hypothesised that force impulse rather than force itself is responsible for particle entrainment. Recently, Dwivedi et al. (2010, 2011) has shown that the higher probability of occurrence of high magnitude force on a spherical sediment particle is induced by sweep events and that outward and inward interactions are of little importance in sediment entrainment.

This paper presents numerical experiments and their interpretations, which supplement and further extend previous studies of saltation (e.g., Bialik, 2011a, 2011b; Bombardelli et al., 2008; Lee et al., 2000, 2006; Lukerchenko et al., 2006, 2008, 2009a, 2009b; Moreno and Bombardelli, 2012; Niño and Garcia, 1994, 1998; Wiberg and Smith, 1985, among others). New information is provided on the incipient motion of saltating grains over immobile-bed flows, associated with the existence of near-bed turbulence structures and their influence on the particles' motion.

MODELS FOR THE PARTICLE SALTATION AND FLOW VELOCITY FIELD

A Lagrangian model of saltating grains, proposed by Bialik (2011a) and further extended to the 3D model by Bialik et al. (2012), is adopted in this work. Only a brief description is presented here; readers are referred to the original works for further details. This model consists of the balance of the fundamental forces exerted on moving particles in a fluid flow: drag force $\boldsymbol{F}_D$, lift force $\boldsymbol{F}_L$, Magnus force $\boldsymbol{F}_M$, virtual mass force $\boldsymbol{F}_v$, Basset force $\boldsymbol{F}_B$ and the force due to gravitational acceleration $\boldsymbol{F}_g$. The general form of this model is as follows:

$$\rho_p \frac{\pi d^3}{6} \frac{\mathrm{d}\boldsymbol{u}_p}{\mathrm{d}t} = \boldsymbol{F}_D + \boldsymbol{F}_L + \boldsymbol{F}_M + \boldsymbol{F}_v + \boldsymbol{F}_B + \boldsymbol{F}_g, \quad (1)$$

where t is time, $\boldsymbol{u}_p$ denotes the particle velocity vector, ρ_p stands for the density of particles and d is the saltating particle diameter.

If Eq. (1) is supplemented with the trajectory equation, it can easily be solved numerically using the fourth-order Runge-Kutta method. Abbott and Francis (1977) reported that the particles' velocity in both the streamwise u_p and vertical w_p directions should be approximately $2u_*$, where u_* is the shear velocity. Therefore, the following initial conditions are usually applied in Lagrangian models of saltation: $u_p(t_0) = 2u_*$ and $w_p(t_0) = 2u_*$. However, in order to analyse the entrainment of sediment particles the initial conditions will be as follows (Bialik et al., 2012): $x_p(t_0) = 0$, $y_p(t_0) = 0$, $z_p(t_0) = 0.5$d, $u_p(t_0) = 0$, $v_p(t_0) = 0$ and $w_p(t_0) = 0$ because the initiation of the particles' movement will be caused by the results of the velocity fluctuations and their influence on the values of the lift and drag forces; coordinates x_p, y_p, z_p describe particle position in streamwise, transverse and vertical directions, respectively.

Moreover, it is important to note here, that for the purpose of this study the Basset and Magnus forces will be neglected. Lukerchenko et al. (2012) reported that the Basset force should be taken into account in the numerical modelling of spherical particle saltation, especially if the processes of particle-particle and particle-bed collisions are considered. This force can be only neglected for 2D models if the particle Reynolds number Re_p is larger than about 4000 and for 3D numerical models of saltation if $Re_p \geq 8000$. However, because in the considered case the particles' velocity is equal to $\boldsymbol{u}_p = (0,0,0)$, $Re_p = 0$. In such a situation, the Basset force can be omitted in computations (Lukerchenko et al., 2012). The findings of Nelson et al. (1995) and Dwivedi et al. (2011) confirmed our considerations that particle motions are dominated only by lift, drag and gravity, especially in the moment of entrainment. A similar explanation may be given regarding the Magnus force, because in the considered situation the particle lies on the channel bottom and does not exhibit any rotation. The lift force arises only due to the influence of the mean velocity gradient or velocity fluctuations and therefore, the Magnus effect does not appear.

