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DEPTH ABOVE A DROP OF THE CHANNEL BOTTOM AFTER FREE-SURFACE DISCONTINUITY DECAY

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This paper reports experimental data on the depth above a bottom drop in a rectangular channel after removal of a shield that produces the initial difference in the free-surface level. It is shown that at a sufficiently large height of the drop, this depth is approximately 40% smaller than that obtained in the first shallow-water approximation.

Key words: *even bottom, dry and flooded bottom, submerged and free conditions, hydraulic jump, depression wave.*

The hydrodynamic processes considered in this paper are typical, for example, for accidents at ship locks due to lock-gate failure. A significant feature of the formulation of the corresponding research problem compared to the classical dam-break problem is that at the lock-gate location there is a drop — a sharp lowering of the bottom level from the upper to the lower lock chamber. In this case, the hydrodynamic processes in the upper and lower chambers are largely controlled by the flow pattern directly above the drop. In particular, the submerged and free states of head and tail conjugation differ appreciably. By the definition [1], the state of conjugation is called free if the processes in the head water do not depend on the processes in the tail water. This is the case if the drop depth h_0 is smaller than the critical depth $h_* = (q^2/g)^{1/3}$ (q is the discharge intensity and g is the acceleration of gravity). One also distinguishes between the bottom and surface states of head and tail conjugation [1]. In stationary flow behind the drop, a change between these states occurs when $h_0 \approx h_*/1.3$ [2]. The depth h_0 also determines the shape of the depression wave in the head water.

The hydrodynamic processes due to lock-gate failure are analyzed in [3] using the first shallow-water approximation. The same approach is developed in [4]. In [3], the submerged state is not considered, but the sought functions include the height and propagation velocity of the wave reflected from the intact gate in the tail water. In [4], the submerged state is also considered, but the channel is unbounded upstream and downstream. The results of [3] were tested in the experiments of [5], and those of [4] in [6].

Previously, the first shallow-water approximation has been used to solve the dam break problem for a channel with an even bottom (see, for example, [7, 8]). In the problem of lock-gate failure, the classical formulation [7, 8] should be supplemented by conjugation conditions above the drop. In [3, 4], this is done by invoking the energy conservation law in addition to the conservation laws for mass and momentum.

According to [3, 4], in the free state, the drop depth $h_0 = h_*$. Experiments [5] performed for one value of the drop height gave a considerably different result. At the same time, in the case of an even bottom at the dam location, the critical depth h_* is indeed established. The present paper gives a more detailed experimental information for drops of various heights and shapes, including the case of dam break above an even bottom with a drop height $b = 0$.

The experiments described here were performed in a rectangular channel 20.2 cm wide with the left butt-end open and the right butt-end closed. The open butt-end was joined to a tank 1 m wide and 3.3 m long, as shown in Fig. 1. At a distance of 4.67 m from the open butt-end, the channel-bottom level began to decrease linearly from

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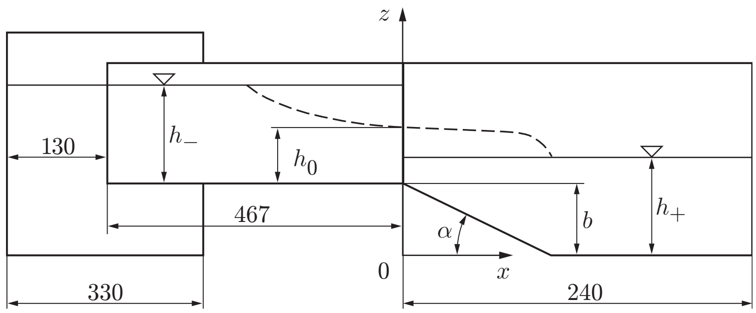

Fig. 1. Experimental setup (dimensions in centimeters).

one constant value to another. In this cross section of the channel, which was taken as the origin of the longitudinal coordinate x, an initial free-surface difference was produced by means of a vertical shield (see Fig. 1). At the time $t = 0$, the shield was removed upward with a lever. The motion of the shield was recorded by a side-wire gauge. The time of exit from water for the lower edge of the shield did not exceed 0.05 sec.

