THE EFFECT OF MOVING IRREGULARITIES ON THE MOTION OF SOLID PARTICLES IN A TURBULENT FLOW

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The statistical processing of a high-frequency motion picture has enabled us to establish that a flow interface consisting of individual discrete particles is a surface which varies in time and space with a deviation from its average position on both sides which is of the same order as the average height of the jumps of the solid particles. The take-off level of the solid particles in these jumps is with large probability higher than the landing level. The distribution of rms deviations of the vertical component of the velocity of the solid particles over the flow depth has two maxima (above the average interface and at the level of the interface). On the distribution curve for the rms deviations of the horizontal velocity component only the first maximum is clearly expressed.

Solid particles at the boundary of a turbulent flow continually penetrate into it and thereby undergo a jumping motion. Phenomena of this type are seen in a number of geophysical problems, namely, in the motion of sediments in rivers and seas, the shifting of sand in the desert, the motion of snow, etc.

The modeling of these phenomena under laboratory conditions for the purpose of studying the trajectories of the solid particles is often done with a fixed irregularity, over which individual particles fed into the flow move. For this it is assumed that the character of the motion of the particles is the same for fixed and moving irregularities. Such an assumption is also found in all of the theoretical schemes for the jumping motion of the solid particles.

It was pointed out in Ref. [1] that moving irregularity differs from a nonmoving one. In the presence of moving particles at the bottom of the flow there appears a secondary, larger irregularity in the form of nodules consisting of several grains of sand. However, the characteristics of this new irregularity, which arises in the interaction of a turbulent flow and its lower deformable boundary, and the effect of this irregularity on the characteristics of the trajectories of the solid particles were not investigated in that paper.

In the present paper, in order to elucidate the role of the mobility of the bottom, we have analyzed the solid-particle trajectories obtained by processing motion pictures taken at the former Laboratory of River-Bed Processes of the Academy of Sciences of the USSR [1] in a trough with a length of 264 cm and a width of 6.1 cm at an average flow velocity of 45 cm/sec and a depth of 1.7 cm. The filming was done at 200 frame/sec. The current carried 0.86-mm grains of sand with a sinking velocity of 8.97 cm/sec and a density of 2.6 g/cm^3. Such particles were also located on the bottom. We analyzed 96 trajectories in all and observed the cases where the particles only rolled, only saltered, or underwent a mixed motion (saltation alternated with rolling).

Statistical processing of the film showed that the moving bottom was a noticeably nonplanar surface that varied in time and space. In determining the coordinates, we noted the positions of the particles when they touched the bottom, assuming that the elevation of the nonmoving bottom was located below the center of gravity of a particle by one half of its diameter. All cases where a particle touched the bottom, its take-off, landing, and rolling, were analyzed in order to discover the laws of the variation of the bottom elevation as measured from an arbitrary plane. We analyzed 560 bottom evelations at different instants of time and different positions of the particle along the flow (along the abscissa). Depending on the value of the coordinate, the elevations of the bottom were divided into groups at a 0.5-mm interval, and then the probability curve for the distribution of bottom elevations (Fig. 1, curve a) was plotted. On the ordinate is plotted the relative distance (y/H) from the average elevation of the bottom, which is shown by the dashed line; on the abscissa, the quantity n/N, where N is the total number of cases, where the bottom is touched and n is the number of such cases in a given distance interval, plotted at the center of each interval. The resulting curve, by virtue of its manner of construction, can be simultaneously considered both the depth distribution of the dwelling time and the concentration of particles at a given level in the case where they touch the bottom. The curve is almost symmetric with respect to the average elevation of the bottom, which is taken as the coordinate origin. The deviation from the average position on either side is of the order of 1.5 mm, an amount equal to almost two particle diameters. At an average jump height of 1.3 mm, this is a substantial quantity.

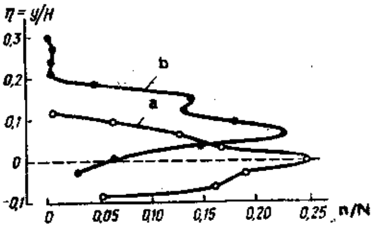

Fig. 1

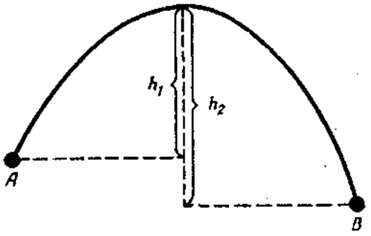

Fig. 2

Fig. 1. Probability distribution of bottom elevation (distribution over the depth of the flow of the dwelling time at a fixed level of rolling particles) (a), and distribution over the flow depth of the dwelling time of saltating particles (b).

Fig. 2. Diagram showing locations of the take-off point A and landing point B.

The variation in time of the bottom elevation is an important feature distinguishing this from the case of fixed irregularity, for which this elevation has some constant value. Thus, in the case of a moving irregularity the structure of the flow in the vicinity of the bottom is determined immediately by the following factors: the enhancement of the irregularity due to the formation of nodules, the presence of solid particles moving in jumps, and the continuous variation of the bottom surface. This last fact has not been considered in any of the earlier papers. In experiments with a moving bottom usually only its average elevation is fixed, as was done, for example, in Ref. [1]. The results show that this information is insufficient.

