National Conference with International Participation
ENGINEERING MECHANICS 2006
Svratka, Czech Republic, May 15 – 18, 2006
paper no. 210

CALCULATION OF THE SALTATION CHARACTERISTICS AS FUNCTIONS OF THE INITIAL PARAMETERS

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Summary: *The results of the 3D simulation of the solid spherical particles saltation in an open channel with rough bed are presented. The dependences of mean saltation length, mean saltation height, mean saltation velocity and mean deviation of angle of particle trajectories with respect to downstream direction were studied and determined as the functions of the saltation process parameters, such as the flow shear velocity and the particle diameter.*

1. Introduction

In the paper a saltation process, one of the bed load transport of sediment modes in open channels and rivers, was studied. During saltation the moving particles follow ballistic like trajectories in the fluid and periodically collide with channel bed. The main parameters of saltation process, e.g. mean saltation length, height, velocity, etc. are interesting from the engineering point of view. For this reason many experimental and theoretical investigations were conducted to determine above mentioned saltation parameters, the results are presented for instance in Abbot & Francis (1977), Nino & Garcia (1998), Lee et al. (2000) etc.

The spherical particle saltation in the open channel with rough bed was studied and described by 3D numerical model, Lukerchenko et al. (2003, 2004). The particle saltation is described by the equations of particle centre of mass translational motion and of the particle rotation around its centre of mass. The stochastic model of the particle collision with channel bed is based on the specification of the particle contact zone, which was determined as the set of points of the particle surface, at which the particle contact with bed was most probable during the relevant collision. The model is verified by means of the comparison of the results of simulation and experimental data of Nino & Garcia (1998).

2. Dimensional analysis

To compute dependences of the saltation parameters on the initial data of saltation process a new way of dimensionless analysis was introduced to obtain more convenient relationships between the saltation parameters and the initial data. The saltation process is very complex and depends on many factors and up to now the suitable and generally accepted system of determination of the dimensionless parameter is not known.

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The kinematical characteristics of saltation, i.e. mean length L_S, mean height H_S, mean streamwise velocity U_S, mean time between consequent particle collision with the bed T_S etc. are subject of determination. The initial parameters, which determine the particle saltation are the particle diameter d_p and its density ρ, roughness of the particle surface ε, flow shear velocity u_*, fluid density ρ_0, channel depth H, bed roughness K_S, kinematical viscosity ν and gravitational acceleration g.

Lee et al. (2000) presented the following functional dependence

$$X = f(\theta, \mathrm{Re}_*, H/d_p, K_s/d_p, \varepsilon/K_s, \rho/\rho_0), \tag{1}$$

where X represents the vector, which components are the dimensionless characteristics of saltation and $\theta = \rho u_*^2/(g(\rho-\rho_0)d_p)$ is dimensionless shear stress, $\mathrm{Re}_* = u_* d_p/\nu$ is the particle Reynolds number. In accordance with the nature of sediment transport they assumed that $H >> d_p$, $K_s = d_p$ and $\varepsilon << K_s$. Combination of the parameters θ, Re_* and ρ/ρ_0, and introduction of the critical flow shear velocity u_{*c} results to the relationship

$$X = f_1(T_*, D_*), \tag{2}$$

where $D_* = d_p\left[\left(\frac{\rho}{\rho_0}-1\right)\frac{g}{\nu^2}\right]^{1/3}$ and $T_* = \frac{\left(u_*^2 - u_{*c}^2\right)}{u_{*c}^2}$. The so-called critical shear velocity u_{*c} can be determined from Shields curve, described for instance by Van Rijn (1984).

Nino & Garcia (1998) proposed different way of dependence of the saltation characteristics on the initial parameters

$$X = f_2(\tau_*, H/d_p, R_p, R), \tag{3}$$

where $\tau_* = u_*^2/(gRd_p)$, $R_p = \sqrt{Rgd_p^3}/\nu$ and $R = (\rho-\rho_0)/\rho_0$. However using of such dimensionless groups makes difficult the graphical representation of results, e.g. the effect of the particle diameter on saltation length or height.

