ISSN 0027-1349, Moscow University Physics Bulletin, 2010, Vol. 65, No. 6, pp. 550–552. © Allerton Press, Inc., 2010.
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The Capture of Large Bottom Particles by Eddies in a Dam Break Flow

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Received April 27, 2010; in final form, July 15, 2010

Abstract—On the base of an experimental study of the boundary layer of the head of a dam break flow it is shown that the thickness of a viscous layer exceeds the bottom particle diameter d_p, increases with d_p, and decreases with the flow velocity (for $d_p < 1.2$ cm). Bottom particles are captured by satellite eddies, which originate from main eddies near the bottom. Main eddies periodically appear in the viscous layer if the flow decelerates downstream. If $d_p > 0.045$ cm the satellite diameter is smaller than d_p. Satellites close in and run into one eddy, which can contain the bottom particles if the flow velocity achieves a critical value U_{dip}. Particles can be captured when the flow velocity has a higher value $U_{cr} > U_{dip}$. It is possible under this condition that a particle starts to rotate in the satellite without slippage.

Keywords: dam break flow, erosion, Vortex interactions, sediment transport.

DOI: 10.3103/S0027134910060238

INTRODUCTION

During the rupture of a natural or artificial dam, a stream flow running over a dry bed occurs. The steep front edge is often called "a wall of water." In some natural observations [1, 2], it has been established that the main portion of the large soil particles is transferred by the head of the wave [3], which was first experimentally studied in [4]. The authors concluded that the head wave sloughs, forming jets. It has been stated in [5] that complex eddies are developed at the front edge of the wave. In [6], it was shown that large and heavy particles could be transported by eddies of similar sizes if the particle density is approximately twice the density of water. To create a prognostic method for soil erosion, it is necessary to know the conditions under which eddies that are able to capture large soil particles are formed. The present paper is devoted to the solution of this problem.

APPARATUS AND METHODS

Experiments were conducted in a straight horizontal channel 3.5 m long and 20 cm wide, with transparent walls. A reservoir was separated from the channel with a shutter and was filled with water. After the shutter was opened (the time of lifting was ca. 0.04 sec) a flow emerged (with a velocity of up to 2 m/s), which was filmed. The water level in the reservoir was $h =$ 27 cm. The height of the shutter lift was 7 cm. The flow was shot by an immovable camera and also by a camera that moved along the flow with a velocity equal to that of the head wave. The moving camera sat on a dedicated car, which drove along a smooth plastic rail. The shooting was conducted by a remote camera and as a close-up. Particles of neutral density made of polystyrene were used to determine the flow velocity. On the bottom of the channel, calibrated particles with average diameters of 0.023, 0.12, 0.4, 0.8, and 1.2 cm were placed, forming a 4 cm-wide layer.

EDDY DEVELOPMENT AND THE CAPTURE OF PARTICLES

Upon dam rupture, main eddies with a diameter close to the depth of the flow formed in the frontal edge of the flow. In the area of flow deceleration, cylinder eddies with $d \approx 2\delta/3$ developed beneath major vortices in the viscous layer with width δ, in which the flow velocity $u = u_0 + \chi y$ is the function of the height coordinate y (χ = const, u_0 is near-bottom velocity). Satellite eddies with smaller diameters d_{sp} appeared between the major vortices and the bottom. These eddies rotated in one direction and merged if they appeared to be sufficiently close to one another under the condition [7] that

$$\frac{d}{d_{sp}} < 3. \quad (1)$$

Upon merging, the new eddies were able to capture larger particles. In a series of experiments we obtained a relationship showing the dependence of the width of the viscous layer δ on the maximal flow velocity on the water surface u_{max} for particles with diameter $d_p \approx 0.23$, 0.12, 0.4, 0.8, and 1.2 cm (Fig. 1). The width of the viscous layer decreased with the increase in flow veloc-

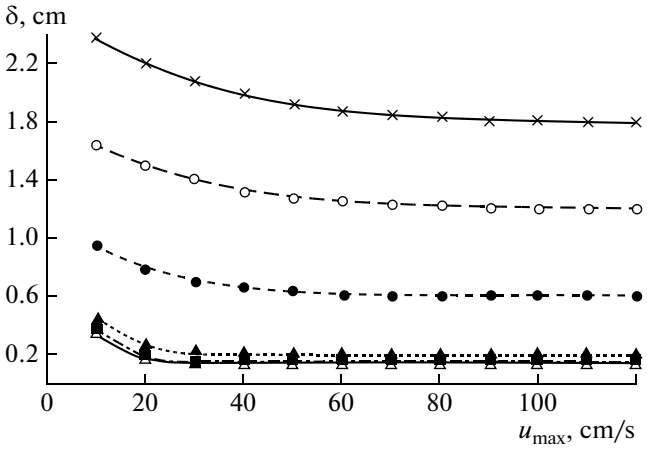

Fig. 1. Dependence of the width of the viscous layer δ on the maximum flow velocity u_{max} for a smooth bottom (slim solid line of the trend), for particles with diameters of 0.023 cm (dashed–dotted line of the trend), 0.12 cm (dotted line), 0.4 cm (slim dashed line), 0.8 cm (bold dashed line), and 1.2 cm (bold solid line of the trend).