The initial depths of the head water h_- and tail water h_+ (see Fig. 1) were measured with measurement needles with an absolute error not worse than 0.02 cm, and the depth in the other cross sections of the channel (in particular, in the shield section h_0) were measured with wavemeters. The principle of operation of the wavemeters is based on the difference in electric conductivity between water and air. The resolution of the wavemeters determined from the double root-mean-square values of their self-noises was 0.02 cm. The upper bound of the oscillation frequency measured by the wavemeters with an error no greater than 10% was approximately 10 Hz. The electrical signals of the side-wire gauges and wavemeters were entered into a computer using a standard eight-channel analog-to-digital ACL-8112 converter. In the analog-to-digital conversion, the step in time did not exceed 0.008 sec. The total random error of the measurements was estimated from the results of repeated measurements under identical conditions. The root-mean-square value of this error did not exceed the size of the experimental points on the plots given below.

The main external parameters of the problem are h_-, h_+, g, and the height b and slope of the drop α (see Fig. 1). At large times, the lengths of the segments from the shield to the open and closed butt-ends of the channel, the geometrical parameters of the tank at the head of the channel, and the energy losses due to friction on the channel bottom and walls are also of significance. The examined value h_0 is a complex function of these parameters and time. For each of its arguments, there are critical conditions in the sense that in the neighborhood of definite values of the argument there are fast changes in h_0 due to changes in the flow pattern. In particular, as regards the parameter h_+, there are considerably different processes of wave propagation over the dry and flooded bottoms, the submerged and free conditions, the bottom and surface states of head and tail conjugation, attached and detached jet regimes or an air cavern in the neighborhood of the drop [9].

According to [3, 4], after removal of the shield, the depth h_0 changes instantaneously from h_- to a smaller constant value; in the free state, as in the case of dam break above an even bottom, this constant value is equal to the critical depth

$$h_* = 4h_-/9.$$

In the experiment, the transition from h_- to the smaller constant value is fast but not instantaneous. In these experiments, the time of attaining the constant value of h_0 did not exceed 0.35 sec. This constant value was kept until the perturbation reached one of the channel butt-ends, resulting in a change in the boundary conditions. The value of h_0 shows an especially fast response to a change in the boundary conditions at the open end of the channel since the upstream flow is subcritical. In the case of an even bottom and the free state, the downstream flow is supercritical and the change in the boundary conditions at the closed end of the channel does not affect h_0. Significant changes in h_0 begin at the moments the reflected waves arrive at the shield location.

The results of measurement of h_0 in the time intervals where its value was constant are given below. This constant value is denoted by h_0. The characteristic linear scale for nondimensionalizing was the initial depth h_-. Nondimensional quantities are denoted by superscript zero.

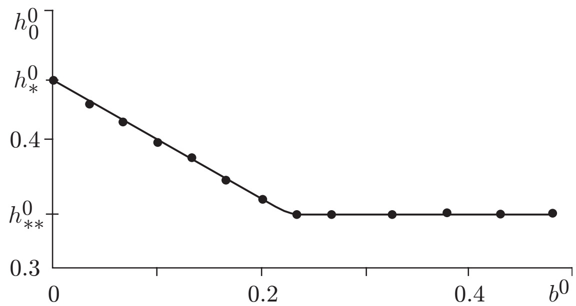

Fig. 2. Experimental curve of the depth at the shield location versus the sill height [$h_- = 15$ cm, $h_+^0 = 0$ (dry bottom), and $\alpha = 90°$).

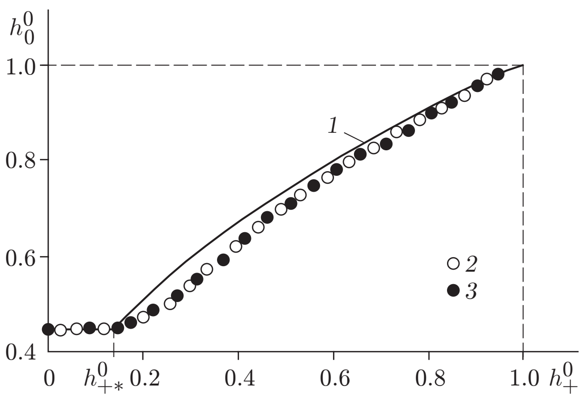

Fig. 3

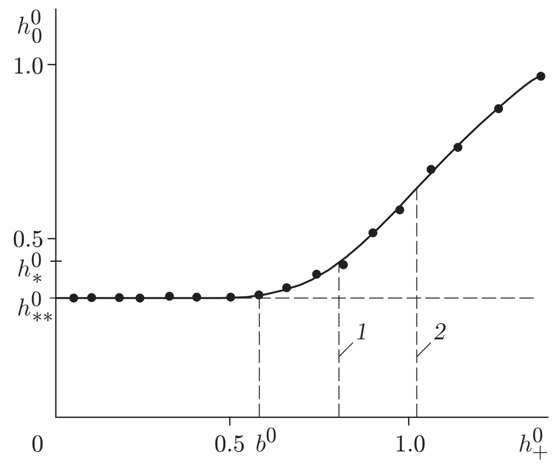

Fig. 4

Fig. 3. Depth at the shield location versus tail-water depth in the case of an even bottom ($b^0 = 0$): curve 1 refers to the theory [8] and points 2 and 3 refer to the experiment at $h_- = 15$ and 22 cm, respectively.

