NUMERICAL MODEL OF SALTATION IN OPEN CHANNEL WITH ROUGH BED

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Abstract: *The present contribution deals with a numerical modelling of a saltation of solid spherical particle in turbulent flow along rough bed in the open channel. The goal of the research is to obtain the dependences of average characteristics of particle saltation motion (as length and height of one particle jump) on flow parameters (which can be characterized e.g. by shear velocity and water depth) and bed roughness. The suggested dependences and calculated results are compared with analogical relationships introduced by other authors in literature.*

Keywords: ***Saltation length, saltation height, bed roughness, bed shear stress, shear velocity.***

1. Introduction. Numerical model and the bed structure

Several types of sediment transport in natural channel exist, e.g. sliding/rolling, saltation, and suspension. The types of sediment transport and its particular characteristics depend on various parameters like flow velocity, size, density, and shape of the moving particles, density and viscosity of carrier liquid, bed structure, and so on. The subject of our contribution would be a saltation motion in open channel above rough bed. Prediction of average characteristics of particle motion (for example, parameters of an average jump, particle's velocity) is a main problem in studying bed load movement in a channel. In the present paper influence of bed structure on saltation parameters, i.e. length and height of the average jump, was investigated. By numerical modelling of this process (Kharlamova et al., 2012) the above mentioned parameters of motion of single solid spherical particles in fluid will be obtained.

In natural open channels (rivers, streams) with low or moderate slope bottom consists from particles predominantly of one size. It happens because finer particles are selectively eroded away, leaving the coarser material on the bottom. In that case the size of residual particles depends on flow velocity. How was measured by Sekkine & Kikkawa, 1992, distribution of sand particle in the bottom layer is normal. In the work Kharlamova & Vlasak, 2012, is describing a bed model which takes into consideration such effects. The model describes a bed structure by specific spatial distribution of spherical bed particles. In horizontal plane bed particles are situated with minimal space between them (hexagonal packing); and in vertical direction they are normally distributed along *y*-axis with standard deviation σ around mean bed level.

Following relation between bed roughness, k_s, size of bed particles, d_b, and value of standard deviation, σ was proposed for describing a bed structure:

$$k_s = 6\sigma + 0.5 d_b \,. \tag{1}$$

2. Numerical experiment

For numerical experiments a basic flow characteristic – shear velocity, u_*, was estimated from the next equation:

$$\frac{Q}{H}=\frac{u_*}{\kappa}\left(\ln\frac{H}{y_0}+\frac{y_0}{H}-1\right) \quad (2)$$

where Q – flow rate, H – flow depth, κ = 0.41, and y_0 = 0.11ν/u_* + 0.33 k_s, kinematic viscosity $\nu = 10^{-6}$ s/m^2. Bed roughness changed depending on σ and d_b. For the numerical experiment the next parameters describing bed and flow were used: four different values of standard deviation, i.e. σ = 0, 1/12d_b, 1/6d_b and 1/3d_b, which together with particle's size defines a bed roughness, and five different sizes of the bed particles, i.e. d_b = 3, 4, 5, 6 and 7 mm; flow rate and flow depth were Q = 0.25 m^3/s and H = 0.2 m respectively. So the values of bed roughness, k_s, calculated according to Eq. (1), were: 0.5d_b, 1d_b, 1.5d_b, 2.5d_b. The size of saltating particle was equal to the size of the bed particles: $d = d_b$.

