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TRANSFORMATION OF A BREAKING WAVE AT A DROP OF A CHANNEL BOTTOM

A. A. Malysheva and I. A. Malysheva

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This paper gives results of an experimental study of incident and reflected waves of the bore type in the neighborhood of a sharp change in the channel bed level. It is shown that under conditions typical of accidents at ship locks, the wave height can reach 8 m.

Key words: *liquid, free surface, breaking wave, experiment.*

Introduction. The term breaking waves is used for downstream waves produced by dam break [1]. In the initial stage, as a rule, a breaking wave has the shape of a classical moving hydraulic jump and then becomes an undular jump. A moving hydraulic jump is termed a bore [2]. Similar waves are caused by breakdown if lock gates. In this case, the wave pattern is significantly affected by the presence of a sudden lowering of the downstream bottom level at the lock site. In particular, under certain conditions, two hydraulic jumps moving one after another are formed behind the drop [3–5]. Breaking waves are also generated by a tsunami or a tidal wave entering a river, by landslides of reservoir shores, falls of meteorites or rock fragments, an abrupt stop of a tanker or an inclined boat lift, wave impingement on a ship deck, etc.

Breaking waves are calculated using the first shallow-water approximation [2–4, 6], Saint-Venant's equations [1, 7, 8] and the finite control volume method [9]. The calculation method based on the mathematical model of [10], which takes into account turbulent mixing in a hydraulic jump, is also promising. This method describes the real shape of a hydraulic jump, whereas in other methods all five possible shapes of the jump are modelled by a free-surface discontinuity. Among experimental studies, [11–13] worth noting.

Investigation of the transformation of breaking waves on bottom irregularities is an urgent problem. In the dam-break problem, this information is necessary for accounting for the effect of local hydraulic resistances. In the problem of breakdown of a lock gate, of interest is the accident in which there is breakdown of the gate between the approach channel and the upper chamber with the second gate open (from above) and the third gate closed. This situation is especially dangerous for a ship that sails from the downstream side and is in the lower chamber at the moment of the accident.

In the present paper, we give results from experimental studies of the transformation of breaking waves on a bottom irregularity in the form of a drop that can be used to check various calculation methods. Such calculations have not yet been performed since the above-mentioned methods require a rather complex adaptation to this problem.

Experimental Technique. Figure 1 shows a diagram of the experiment and the coordinate system used. The experiments were performed in a rectangular channel of width 0.2 m. A drop of height $b = 0.072$ m was at a distance $l = 2.4$ m from the right closed end of the channel. The left open end of the channel was attached to a tank of width 1 m. This simulated the boundary conditions typical of a ship lock ahead of which there is a outside harbor with a large free-surface area. The initial difference between the free-surface levels $h_- + b - h_+$ was produced by a flat shield located at $l_1 = 1.21$ m upstream of the drop. For the parameter h_+ in the initial conditions, it is necessary to distinguish between the ranges $h_+ \leqslant b$ ("dry bottom" on the segment from the shield to the drop) and

Novosibirsk State Architectural-Building University, Novosibirsk 630008; bukreev@hydro.nsc.ru. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 46, No. 2, pp. 115–121, March–April, 2005. Original article submitted August 9, 2004.

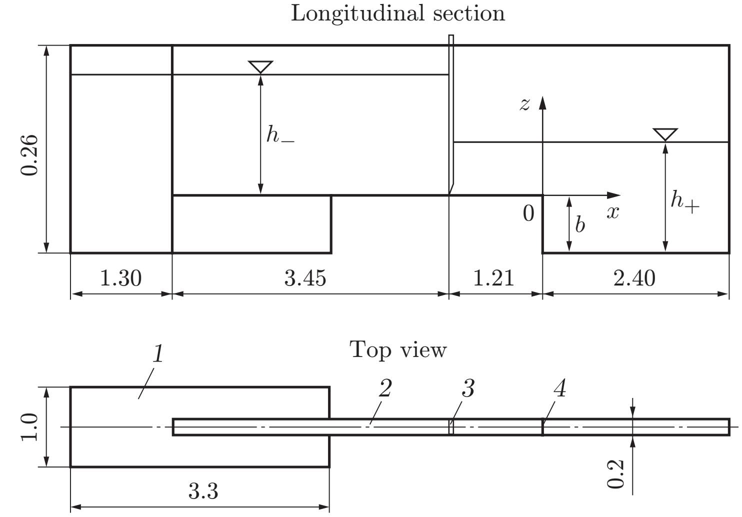

Fig. 1. Experimental setup (sizes in meters): tank (1), channel (2), flat shield (3), and drop (4).