To avoid this inconvenience let us present the functional dependence

$$X = f_3\left(\frac{d_p}{\sqrt[3]{\nu^2/g}}, \frac{u_*}{\sqrt[3]{\nu g}}, \frac{\rho}{\rho_0}, \frac{H}{\sqrt[3]{\nu^2/g}}, \frac{K_s}{\sqrt[3]{\nu^2/g}}, \frac{\varepsilon}{\sqrt[3]{\nu^2/g}}\right), \tag{4}$$

By the combination of the parameters ν and g it is possible to set up the groups with dimensions of time, length and velocity: $[t] = \sqrt[3]{\nu/g^2}$, $[l] = \sqrt[3]{\nu^2/g}$ and $[v] = \sqrt[3]{\nu g}$, respectively. If the effect of the particle surface roughness and channel depth are negligible (particle is smooth and channel is deep in comparison with particle diameter) and the bed surface roughness is equal to the particle diameter $K_s = d_p$ then the equation (4) transforms to

$$X = f_4\left(\tilde{d}_p, \tilde{u}_*, \tilde{\rho}\right), \tag{5}$$

where $\tilde{d}_p = d_p / \sqrt[3]{\nu^2 / g}$, $\tilde{u}_* = u_* / \sqrt[3]{\nu g}$, and $\tilde{\rho} = \rho / \rho_0$. The dimensionless relationship (5) contains only three parameters, dimensionless particle diameter, fluid shear velocity and particle density. So the saltation characteristics can be made dimensionless by the following way

$$\tilde{L}_s = L_s / \sqrt[3]{\nu^2 / g} \tag{6}$$

$$\tilde{H}_s = H_s / \sqrt[3]{\nu^2 / g} \tag{7}$$

and

$$\tilde{U}_s = U_s / \sqrt[3]{\nu g} . \tag{8}$$

The dimensionless group determined in this way differs from the usually used and allows reaching more convenient representation of the relationships between the saltation characteristics and the saltation process initial parameters.

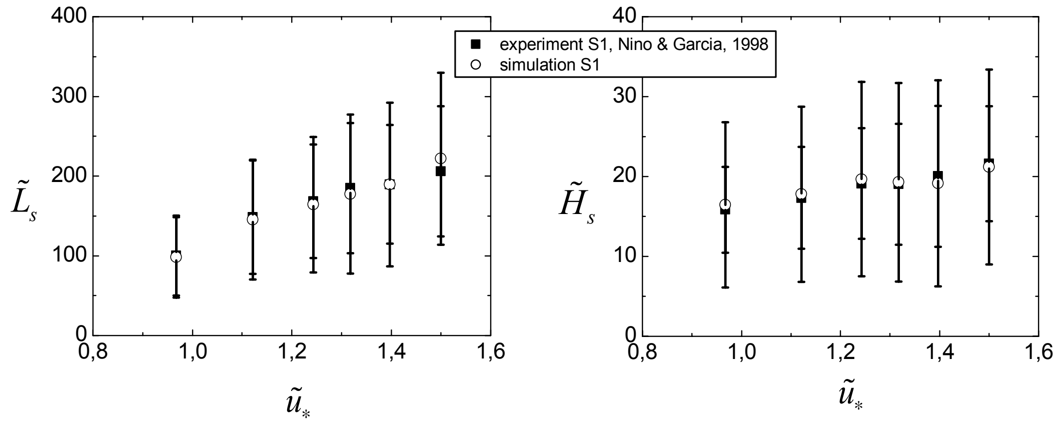

Figure 1 Comparison of the simulated parameters with the experimental data of Nino & Garcia (1998)

The comparison of the calculated values of the saltation length and height with experimental results of Nino & Garcia (1998) is shown in Fig. 1. The data is presented in the dimensionless form, described above. The good fitting of the calculated results with the experimental ones is evident.