In addition, one of the key components that enter Lagrangian models of saltation and on which particles motion depends, is the flow velocity field. For this purpose, the Monte-Carlo based generator, initially proposed by Nikora et al. (2001) and further used to model of saltating grains movement in 2D by Bialik et al. (2010) and Bialik (2011a) and recently applied to 3D model by Bialik et al. (2012), will be used in this study. This model is even more important because it will be used for the generation of coherent structures, the importance of which in the incipient motion of saltating grains, is what we want to show in this paper. The main rules of this generator are as follows (for details see Bialik et al., 2010, 2012):

1. Flow velocity in streamwise, vertical and transversal directions are decomposed into mean flow velocity $\overline{u}_f$, $\overline{w}_f$ and $\overline{v}_f$ and velocity fluctuations u', w' and v', respectively. Moreover, it is assumed that the logarithmic law holds in the near-bed regions and that $\overline{w}_f$ and $\overline{v}_f$ are negligible small.
2. The wave-number auto-spectra of velocity components consisting of four ranges (Nikora 1999, 2005) are assumed to be known at any distance from the channel bed. In addition, the vertical distributions of relative turbulence intensities are described by well-known (Nezu and Nakagawa, 1993) formulae (Eq. (2)):

$$\frac{\sigma_{u,w}(z)}{u_*} = D_{u,w} \exp\left(-\left(\frac{z}{H}\right)\right), \quad (2)$$

where σ_u, σ_w stand for the streamwise and vertical relative turbulence intensities, respectively, u_* is the shear velocity, $D_{u,w}$ is another parameter for the components u and for w, respectively, z is the distance from the bed and H is the flow depth.
3. Inverse Fast Fourier Transform is then applied to obtain the time series in the streamwise and vertical directions, as the shapes of the auto-spectra in these directions are also assumed to be known.
4. Moreover, the flow is divided into layers equal to half the diameter of the moving particle. For each layer, the flow is generated separately using the Monte Carlo approach and the time series in the neighbouring layers are correlated using the same phases of spectral components of velocity signals across the flow. In addition, the velocities in the streamwise and vertical directions are correlated and they are generated by trial and error until the experimental formula of this correlation (Eq. (3)), given by Nezu and Nakagawa (1993), is satisfied:

$$0.4 < -\frac{\overline{uw}}{u'w'} < 0.5. \quad (3)$$

5. Finally, the time series in the transversal direction is calculated based on the continuity equation.
6. Moreover, it is assumed that the Taylor's hypothesis about eddies frozen in the mean flow that are advected downstream without change is valid.

The main advantages of this method are that it is relatively simple and fast in comparison with other procedures, such as Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) or the Lattice Boltzmann Method (LBM). The hypothetical instantaneous quasi-Lagrangian fluctuating flow velocities in the streamwise and vertical directions, obtained with use of the described Monte Carlo generator, are shown in Fig. 1. The adoption of the term "quasi-Lagrangian" is based on the numerical comparison between the mean Eulerian spectrum and the "quasi-Lagrangian" one, which is calculated based on the proposed methodology and presented in Bialik et al. (2010) who showed that the obtained slope of "–2" for this spectrum fits well the theoretically based Lagrangian one (Monin and Yaglom, 1971) (see Bialik et al., 2010 for details). In addition, the presented results confirm the ability of this method to generate turbulence eddies and coherent structures. A very strong sweep event with a long lifetime is marked in this Fig. 1. Dwivedi et al. (2011) noted that Q_4 events generate sufficient values of the drag and lift forces required for entrainment and thus, we believe those results show the potential of the model for analyses of sediment entrainment. Moreover, all other events are also easy to recognize in Fig. 1, i.e., a long lifetime ejection just before the considered sweep but they are not indicated here for better clarity of this plot.