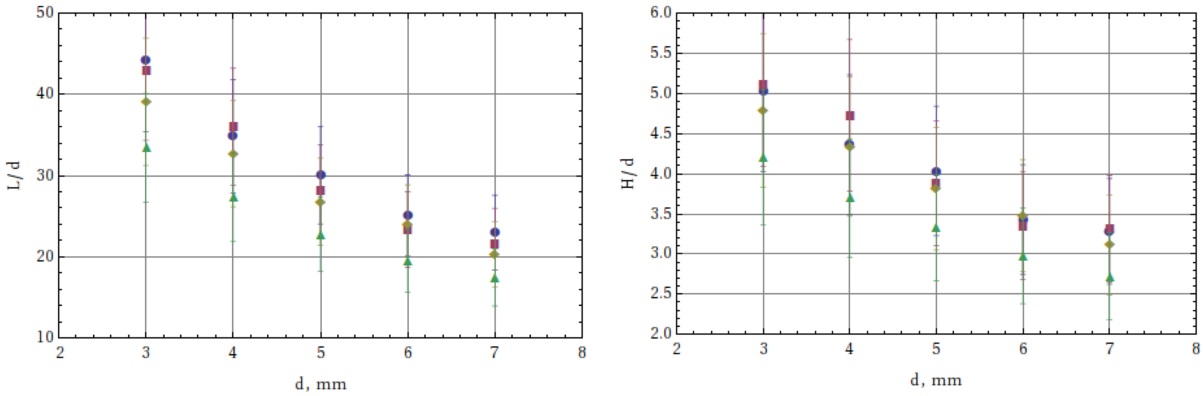


Fig.1 Effect of particle diameter on dimensionless length and height (standard deviation 20%). Blue points - σ = 0, k_s = 0.5d_b; red points - 1/12d_b, k_s = d_b; yellow points - 1/6d_b, k_s = 1.5d_b; and green points - 1/3d_b, k_s = 2.5d_b.

The result of the simulation is shown in the Fig. 1. Length and height of average particle jump decrease with increasing size of saltating and bed particles and decrease with increasing bed roughness, (value of standard deviation σ), i.e. small particles saltating over bed with small bed roughness reaches the largest jumps.

3. Comparison of the simulation with real experiments

Van Rijn, 1984, Nino & Garcia, 1998, Ancey et al., 2002, and Lee et al., 2006 investigated experimentally saltation of sand particles in channel with rough stationary bed, which consists from glued sand particles of the same (or approximately the same) size. Exact vertical distribution of sand particles in glued layer is unknown, however we suppose it might be described by normal distribution with maximal standard deviation - σ = 1/3 d_b, like in natural channel (Sekkine & Kikkawa, 1992), or less. Therefore we compared results of our simulation for rough bed using standard deviation σ = 1/3 d_b and with minimal standard deviation - σ = 0 with experimentally obtained dependences of Van Rijn, 1984, Ancey et al., 2002, and Lee et al., 2006.

More information about above mentioned experiments is given in Table 1. Comparison of the result of our simulation and experimental dependences of the others authors are shown in Fig. 2.

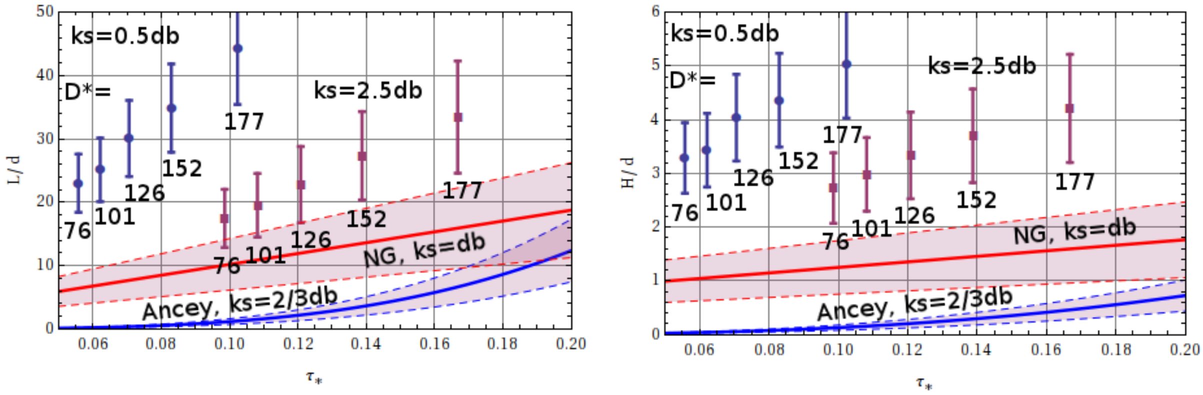
Table 1. Experimental investigation of saltation over rough bed.