3. Results

The calculation were carried out for values of the flow shear velocity u_* varied from 0,03 m/s to 0,045 m/s and the particle diameter d_p varied from 0,5 mm to 1 mm. The particle density was 2650 kg/m^3, the same value as the density of sand. The value of the bed roughness was supposed to be equal to the diameter of saltating particle as it is usual in natural rivers, where sand bed-load transport occurs (Sekine & Kikkawa, 1992).

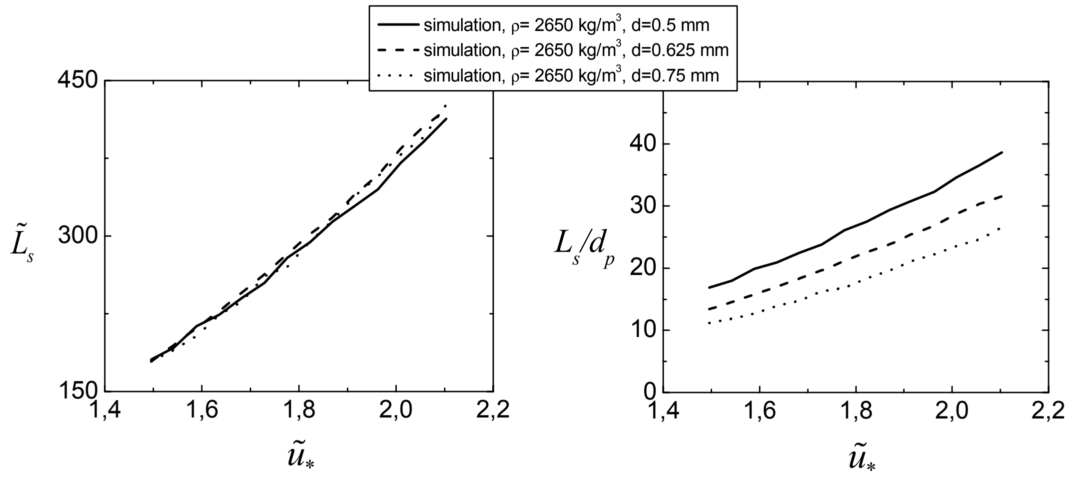

Figure 2 The mean saltation length versus the flow shear velocity

The dependence of the mean saltation length on the flow shear velocity is presented in the Fig. 2, where the particle diameter is used as parameter. The plots are made in two variants. The left side graph uses the dimensionless mean saltation length defined by Eq. (6) and the right side part is made in traditional way using the ratio of saltation length and particle diameter. The course of the both dependences is close to linear. However, the absolute value of the dimensionless mean saltation length defined by Eq. (6) is nearly independent on the particle diameter, but the value of the ratio of mean saltation length over the particle diameter decreases with growing particle diameter.

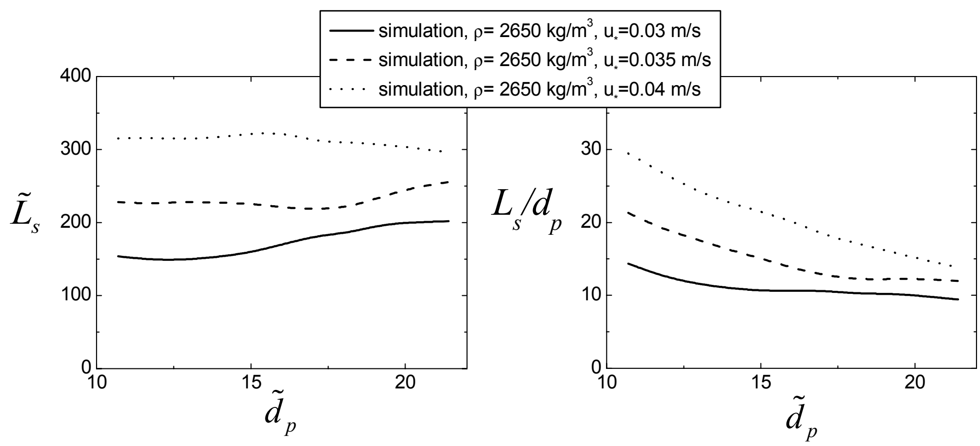

Figure 3 The mean saltation length versus the particle diameter

The similar dependence of the mean saltation length on the particle diameter is shown in the Fig. 3, where the flow shear velocity serves as parameter. Based on the calculation the following linear relation between $\tilde{L}_s$ and $\tilde{u}_*$ were found