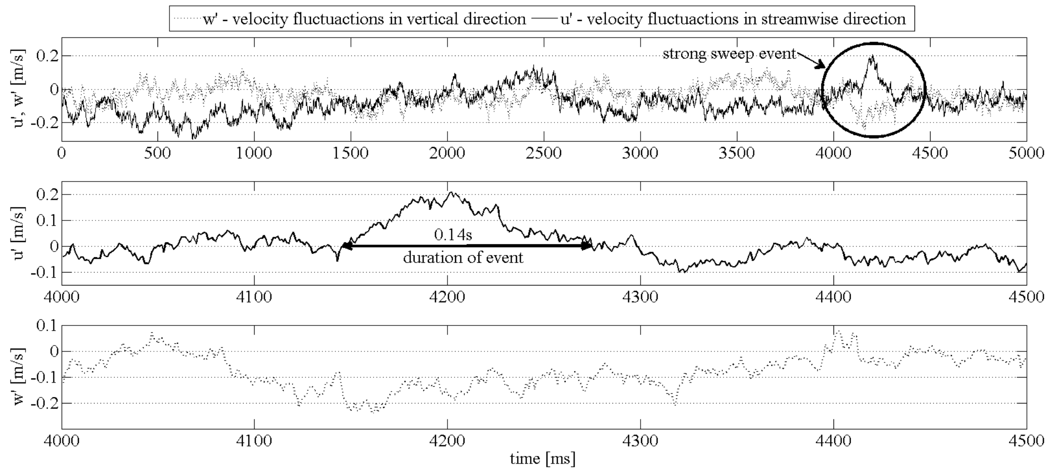

Fig. 1. Time series of exemplary, quasi-Lagrangian instantaneous streamwise and vertical velocity fluctuations.

INITIATION OF SALTATING GRAINS MOVEMENT

In this section, the role of near-bed turbulence structures in the initiation of saltating grains movement for three values of particle mobility parameter: K = 1.1; 1.5; 2.5 and for three values of relative sizes of saltating particles; d/D = 0.5; 1; 2 will be briefly assessed; d denotes flying particle and D stands for the bottom particle. The mobility parameter K is required to calculate the fluid shear velocity u_* needed for computations of initial conditions and is defined as (Bialik et al., 2012)

$$K = \frac{1}{\tau_{cr}} \frac{\rho u_*^2}{\left(\rho_p - \rho\right) g d}, \tag{4}$$

where τ_{cr} = 0.05 is the critical value of the bed shear stress. The considered values of particle mobility parameter correspond to the three regimes: (1) for K = 1.1 the sediment is hardly moving; (2) for K = 1.5 the weak bed load transport appears; and (3) for K = 2.5 there is the bed load during large flood.

This work aims to explain the incipient motion of saltating particles from the Lagrangian perspective, based on an extension of previous research presented by Bialik et al. (2012). It aims to answer the question of which coherent structures are responsible for sediment entrainment and whether this process is dependent on the parameters of the particles' mobility and relative sizes of saltating and bottom grains.

By analogy with the popular quadrant analysis of the Eulerian fluctuating velocities (e.g., Nezu and Nakagawa, 1993), we decomposed the distribution of the generated Lagrangian velocity fluctuations (u' and w') into four quadrants: quadrant I ($u' > 0$, $w' > 0$, outward interactions), quadrant II ($u' < 0$, $w' > 0$, ejections), quadrant III ($u' < 0$, $w' < 0$, inward interactions) and quadrant IV ($u' > 0$, $w' < 0$, sweeps). In the conventional Eulerian approach, only those events for which an individual product of fluctuating velocities is larger than $H_t \sigma_u \sigma_w$ (Luchik and Tiedermann, 1987; Nezu and Nakagawa, 1993; Nikora, 2005) are taken into account; where σ_u and σ_w are the relative turbulence intensities in the streamwise and vertical directions, respectively. The value of the threshold level H_t is taken arbitrary (Nezu and Nakagawa, 1993). On the one hand, very small value of H_t or even equal to 0 usually is selected to analyse both strong and weak events together and to make the results comparable with the laboratory data (see i.e. Nikora, 2005). In addition, the large value of H_t is used only if the strong events are interesting for consideration. For example, Luchik and Tiederman (1987) suggested that the best agreement with visually detected events is given for the H_t = 1.2. In this study we used an arbitrarily low H_t = 0.2, in order that weak events could be also considered. Moreover, we employ the definition of particles' entrainment proposed by Drake et al. (1988), who claimed that entrainment of particles exists, if with constant motion they cover a horizontal distance equal to that of one of their diameters (see Fig. 2). It is important to note here that particles are simulated one by one and for each of them the time series of velocity fluctuation is generated separately.

Fig. 3 shows an example of the quadrant analysis for the simulations of entrainment of saltating grains for the particle mobility parameter K = 1.5 and the relative particle size d/D = 1. The number of events assigned to the appropriate quadrant has been summed up during the period between initiation of particle movement and the entrainment, i.e., when the particle covers a distance equal to that of one its diameters (see Fig. 2). The strong correlation between the entrained particles and the positive value of the streamwise velocity, related to the outward interactions and sweeps, can be seen in this figure. As discussed above, these results support earlier observations given, for example, by Nelson et al. (1995), who claimed that sweeps and outward interactions move much more sediment than ejections and inward interactions. This is despite the fact that the turbulence is almost totally generated by ejections and sweeps (Nezu and Nakagawa, 1993) and that these two events are much more common in rivers than inward and outward interactions. The generality of this relationship will be presented in the next part of this section; as until now, all the observations were made under very limited hydrodynamic conditions and need further analysis.

