IMPROVEMENTS OF SALTATION MODEL

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Abstract: The present paper introduces a new model of a bed-load transport. The model simulates a particle motion in the channel with turbulent flow and rough bed. The effects of mutual interaction of conveyed particles with carrier liquid, with bed particles, and also with other conveyed particles are taken into account. The model predicts average saltation characteristics, e.g. saltation length and height, particles distribution in vertical direction, and mass rate of conveyed particles per unit area of channel bed.

1. Introduction. Improvements of the saltation model

Saltation is a specific type of particle sediment transport by stream of fluids such as water or air. It occurs when particulate material is removed from a surface and carried by the fluid, in the form of consecutive jumps. Examples include pebble transport by rivers, sand drift over desert surfaces, soil blowing over fields, or even snow drift over smooth surfaces such as those in the Arctic or Canadian Prairies.

For describing this phenomenon a lot of numerical models were offered (van Rijn, 1984; Nino and Garcia, 1994; Lee at al., 2000; and others). Kharlamova et al. (2012) introduced a numerical model for description a saltation motion in open channel with rough unmovable bed in averaged turbulent flow. The average characteristics of particle motion (length and height of one jump) are the basic outcome of the model.

However, some weaknesses have place in the above mentioned model:

- A mutual interaction of the moving particles or mutual collisions of conveyed particles were not taken into consideration in the model;
- Only an averaged turbulent flow was considered in the simulation, also an interaction of the fluid and conveyed particles was not taken into consideration.

For solution of the first problem the mutual collisions of conveyed particles will be included in the simulation. The probability of the collisions is proportional to a concentration of conveyed particles. The concentration depends on depth and velocity of the flow. Fig. 1 shows a saltation of one particle for two different flow velocities. At higher flow velocity particles reached the higher layers. Figure 2 shows distribution of the particles in separate horizontal layers. Normalized concentration of the saltating particles was estimated in the separate layers of thickness (0-2; 2-4; 4-6; …)**d*. At higher velocity particles are distributed almost in all layers, at lower velocities particles are located in the lower layers. Depth of the flow is $H = 20\,d$, where d is diameter of the particles. In examples the diameter of the sand particle $d = 1$ mm, and it saltates in water above consolidate bed from the same particles. Velocity of the flow is defined by log-law: $v(y) = u_*/k \ln(y/y_0)$. Particle moves in channel stream with shear flow velocity u_* that varies from u_{*cr} to $6\,u_{*cr}$. Here u_{*cr} is a flow velocity at which particles start their motion. It is found from Shields curve, an equation describing the curve can be found in Guo (2002).

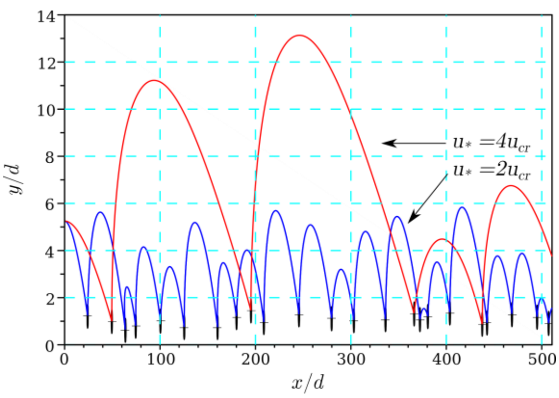

Fig. 1 Saltation of one particle with various flow velocities: effect of shear velocity on trajectory.

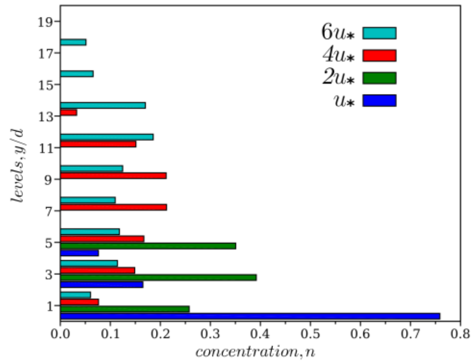

Fig. 2 Normalized concentration of the saltating particles in the separate layers [0-2; 2-4; …] d for various flow velocities, u_*. Depth of the flow is H = 20 d.