$$\tilde{L}_s = K_L \tilde{u}_* + B_L \,, \quad (9)$$

where coefficients K_L and B_L depend mainly on the particle diameter and also on other parameters of the system, their values are shown in the Table 1.

Table 1 Approximate coefficients values

d_p [mm]	K_L	B_L	K_H	B_H
0.5	381.2	-397.2	18.1	-15.94
0.625	404.9	-433.3	22.1	-21.6
0.75	408.2	-443.6	23.8	-24.3

The dependence of the mean saltation downstream velocity and the mean saltation height on the particle diameter or the flow shear velocity is shown in Fig. 4. The mean saltation downstream velocity grows linearly when the flow shear velocity increases or the particle diameter decreases. The slope of the lines describing this dependence does not depend on the value of the particle diameter.

It can be introduced the following relationship describing effect of the dimensionless flow shear velocity and particle diameter on dimensionless downstream mean saltation velocity

$$\tilde{U}_S = K_U^{(1)} \tilde{u}_* + K_U^{(2)} \tilde{d}_p + B_U \,, \quad (10)$$

where the coefficients $K_U^{(1)}, K_U^{(2)}, B_U$ are independent on the values of the flow shear velocity and the particle diameter and based on the results of simulation they could be established approximately equal to 13.2, -0.2 and -5.5, respectively.

The dependence of the dimensionless mean saltation height on the dimensionless flow shear velocity

$$\tilde{H}_s = K_H \tilde{u}_* + B_H \quad (11)$$

is also nearly linear. The values of the coefficients K_H and B_H depend on the particle diameter (see Table 1) and the slope of the line following from the dependence (11) increases when the particle diameter increases.

On the contrary, the dependence of the mean saltation height on the particle diameter and dependence of the particle trajectory angle of deviation with respect to downstream direction (see Figs. 4 and 5) are strongly non-linear.

The mean angle of deviation of particle trajectories with respect to downstream direction was calculated as function of the flow shear velocity and the particle diameter. The value of the angle decreases with growing flow shear velocity and grows when the particle diameter increases. The results are shown in Fig. 5.