Figs 4, 5 and 6 summarise the simulation results obtained for a range of relative particle sizes, from d/D = 2 to d/D = 0.5 and three values of the particle mobility parameter: K = 1.1, 1.5 and 2.5. The results are presented in the histograms representing the time fractions of four quadrants. In general, one may observe that for all the considered cases, the outward interactions (Q_1) and sweeps (Q_4) are the major contributors to sediment entrainment with 60% to 70% of the particles entrained by these events. Marion and Tregnaghi (2013) based on the very accurate PIV measurements also have recently shown that about 70% of entrainment events were associated to peak values of the streamwise velocity. However, it should be noted that based on our simulations, in contrast to some theoretical considerations, the ejections (Q_2) take the smallest part in the initiation of particles' movements. For d/D = 2 (Fig. 4) with an increase of the K parameter, the number of sweeps and inward interactions increase and the number of ejections and outward interactions decrease by about 15%. For this case, the dominant role of the Q_1 and Q_4 events is not as visible as for the other considered situations (Figs 5 and 6). However, the more important role of the Q_3 events compared with that of the Q_2 events in initiation of particle movement is clearly noticeable for K = 2.5 and d/D = 1 and d/D = 0.5. These results suggest that the velocity fluctuations and thus, the turbulence play a much more important role in the entrainment of saltating grains than the mean velocity. It also shows the strong relationship between the drag and lift forces exerted on the particle at the moment of entrainment. In summary, with a decrease of the relative particle sizes the outward interactions (Q_1) and sweeps (Q_4) undoubtedly play major roles in this process.

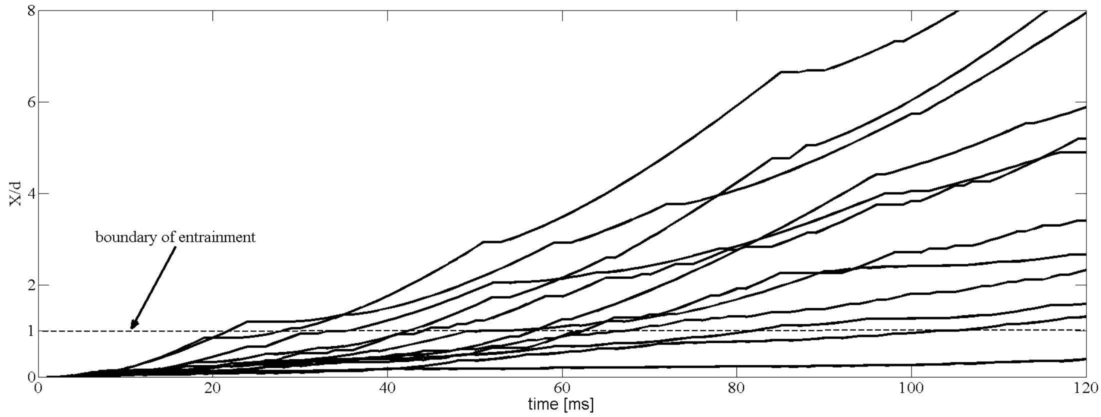

Fig. 2. Schematic of the boundary of entrainment and exemplary particles' positions $X(t)/d$ (adapted from Bialik et al., 2012).