Author	Diameter of bed particle, d_b	Diameter of salt. particle, d and D_*	Bed roughness, k_s	Saltation parameters, L/d, H/d	Information
Van Rijn, 1984	Flat bed, ---	0.1-2 mm, $2.5 \leq D_* \leq 50.6$	$k_s = 2d_b$	$L/d = 3D_*^{0.6}T^{0.9}$ $H/d = 0.3D_*^{0.7}T^{0.5}$	$D_* = d(Rg/\nu^2)$ $T = \frac{u_*^2 - u_{*cr}^2}{u_{*cr}^2}$, $u_{*cr} = f(d$ or $d_b)$, ρ = 2.65 g/cm^3
Nino & Garcia, 1998	Fixed bed with glued particle, 0.53 mm	0.5 mm, $D_* = 12.6$	Hypothetically (from Nino & Garcia, 1994) $k_s = d_b$	Our fit to their data $L/d = 85.55\tau_* + 1.61$ $H/d = 5.15\tau_* + 0.73$	ρ = 2.65 g/cm^3
Ancey et al., 2002	Half cylinders, 3, 6, 8 mm	3 mm, 6 mm, $73.5 \leq D_* \leq 243$	$k_s = 2/3\ d_b$	$L/d = 3130\tau_*^{3.44}$ $H/d = 43\tau_*^{2.54}$	ρ = 2.5 g/cm^3, ρ = 7.75 g/cm^3
Lee et al., 2006	Glued bed, 6 mm	6 mm, $55.3 \leq D_* \leq 134.5$	Hypothetically (from Lee & Hsu, 1994) $k_s = 2d_b$	$L/d = 2.26D_*^{0.15}T^{0.91}$ $H/d = 0.3D_*^{0.45}T^{0.33}$	$1.08 \leq \rho \leq 2.15$ g/cm^3
Present numerical simulation	Fixed bed, 3-7 mm	3-7 mm, $76 \leq D_* \leq 177$	$k_s = 2.5d_b$, ($\sigma = 1/3\ d_b$)	$L/d = 4007.3D_*^{-1.05}T^{-0.12}$ $H/d = 90D_*^{-0.66}T^{-0.07}$	ρ = 2.65 g/cm^3

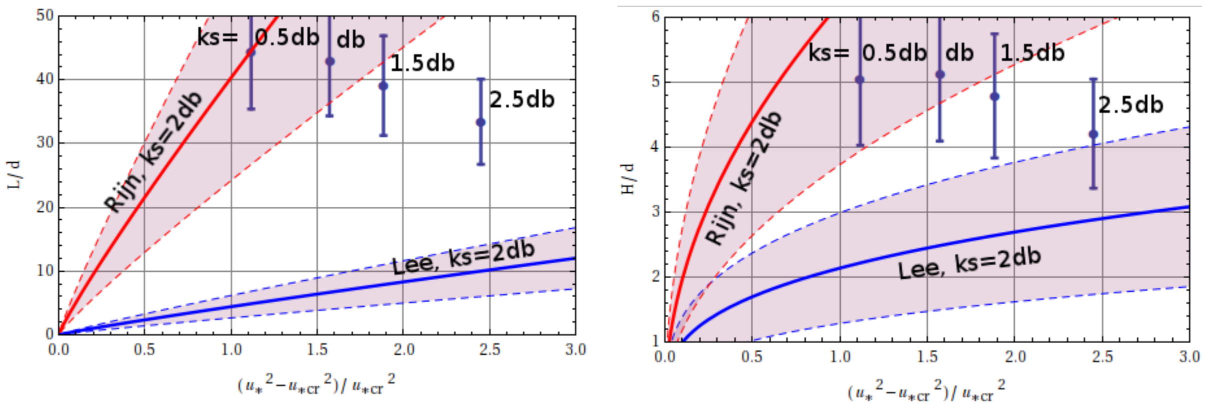
For comparison of different dimensionless parameters were used dimensionless bed shear stress - $\tau_* = u_*^2/(Rgd_b)$, transport stage - $T = (u_*^2 - u_{*cr}^2)/u_{*cr}^2$, and dimensionless particle diameter $D_* = d(Rg/\nu^2)^{1/3}$. These parameters are used in majority investigations for describing bed load transport. Some authors used for presentation of their results dimensionless bed shear stress, some - transport stage and dimensionless particle diameter D_*, see Table 1. These parameters contain d - diameter of saltating particle, d_b – diameter of bed particles, particle apparent density $R = \rho / \rho_f - 1$, ρ – density of bed particles (ρ = 2.65·10^3 kg/m^3), ρ_f – density of liquid (ρ_f = 10^3 kg/m^3), for sand in water R = 1.65. Critical value of shear velocity u_{*cr} can be determined from the Shields curve.

How can be seen from Fig. 2, the tendency of dimensionless length and height of average jump is the same like in experiments. From comparison of our results with Ancey's and Nino & Garcia's experimental trends can conclude that values obtained in our simulations are considerably higher than values from the experiments, see Fig. 2a. Also the results of Ancey do not agree with results of Nino & Garcia. Generally, experimental data presents wide scattering, which reaches about 40%. Values obtained in the simulation for standard deviation (σ = 1/3 d_b) and hence for the bed roughness (k_s = 2.5d_b) are situated closer to result of Nino & Garcia.