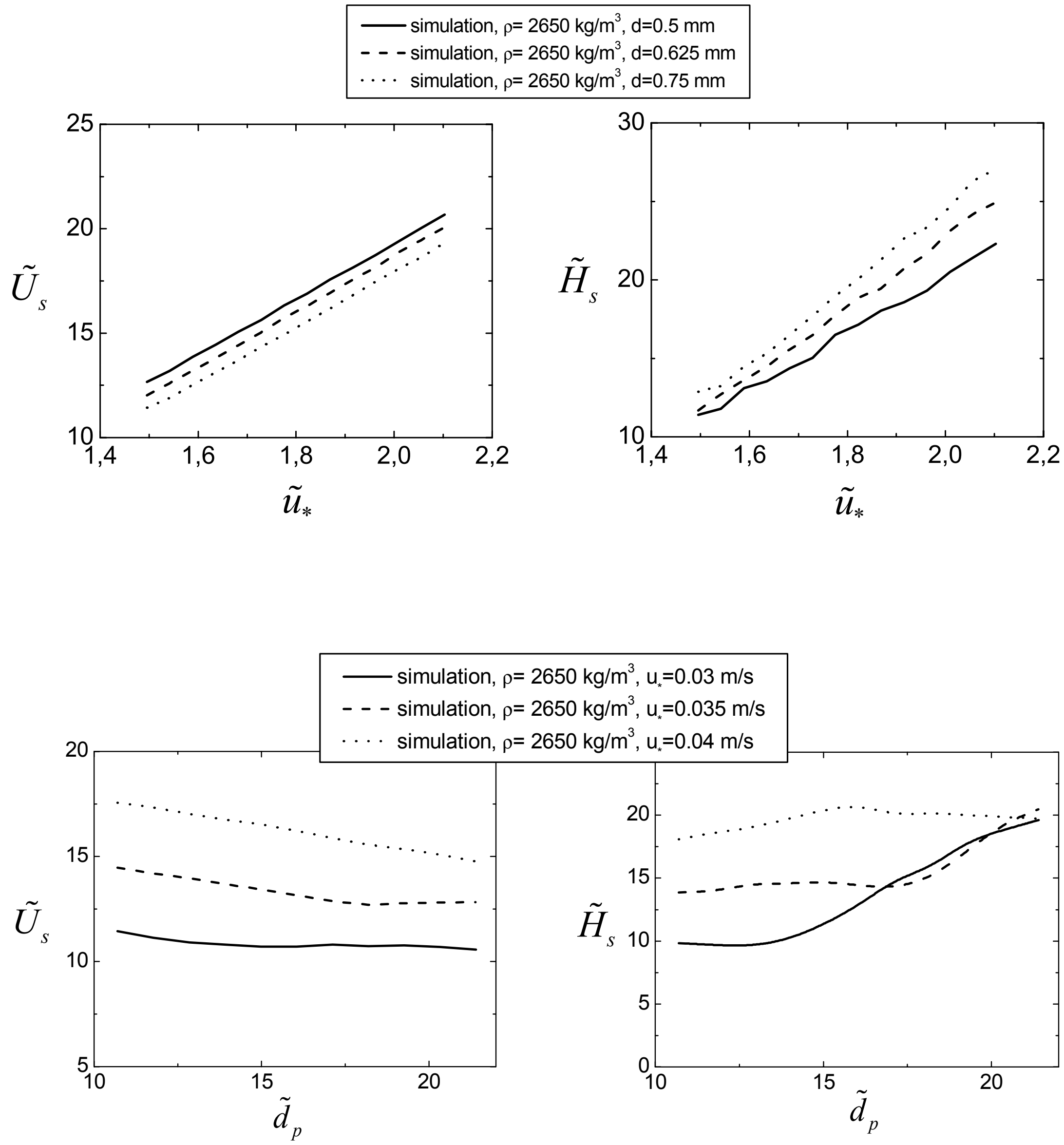

Figure 4 The mean saltation downstream velocity and the mean saltation height versus the particle diameter and the flow shear velocity

4. Conclusions

Compare to mostly used 2D models of saltation process in open channel the suggested 3D model bring possibility to determine a new quantity, the mean angle of deviation of particle trajectories with respect to downstream direction and describe the lateral turbulent dispersion of particles.

Since the effect of particle space shape is taken into the account during the contact and rebound phases of the saltation the 3D model makes also possible to compute more precise values of the different parameters of the saltation, i.e. the mean saltation length, height and velocity, respective.

The dependences of mean saltation length, mean saltation height, mean saltation velocity and mean deviation of angle of particle trajectories with respect to downstream direction were determined as the functions of the flow shear velocity and the particle diameter. Most of them can be approximated by linear or nearly linear dependency, what is favourable from engineering application point of view.