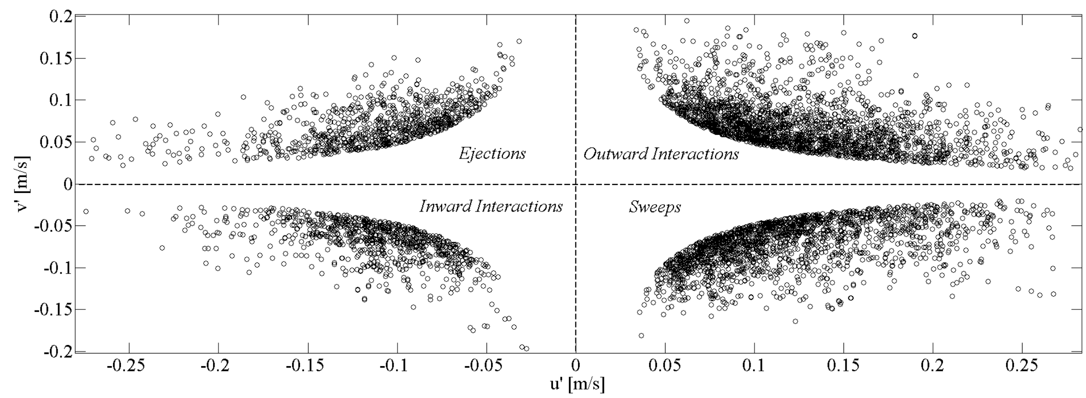

Fig. 3. Schematic representation of bursting events including a threshold level H_t = 0.2 (taken arbitrarily), associated with the existence of particles' entrainment and calculated based on the proposed model.

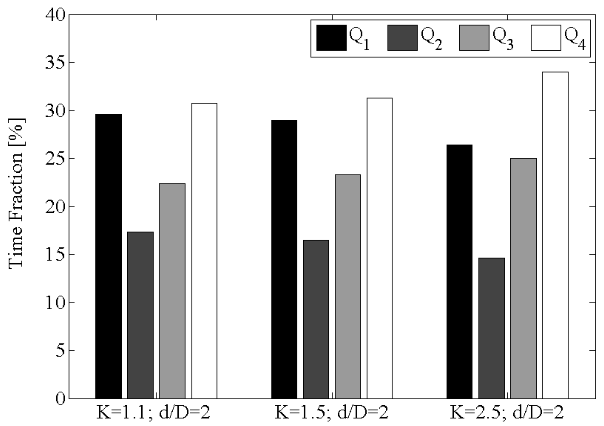

Fig. 4. Time fractions of four quadrants for d/D = 2 and three values of parameter K = 1.1, 1.5, 2.5.

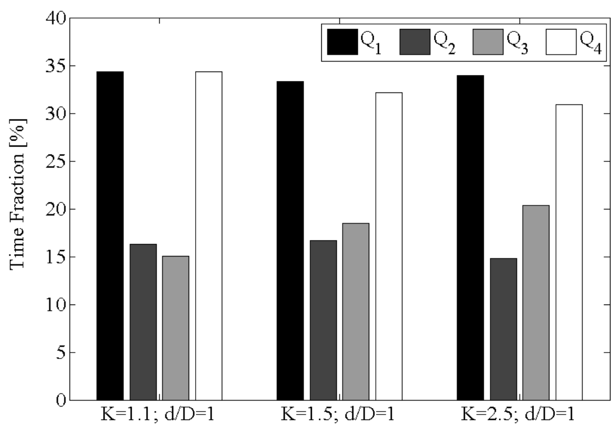

Fig. 5. Time fractions of four quadrants for d/D = 1 and three values of parameter K = 1.1, 1.5, 2.5.

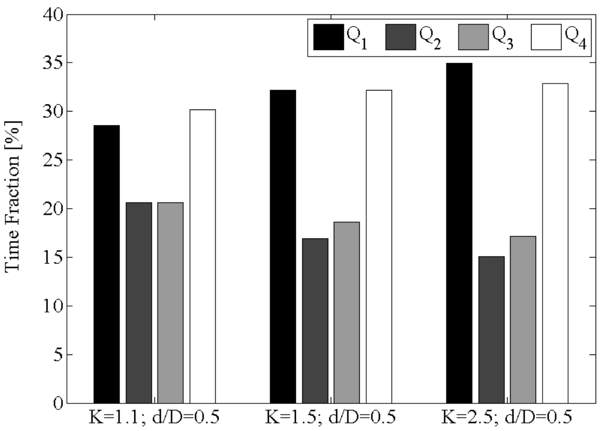

Fig. 6. Time fractions of four quadrants for d/D = 0.5 and three values of parameter K = 1.1, 1.5, 2.5.