We will analyze further the distribution curve (Fig. 1, curve b) of the concentration (the dwelling time at a fixed level) of saltating particles (without taking into account the positions for the cases of particles touching bottom). This curve, constructed for 558 positions of particles on different trajectories, is similar to the distribution curve of the dwelling time of the particles at a given level in the case where they touch the bottom (curve a), but it is located somewhat higher. The distribution of the concentration of saltating particles is asymmetric. Positive deviations from the most probable value of the concentration are encountered more often than negative. To determine the aggregate solid flow rate it is necessary to sum both distribution curves after multiplying each concentration by the corresponding value of the average velocity of the moving particles.

In the case of a moving bottom, the height of the take-off point A can be different from the height of the landing point B (Fig. 2). Therefore, the height of a jump can be different when calculated from the take-off point A or the landing point B (h_1 and h_2, respectively). Figure 3 shows a histogram of the distribution of differences in height $\Delta h = h_2 - h_1$. The results show that in 81% of the cases one has $\Delta h > 0$, i.e., with a high probability the particles take off from a higher level than they land on. In the case of a fixed irregularity, $\Delta h = 0$.

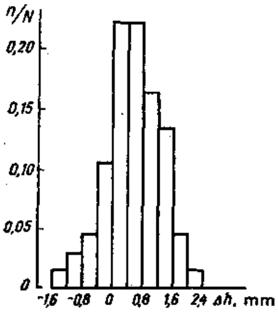

Fig. 3

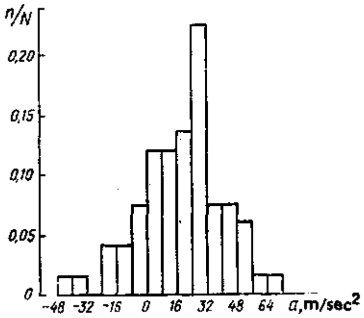

Fig. 4

Fig. 3. Histogram of the distribution of the difference of the take-off and landing levels $\Delta h = h_2 - h_1$.

Fig. 4. Histogram of the distribution of initial accelerations.

By analyzing the available data, we constructed a histogram (Fig. 4) of the distribution of the acceleration a of the solid particles at their instant of take-off. This quantity is defined as $a = 2\Delta y/(\Delta t)^2$. Here Δy is the height of the ascent of a particle in time Δt, defined as $\Delta y = y_1 - y_0$, where y_0 is the position of the particle in a state of rest, measured from the arbitrary reference plane, and y_1 is the distance from the center of the particle to this same plane in the next frame (after time Δt), when the particle is in a suspended state. Here, of course, one must keep in mind that the accuracy with which the instant take-off can be determined depends on the number of frames per second, as was pointed out in Ref. [2]. The acceleration determined in this way is the average over a time Δt. For a large enough value of Δt (small number of frames per second) the definition of "initial" acceleration loses meaning. The most probable value of the initial acceleration is equal to 28 m/sec^2, i.e., almost three times larger than the acceleration due to gravity. There were cases in which the intial acceleration had a negative value. It should be stressed that in the case of a fixed irregularity a particle can only move upward at the initial instant of take-off. In our case, for a moving irregularity, downward motion was observed in 18% of the cases. It is these cases that correspond to negative values of the acceleration. The average values of the take-off and landing angles were the same in absolute magnitude and were equal to 12°. The most probable duration of a jump was 0.05 sec.

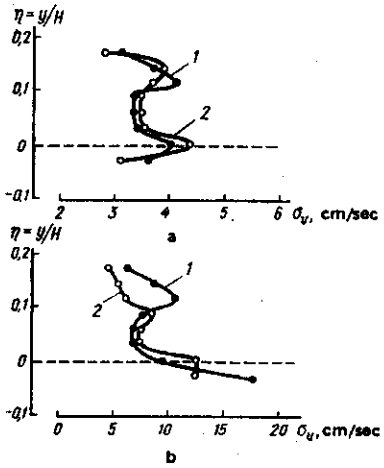

Fig. 5. Vertical distribution of the rms deviation of the vertical (a) and horizontal (b) components of the velocity of the solid particles (σ_v and σ_u, respectively): 1) on the ascending part, 2) on the descending part of the trajectory.

We have considered the curves of the distribution over the flow depth of the rms deviations of the vertical σ_v (Fig. 5,a) and horizontal σ_u (Fig. 5,b) components of the velocity for the ascending (curve 1) and descending (curve 2) parts of the solid-particle trajectories. The average position of the bottom elevation is shown in the figures. The distribution of σ_v is characterized by the presence of two maxima. One of these is located at a relative depth of 0.12H, and the other is at the level of the average elevation of the bottom (where, with a high probability, the take-off of the particles occurs). For the ascending parts of the trajectories the maximum of σ_u is somewhat higher than for the descending parts. The second maximum of σ_u (below the average elevation of the bottom) is not clearly detected.

DISCUSSION OF RESULTS

1. A moving bottom consisting of individual discrete particles is a surface that changes in time and space; its total deviation from the average position on either side is of the same order of magnitude as the height of a jump by one of the solid particles.

2. The take-off levels of the solid particles are, with a high probability, higher than their landing levels.

3. The distribution over the flow depth of the rms deviations of the vertical component of the velocity of the solid particles has two maxima (one higher than the average elevation of the interface and one at this level). The distribution of the rms deviations of the horizontal component of the velocity displays clearly only the first maximum.

4. At the moment of take-off the solid particles have a very substantial acceleration. For example, at a particle fineness of 0.86 mm and a density of 2.6 g/cm^3 the most probable value of the initial acceleration is 28 m/sec^2.

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