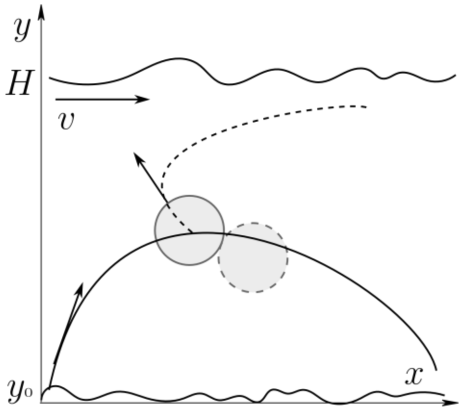

Fig. 3 The sketch of particle-particle collision. Dashed line – new trajectory of the saltating particle after collision with hypothetical particle.

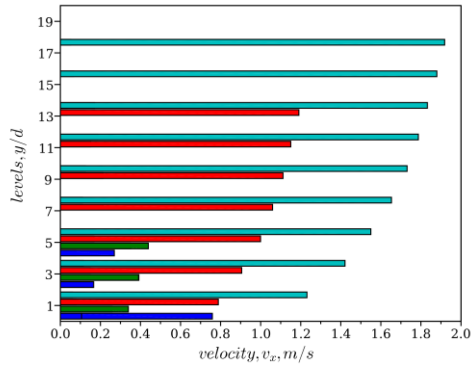

Fig. 4 Distribution of the saltating particle's velocities, v_x, averaged in each layers [0-2; 2-4; …], for various flow velocities, u_*. For legend see in Fig. 2.

Since the probability of the collisions of conveyed particles depends on their concentration at individual layer, we propose to put a lot of hypothetical particles on the path of saltating particle, see Fig. 3. The number of the hypothetical particles is proportional of the saltation particle's concentration. Bialik (2011) proposed a procedure how to include particle-particle collisions in the model that calculate motion of only one particle. For calculation of the particle-particle collisions it is necessary know a distribution of the particle's velocities in horizontal layers. For example in Fig. 4 is shown a distribution of the saltating streamwise particle's velocities, v_x, averaged in each layers. Obviously, particles that are located in higher layer will reach the higher velocity, then the particles near the bottom.

From kinetic theory of gases it is known that two particles with the same diameters d collide with the following frequency:

$$f_c = \frac{1}{t_c} = \pi d^2 \left|\overrightarrow{u_1 - u_2}\right| n_p \,, \tag{1}$$

where t_c – time between collisions, $\left|\overrightarrow{u_1 - u_2}\right|$ - relative velocity between two collided particles, n_p – number of particles in unit volume ([number/m^3]).

The probability of a collision which take place in time $\Delta t = t - t_0$:

$$P(\Delta t) = 1 - \exp(-\pi d^2 \left|\overrightarrow{u_1 - u_2}\right| n_p \Delta t) \,. \tag{2}$$

It is impossible to found directly u_2 and n_p. From simulation of motion of one particle it is necessary to find a distribution of particles in horizontal layers, see Fig. 2; and find a distribution of averaged particle's velocities in each layers: v_x, v_y, v_z, together with their derivations from average: δv_x, δv_y, δv_z. Later for determination of the velocity of hypothetical particle, u_2, which will collide with moving particle in the simulation, we will choose the velocity's components in some intervals uniformly:

$$u_2 = random[v_x \pm \delta v_x, \pm(v_y \pm \delta v_y), \pm(v_z \pm \delta v_z)]. \tag{3}$$

The signs before *y*- and *z*-component will be also randomly chosen, it allows simulating of motion of a hypothetical particle in upward or downward, left or right direction.

According to Bialik (2011) the probability *P* (Eq. 2) of the collisions must be compared with the probability *P*(RNG) obtained from uniformly distributed numbers between 0 and 1 with help of Random Numbers Generator (RNG). If *P* > *P*(RNG) then the collision of hypothetical particle is taken into account to the simulation of motion of one particle.

Finally, velocity of the saltating particle after the collision is calculated from Crowe et al. (1998) expression:

$$\vec{u}_{1after} = \vec{u}_{1berofe} - \frac{1+e}{2}(\vec{n} - f\vec{\tau})(\vec{n}\cdot(\vec{u}_{1before} - \vec{u}_2)) \,, \tag{4}$$

where n and τ are normal and tangential vectors in a plane of collision; *e* and *f* – are the coefficients of restitution and friction. A hypothetical trajectory of the saltating particle is shown in Fig. 5.

For solution of the second problem – taking into account an interaction of the fluid and conveyed particles, the instant fluctuations will be added to the velocity profile: $v(y, t) = v(y) + v'(y, t)$. Fluctuation depends on time and coordinates. Also the velocity profile will include an influence of flow depth and wavy surface, see Fig. 6:

$$v(y) = \frac{u_*}{\kappa} \ln(\frac{y}{y_0}) \ + \ \frac{2W}{\kappa} \sin^2 \frac{\pi y}{2H} \,, \tag{5}$$

where W = 0.01 – wake parameter or the constant in the Coles' law (Song & Lemmin, 1994).