CONCLUSIONS

In this paper, a Lagrangian perspective is adopted to investigate the role of coherent structure in saltating grains entrainment. First, the earlier laboratory experimental and field observations (i.e., Drake et al., 1988; Thorne et al., 1989; Nelson et al., 1995; Marion and Tregnaghi, 2013) have been confirmed. These show that the initiation of sediment movement is strongly correlated to positive streamwise velocity fluctuations and thus, the sweeps and outward interactions play a crucial role in the initiation of saltating particles' movement. Secondly, for the first time, it has been shown that for some specific hydrodynamic conditions, the role of the inward interactions in sediment entrainment may be almost the same as that of the outward interactions and more important than the ejections, despite the fact that the other events are much more common in fluid flow. The role of the Q_3 events requires further investigation through experimental works to verify this result. Finally, this paper shows the potential of Lagrangian modelling for analysing the incipient motion of a particle by using zero initial conditions, which do not require the first 20 jumps of a particle to be discarded, as has usually been the case in Lagrangian models of saltation. Despite the value of the presented results, much more remains to be done in exploring sediment entrainment and the aspect of coherent structures requires further attention in experimental and numerical investigations.

Acknowledgements. This work has been supported by the Polish Ministry of Sciences and Higher Education under the "IUVENTUS PLUS II" project No. 0028/IP2/2011/71. The author appreciates the thoughtful discussions with Vladimir Nikora and Paweł Rowiński with whom he has been privileged to interact on this subject. The author dedicates this paper to Stephen Coleman and Nikolay Lukerchenko who suddenly passed away in 2012, in honour and memory of their work on sediment transport.

REFERENCES

Abbott, J.E., Francis, J.R.D., 1977. Saltation and suspension trajectories of solid grains in a water stream. Phil. Trans. R. Soc. Lond. A., 284, 1321, 225–254.

Bialik, R.J., Nikora, V.I., Rowiński, P.M., Czernuszenko, W., 2010. A numerical study of turbulence influence on saltating grains, Proc. River Flow, 1, 105–112.

Bialik, R.J., 2011a. Particle-particle collision in Lagrangian modeling of saltating grains. J. Hydraul. Res., 49, 1, 23–31.

Bialik, R.J., 2011b. Numerical study of saltation of non-uniform grains. J. Hydraul. Res., 49, 5, 697–701.

Bialik, R.J., Nikora, V.I., Rowiński, P.M., 2012. 3D Lagrangian modelling of saltating particles diffusion in turbulent water flow. Acta Geophys., 60, 6, 1639–1660.

Bombardelli, F.A., González, A.E., Niño, Y.I., 2008. Computation of the particle Basset force with a fractional-derivative approach. J. Hydraul. Eng. ASCE, 134, 10, 1513–1520.

Czernuszenko, W., Rowiński, P.M., 2008. Shear stress statistics in a compound channel flow. Arch. Hydro-Engin. Environ. Mech., 55, 1-2, 3–27.

Diplas, P., Clint, D.L., Ahmet, O.C., Manousos, V., Krista, G., Tanju, A., 2008. The role of impulse on the initiation of particle movement under turbulent flow conditions. Science, 322, 717–720.

Drake, T.G., Shreve, R.L., Dietrich, W.E., Whiting, P.J., Leopold, L.B., 1988. Bedload transport of fine gravel observed by motion-picture photography. J. Fluid Mech., 192, 193–217.

Dwivedi, A., Melville, B., Shamseldin, A.Y., 2010. Hydrodynamic forces generated on a spherical sediment particle during entrainment. J. Hydraul. Eng., 136, 10, 756–769.

Dwivedi, A., Melville, B.W., Shamseldin, A.Y., Guha, T.K., 2011. Flow structures and hydrodynamic force during sediment entrainment. Water Resour. Res., 47, W01509.

Heathershaw, A.D., Thorne, P.D., 1985. Sea-bed noises reveal role of turbulent bursting phenomenon in sediment transport by tidal currents. Nature, 316, 339–342.

Lee, H.-Y., Chen, Y.-H., You, J.-Y., Lin, Y.-T., 2000. Investigations of continuous bed load saltating process. J. Hydraul. Eng., ASCE, 126, 9, 691–700.

Lee, H.-Y., Lin, Y.-T., Chen, Y.-H., You, J.-Y., Wang, H.-W., 2006. On three-dimensional continuous saltating process of sediment particles near the channel bed. J. Hydraul. Res., 44, 3, 374–389.

Lu, S.S., Willmarth, W.W., 1973. Measurements of the structure of the Reynolds stress in a turbulent boundary layer. J. Fluid Mech., 60, 481–571.