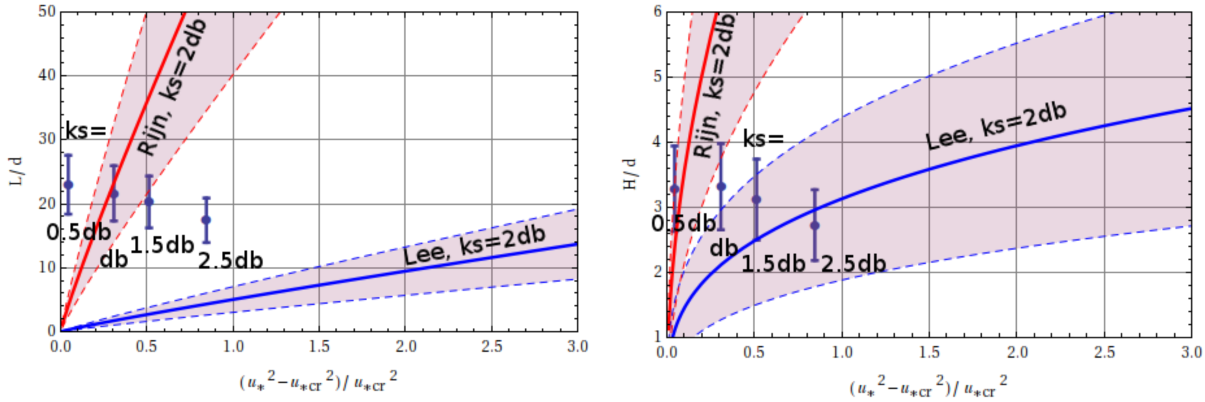
From comparison of our results with experimental results of van Rijn and Lee is evident that van Rijn's and Lee's results significantly differ, see Fig. 2b, c. The simulation results are closer to van Rijn's results in both cases, for particle diameter d = 3 mm (D_* = 76), and d = 7 mm (D_* = 177).



a) comparison with Ancey et al., 2002 and Nino & Garcia, 1998.



b) comparison with van Rijn, 1984 and Lee et al., 2006; particle diameter 3 mm (sand), D_* = 76.



c) comparison with van Rijn, 1984 and Lee et al., 2006; particle diameter 7 mm (sand), $D_* = 177$.

Fig. 2. The dependences of dimensionless length and height of average jump and their comparison with experimental trends (standard deviation 40%). Points – values obtained in the simulation for various particle's diameters and bed roughness.

4. Discussion

The possible reasons why simulation results differ from experimental results and why particular experimental results significantly mutually differ are discussed below.

The simulation does not take into account an interaction of the flow and conveyed particles. The presence of solid particles in the channel slows down the original velocity of the carrier liquid. Therefore in real channel the velocity of the liquid on the same depth would be less then it is in the simulation where a motion of only one particle is considered, Spekkers et al., 2008, Vlasak et al., 2012. The presence of different rough elements on the channel bed slows down the liquid velocity, too, Bergstrom et al., 2002. The rougher is bottom surface the larger is difference between velocity profile and logarithmic profile in the bottom region; i.e. in real experiments the velocity near rough bed is less than it is in the simulation with logarithmic profile.

The form of roughness considerably effect on the flow profile. Profiles would be different even they nominally conform to the same values of average velocity and equivalent bed roughness, Krogstad, Antonia, 1999. That's why results of Ancey et al., 2002, so differ from others; Ancey in their experiments used cylinders as rough elements. The profile of the velocity above bed with cylinders differs from profile above sand bed.

Also the shape of conveyed particles play important role. Saltation height and length of irregular particles (like sand and gravel) are significantly lower than for that for spherical particles of the same mean diameter (Vlasak et al., 2012). In the simulation we used spherical glass particles.

The mutual interaction of the moving particles did not take into account in the simulation. This is also one more reason, why the parameters of particles trajectory in real experiments might be less than they are in the simulation.

5. Conclusions

In the result of modelling of different bed geometries, the dependencies of saltating parameters (length and height of average jump) on bed parameters (d_b, σ) were obtained. It was found that for equal saltating and bed particles ($d = d_b$) length and height decrease with increasing particle diameter and decrease with increasing of the bed roughness. There bed roughness is defined mainly by standard deviation of bed particles in vertical direction.

It was conducted, that average jump's parameters determined from numerical simulation, reach higher values then parameters obtained in experiments provided in laboratory channels. However, the tendency obtained from simulation are similar as the experimental ones.

Acknowledgement

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