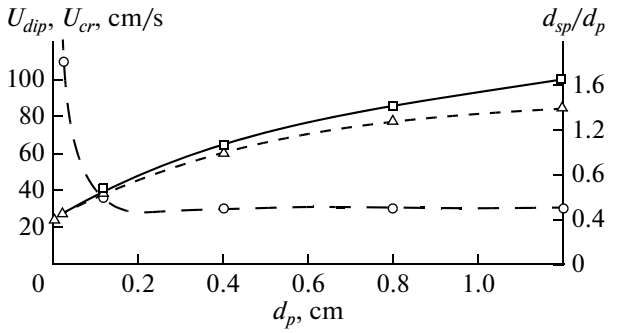

Fig. 2. Dependencies of the relationship d_{sp}/d_p (dashed line of the trend), critical velocity of the flow for the formation of dipoles U_{dip} (dotted line of the trend), and critical flow velocity U_{cr}, at which the capture of large soil particles starts (solid line of the trend), on the diameter of the bottom particles.

ity, reached the minimum value σ_{min}, and remained constant with further increases of velocity. The width of the minimum layer surged with the increase in particle diameter, exceeding it by approximately one-third. For this layer, the relationship d/d_{sp} satisfies the condition of eddy merging (1) (Table) for all particle dimensions. For $d_p > 0.2$ cm, this relation hits the minimum $d/d_{sp} = 2$, and with the merging of satellites, the size of the new eddy proved to be close to the size of the main vortex. This pair of vortices rotated in opposite directions. The pairs ascended, reaching the water surface. For $d_p < 0.2$ cm, the merged satellite eddies were smaller than the main ones; the emerging dipoles moved along an arc trajectory due to the rotation of the system of eddies.

Figure 2 shows the dependence d_{sp}/d_p on the particle size. When $d_{sp}/d_p < 1$ (for $d_p < 0.05$ cm), the particles could be seized by a satellite eddy, while for the capture of larger particles, it was necessary that the merger of satellite eddies occur. For $d_p > 0.2$ cm, the minimum value of the relation $d_{sp}/d_p = 0.5$. In this case, the diameter of the eddy upon the merger of satellite eddies was close to the diameter of a soil particle. This provides for the possibility of the particle capture by a dipole, if the flow velocity exceeds the critical value U_{dip}, at which the dipoles are formed. The dependence $U_{dip}(d_p)$ was determined in a series of experiments (Fig. 2). Can a vortex retain a large particle under the conditions of dipole formation?

It was shown in [6] that eddies are able to hold such particles if their density is about two times greater than that of water and the particles rotate without slippage. For a particle to rotate in an eddy without such slippage, the rotation velocity ω_{sp} of the satellite eddy should be sufficiently high. In accordance with [7]:

$$\omega_{sp} = \frac{d}{d_{sp}}\frac{2u_0}{\delta}. \quad (2)$$

When the width of the viscous layer reaches the minimum value δ_{min}, the relationship of eddy diameters is steady, meaning that the angular velocity is conditioned only by the bottom velocity u_0. Experimental data indicate that within a range of velocity values for which $\delta = \delta_{min}$, $u_0 \approx u_{max}/10$. Accounting for (2), we obtain:

$$\omega_{sp} = 0.2\frac{d}{d_{sp}}\frac{u_{max}}{\delta_{min}}. \quad (3)$$

Hence, ω_{sp} is determined solely by the flow velocity on the surface. In a series of experiments we determined the dependence of the critical value of this parameter U_{cr}, at which the capture of large particles of soil starts, on the size of particles ($d_p > 0.045$ cm) (Fig. 2). The capture and carrying of large soil grains (0.2–0.4 cm) by eddies is shown in Fig. 3. The particle is located with its long side along the eddy axis. It appeared that $U_{cr} > U_{dip}$, and the gap increases with the increase in the particle diameter.

Dependence of the width of a viscous layer and the relationship between the diameters of the main vortex and satellite eddies on the diameters of soil particles

d_p, cm	δ_{min}, cm	d/d_{sp}
0	0.14	2.6
0.023	0.14	2.4
0.12	0.2	2.1
0.4	0.6	2
0.8	1.2	2
1.2	1.8	2

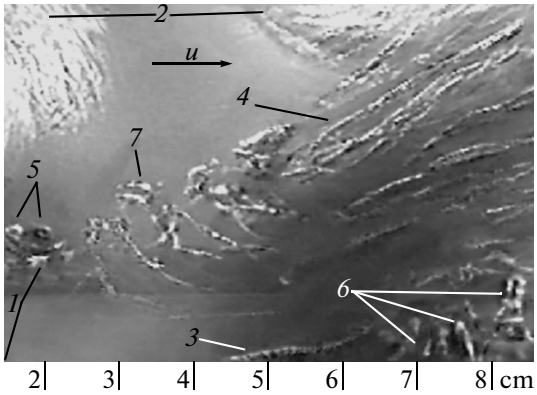

Fig. 3. The bottom layer of the flow in the head wave of a break. *1*, bottom of the channel cleared of rubble; *2*, large eddy bunches; *3*, eddies formed in the viscous layer of the flow above the rubble; *4*, eddies that ascended; *5*, eddy dipoles formed over the rubble $d = 0.4$ mm; *6*, vertical edges of eddies with the captured rubble; and *7*, eddy dipoles emerging above a smooth bottom $d = 0.15$ mm.

CONCLUSIONS

On the basis of an experimental study of the boundary layer of the head of a dam break flow it was shown that the thickness of a viscous layer exceeds the bottom particle diameter d_p, increases with d_p, and decreases with the flow velocity (for $d_p < 1.2$ cm). Bottom particles are captured by satellite eddies, which originate from main eddies near the bottom. Main eddies periodically appear in the viscous layer if the flow decelerates downstream. If $d_p > 0.045$ cm the satellite diameter is smaller than d_p. Satellites close in and run into one eddy, which can contain the bottom particle if the flow velocity achieves a critical value U_{dip}. Particles can be captured when the flow velocity has a higher value $U_{\text{cr}} > U_{\text{dip}}$. It is possible under this condition that the particle starts to rotate in the satellite without slippage and the eddy can retain it.

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