Luchik, T.S., Tiederman, W.G., 1987. Timescale and structure of ejections and bursts in turbulent channel flows. J. Fluid Mech., 174, 529–552.

Lukerchenko, N., Chara, Z., Vlasak, P., 2006. 2D numerical model of particle-bed collision in fluid-particle flows over bed. J. Hydraul. Res., 44, 1, 70–78.

Lukerchenko, N., Kvurt, Y., Kharlamov, A., Chara, Z., Vlasak, P., 2008. Experimental evaluation of the drag force and drag torque acting on a rotating spherical particle moving in fluid. J. Hydrol. Hydromech., 56, 2, 88–94.

Lukerchenko, N., Piatsevich, S., Chara, Z., Vlasak, P., 2009a. 3D numerical model of the spherical particle saltation in a channel with a rough fixed bed. J. Hydrol. Hydromech., 57, 2, 100–112.

Lukerchcenko, N., Piatsevich, S., Chara, Z., Vlasak, P., 2009b. Numerical model of spherical particle saltation in a channel with a transversely tilted rough bed. J. Hydrol. Hydromech., 57, 3, 182–190.

Lukerchcenko, N., Dolansky, J., Vlasak, P., 2012. Basset force in numerical models of saltation. J. Hydrol. Hydromech., 60, 4, 277–287.

Marion, A., Tregnaghi, M., 2013. A new theoretical framework to model incipient motion of sediment grains and implications for the use of modern experimental techniques. GeoPlanet: Earth and Planetary Sciences., 85–100.

Monin, A.S., Yaglom, A.M., 1971. Statistical fluid mechanics: Mechanics of turbulence, 1, MIT Press, Cambridge, USA.

Moreno, P.M., Bombardelli, F.A., 2012. 3D numerical simulation of particle-particle collisions in saltation mode near stream beds. Acta Geophys., 60, 6, 1661–1688.

Nezu, I., Nakagawa, H., 1993. Turbulence in Open-Channel Flows. Balkema, Netherlands.

Nelson, J.M., Shreve, R.L., McLean, S.R., Drake, T.G., 1995. Role of near-bed turbulence structure in bed load transport and form mechanics. Water Resour. Res., 31, 8, 2071–2086.

Nikora, V., 1999. Origin of the "-1" spectral law in wall bounded turbulence. Phys. Rev. Lett., 83, 4, 734–736.

Nikora, V., Heald, J., Goring, D., McEwan, I., 2001. Diffusion of saltating particles in unidirectional water flow over a rough granular bed. J. Phys. A Math. Gen., 34, 743–749.

Nikora V., 2005. Flow turbulence over mobile gravel-bed: spectral scaling and coherent structures. Acta Geoph. Pol., 53, 4, 539–552.

Niño, Y., Garcia, M., 1994. Gravel saltation. 2. Modeling, Water Resour. Res., 30, 6, 1915–1924.

Niño, Y., Garcia, M., 1998. Using Lagrangian particle saltation observations for bedload sediment transport modeling. Hydrolog. Process., 12, 8, 1197–1218.

Papanicolaou, A.N., Diplas, P., Dancey, C.L., Balakrishnan, M., 2001. Surface roughness effects in near-bed turbulence: Implications to sediment entrainment. J. Eng. Mech., 127, 3, 211–218.

Schmeeckle, M.W., Nelson, J.M., 2003. Direct numerical simulation of bedload transport using a local, dynamic boundary condition. Sedimentology, 50, 2, 279–301.

Thorne, P.D., Williams, J.J., Heathershaw, A.D., 1989. In situ acoustic measurements of marine gravel threshold and transport. Sedimentology, 36, 1, 61–74.

Valyrakis, M., Diplas, P., Dancey, C.L., Greer, K., Celik, A.O., 2010. Role of instantaneous force magnitude and duration on particle entrainment. J. Geophys. Res., 115, F02006.

Wiberg, P.L., Smith, J.D., 1985. A theoretical model for saltating grains in water. J. Geophys. Res., 90, C4, 7341–7354.

Williams, J.J., Thorne, P.D., Heathershaw, A.D., 1989. Measurements of turbulence in the benthic boundary layer over a gravel bed, Sedimentology. 36, 6, 959–971.

Wu, F.C., Jiang, M.R., 2007. Numerical investigation of the role of turbulent bursting in sediment entrainment. J. Hydraul. Eng., 133, 3, 329–334.

Received 26 September 2012
Accepted 2 April 2013