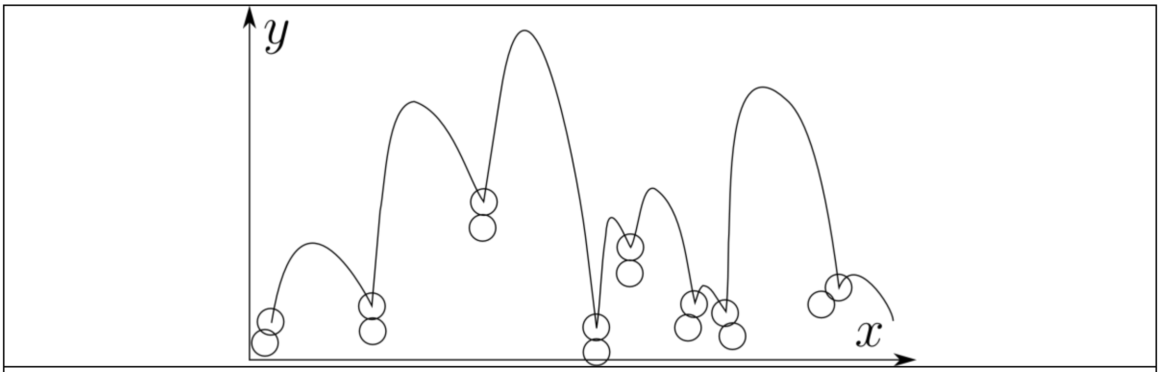

Fig. 5 A hypothetical trajectory of the saltating particle after its collisions with other conveyed particles and bed particles.

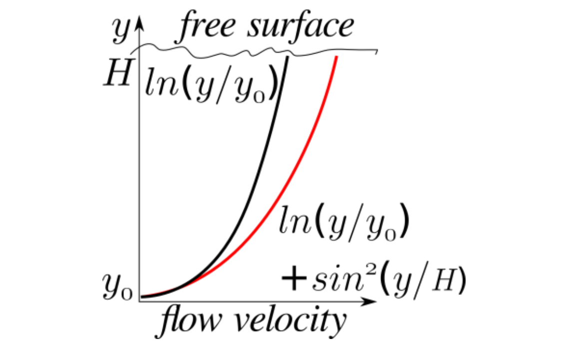

Fig. 6 The velocity profiles: standard averaged turbulent profile (the log-law) and profile with influence of the flow depth and wavy surface.

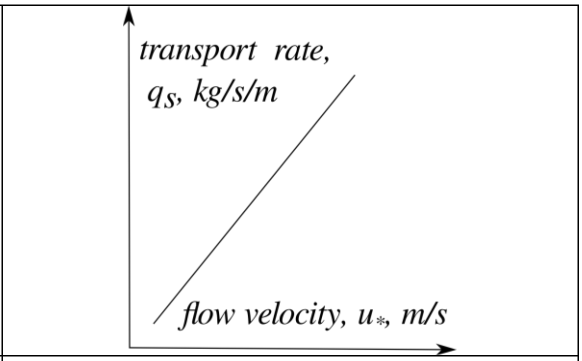

Fig. 7. Tentative dependence of bed load transport rate, q_s, on flow velocity, u_*.

For calculation of a bed load transport rate q_s the formula proposed by Lee at al. (2000) is used: $q_s = C_b\, H_p\, V_p$, where C_b is a bed load concentration, H_p - dimensionless average height of the jump of saltating particle, V_p - dimensionless streamwise velocity of the particle. Later a dependence of bed load rate on shear stress $q_b(\tau_*)$ will be found, and it will be compared with already known dependences from Lee at al. (2000), Van Rijn (1984), Nino and Garcia (1994), Sekine a Kikkawa (1992). A tentative dependence of bed load transport rate, q_s, on flow velocity, u_*, is shown in Fig. 7.

The comparison of trajectories obtained from the present simulation with trajectories obtained by Bialik (2011) will be realized.

2. Conclusions

The saltation model, published in Kharlamova et al. (2012) was improved by introducing particle-particle collisions, interaction of the carrier fluid and conveyed particles, and taking into account turbulent velocity fluctuations. These improvements of the model allowed a better description of the bed load transport process, more accurate computation of the particle saltation parameters, height and length of jump, and also description of particles distribution in vertical direction, and computation of mass rate of conveyed particles per unit area of the channel bed.

3. Literature

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