Fig. 4. Depth at the shield location versus tail-water depth in the presence of a drop ($h_- = 12.5$ cm, $b^0 = 0.576$, and $\alpha = 90°$): 1 and 2 refer to the upper bound of the free state (experiment and theory [3], respectively).

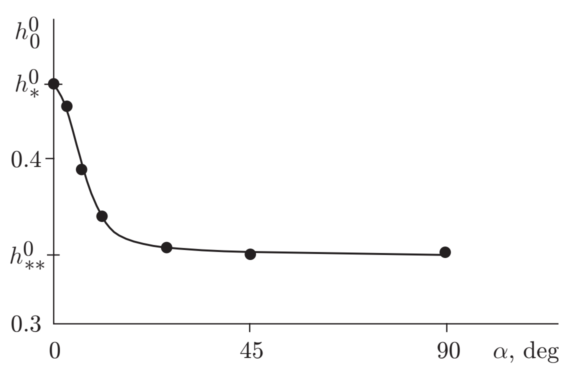

Fig. 5. Experimental curve of the depth at the shield location versus α [$h_- = 15$ cm, $b^0 = 0.48$, and $h_+^0 = 0.133$ (free state)].

Figure 2 gives a curve of h_0^0 versus b^0 for constant values of h_-, h_+, and α. The experimental points in this figure were obtained for the case of a sudden lowering of the bottom ($\alpha = 90°$) and the free state of head and tail conjugation for all values of b^0, including the case of an even bottom ($b^0 = 0$). The values $h_*^0 = 4h_-/9$ and $h_{**}^0 \approx h_*^0/1.3$ are shown by dashes.

Recently, it has been found experimentally (see, for example, [2, 10]), that along with h_*, the quantity h_{**} is one more critical parameter in a number of problems of open-channel hydraulics. In particular, exactly this depth is established on the boundary between the channel exit and the atmosphere [10] and it is also a convenient parameter for the identification of different forms of hydraulic jumps and transition from the bottom to the surface state of head and tail conjugation [2]. In this connection, in [2, 10], h_{**} is referred to as the second critical depth.

The experimental data in Fig. 2 show that the result $h_0^0 = h_*^0$ (in the free state) obtained in the first shallow-water approximation was confirmed only in the case of an even bottom, and that for $b^0 > 0.23$, the second rather than the first critical depth was established at the shield location. One should expect that the observed regularity holds as b^0 increases beyond the experimental values since it also occurs in flow passage from the channel to the atmosphere ($b^0 \to \infty$) [10].

Figure 3 shows a curve of $h_0^0(h_+^0)$ for $b^0 = 0$ (even bottom) in both the submerged and free states. According to [8], in the free state (in particular, in the case of a dry bottom, where $h_+^0 = 0$) $h_0^0 = h_*^0$ and the upper bound of the free state is specified by the condition $h_+^0 = h_{+*}^0 \approx 0.138$. These results were confirmed. In the submerged state, the experimental value of h_0^0 is smaller than the theoretical value. The difference is lower than 10%.

Figure 4 shows a curve of h_0^0 versus h_+^0 for $b^0 = 0.576$ and $\alpha = 90°$. For this value of b^0 there is a range of the parameter h_+^0 in which, unlike in the range obtained in [3, 4], the second rather than the first critical depth is established above the drop (see Fig. 2). In example considered, this occurred at $h_+^0 < b^0$. In the presence of a drop, the experimental data are in conflict with those of [3, 4] for the upper bound of the free state too. According to [3, 4], this bound corresponds to $h_{+*}^0 = b^0 + h_*^0$. In the experiment it was found that $h_{+*}^0 \approx b^0 + 0.5h_*^0$.

Figure 5 gives an experimental curve of $h_0^0(\alpha)$ for fixed values of the other parameters. This dependence has not been studied theoretically. According to the assumptions of the first shallow-water approximation, the smaller the value of α, the better. The example in Fig. 5 shows that the experimental points deviate markedly from the dependence $h_0^0 = h_*^0$ even for $\alpha = 3°$, and for $\alpha > 30°$, the second rather than the first critical depth is established above the drop.

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