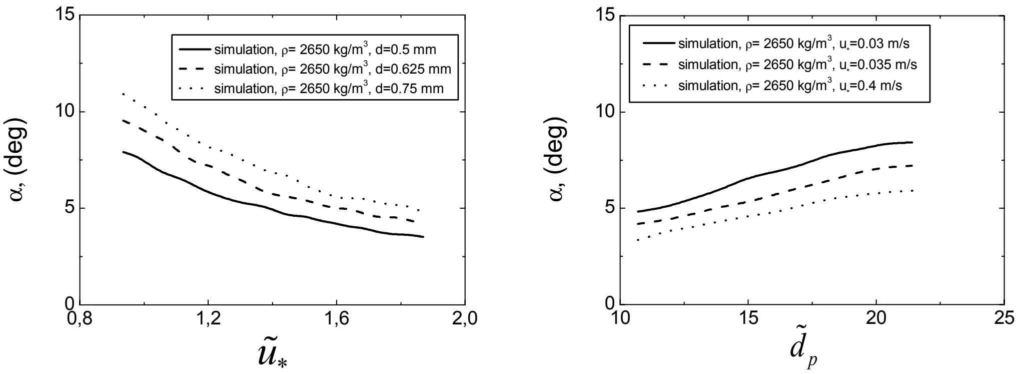

Figure 5 The particle trajectory angle of deviation with respect to downstream direction versus the particle diameter and the flow shear velocity

5. Acknowledgements

The support under the project No. 103/06/1487 of the Grant Agency of the Czech Republic, No. A 2060201 of the Grant Agency of Academy of Sciences of the Czech Republic, and the Institutional Research Plan No. AV0Z20600510 of the Academy of Sciences of the Czech Republic is gratefully acknowledged.

6. Notation

d_p – particle diameter;
$\tilde{d}_p$ – dimensionless particle diameter;
D_* - dimensionless parameter;
g – gravitational acceleration;
H – flow depth;
H_s – mean saltation height;
$\tilde{H}_s$ – dimensionless mean saltation height;
K_s – bed roughness;
L_s – mean saltation length;
$\tilde{L}_s$ – dimensionless mean saltation length;
R – particle submerged specific density;

R_p – dimensionless parameter;
Re_* − Reynolds number;
T_* − dimensionless parameter;
T_s – mean saltation time;
U_s – mean saltation velocity;
$\tilde{U}_s$ – dimensionless mean saltation velocity
u_* − flow shear velocity;
$\tilde{u}_*$ – dimensionless flow shear velocity;
u_{*c} – critical flow shear velocity;
α – mean deviation angle;
ε – particle roughness;
θ – dimensionless parameter;
ν – kinematic viscosity;
ρ – particle density;
$\tilde{\rho}$ – dimensionless particle density;
ρ_0 – fluid density;
τ_* – dimensionless parameter.

7. References

Abbot J. E. & Francis J. R. D. (1977) Saltation and suspension trajectories of solid grains in a water stream. *Philos. Trans. R. Soc. London*, 284, pp. 225 – 254.

Lee H.-Y., Chen Y.-H., You J.-Y., Lin Y.-T. (2000) Investigations of continuous bed load saltating process. *J. Hydr. Engrg.,* Vol. 126, No. 9, pp. 691 – 700.

Lukerchenko N., Chara Z. & Vlasak P. (2003) 3D mathematical model of spherical particle saltatory movement in open channel with rough bed. *Engineering Mechanics 2003,* Svratka (Czech Republic), May 12-15, 2003, Book of Extended abstracts, 186-187 (CD ROM – 7 pages).

Lukerchenko N., Chara Z. & Vlasak P. (2004) 3D numerical model of particle-bed collision in particle-laden flow in channels with rough bed. Proc. of the *12th International Conference on Transport and Sedimentation of Solid Particles,* Prague (Czech Republic), 20-24 September 2004, Vol. 2, 493-499.

Nino Y. & Garcia M. (1998) Experiments on saltation of sand in water. *J. Hydr. Engrg*., Vol. 124, No. 10, pp. 1014 – 1025.

Sekine, M. & Kikkawa, H. (1992) Mechanics of saltating grains, II. *J. Hydraul. Eng*., ASCE, Vol. 118, pp. 536-558.

Van Rijn L. C. (1984) Sediment transport, part I: Bed load Transport. *J. Hydraul. Eng.,* ASCE, Vol. 110, No. 10, pp. 1431-1456.