$h_+ > b$ ("flooded bottom"). The parameters b, l, and l_1 did not vary in the experiments. The initial free-surface levels were determined by measuring needles with an absolute error not higher than 0.05 cm. Head-water depths were measured from the channel bottom ahead of the drop, and tail-water depths from the bottom behind the drop.

At the time $t_0 = 0$, the shield was removed manually from the channel. The law of its motion was recorded by a reochord sensor. The deviation of the free surface from the initial level η as a function of time t at specified points along the longitudinal coordinate x was measured by wavemeters, whose operating principle was based on the difference in electrical conductivity between water and air. The resolution of the wavemeters was 0.2 mm. The upper bound of the oscillation frequency recorded by the wavemeters with an error not higher than 10% was 10 Hz. Photography was also performed. Primary material was processed on a computer.

In the experiment, difficulties arose in measuring the speed of propagation of the waves considered. First of all, a rigorous definition of the propagation speed can be given only for stationary waves whose shape is unchanged in a coordinate system moving together with the wave or for self-similar solutions. The stationarity or self-similarity conditions, strictly speaking, are not satisfied because of energy dissipation. Another complicating factor is the presence of an unstable roller at the leading edge of a classical hydraulic jump.

In the experiments, the speed of wave propagation is taken to be the speed of motion of an isolated point on the wave profile. Experimental data were obtained for the point at the middle of the height of the wave leading edge by measuring the traveling time Δt of this point in a specified interval of the longitudinal coordinate Δx between two fixed wavemeters. Of significance is the coordinate x of the middle of the interval Δx, by which the measured values $D = \Delta x/\Delta t$ are normalized. In the experiments, we chose the values of x (downstream) at which the depth behind the jump was constant. The values of Δx varied from 20 to 40 cm with other conditions being equal. In this case, the spread in the measurement data was within the random error due to instability of the hydraulic-jump roller. Three to four repeated experiments were performed and their results were averred to reduce the random error for some combinations of parameters. Nevertheless, the experimental error of D was higher than the error in determining the characteristic depths.

Experimental Results. Figure 2 shows a plot of the law of motion of the lower edge of the shield $z_*(t)$ (curve 1), from which the time of removal of the shield from water was determined. It did not exceed 0.05 sec. The figure also gives curves of the free-surface level $\eta(t)$ at three points on the longitudinal coordinate (curves 2–4). The wavemeter does not distinguish the directions of wave propagation (in the figure, their leading edge is located on the left). According to the diagram given in Fig. 1, the waves propagated from left to right. In this example, the wave height had the largest value among all values obtained for various combinations of parameters.

In the case of an even bottom with $h_- = 15$ cm and $h_+ - b = 5$ cm, as in the example considered, a breaking wave with one hydraulic jump propagated downstream [3, 11]; the mean height of the jump's leading edge (the

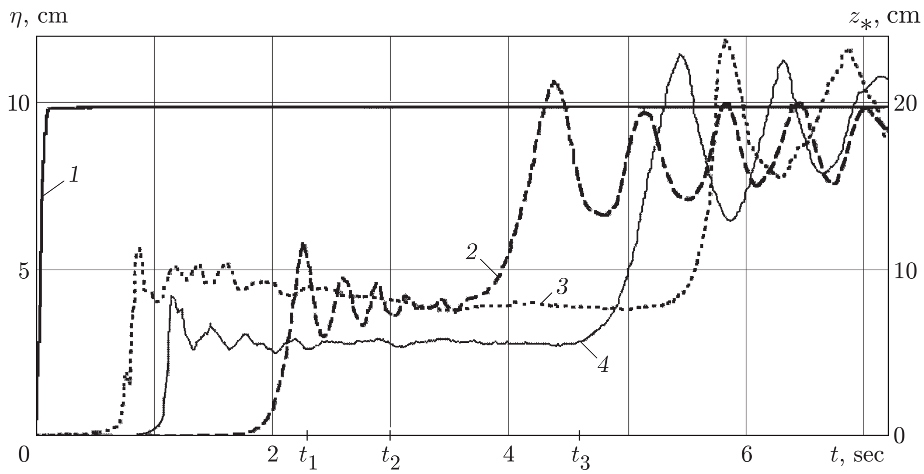

Fig. 2. Law of motion of the shield (curve 1) and level fluctuations at three characteristic points (curves 2–4) for $b = 7.2$ cm, $h_- = 15$ cm, and $h_+ - b = 5$ cm: $x = 120$ cm (2), -41 cm (3), and $= 0$ (4).

difference between the free-surface levels behind and ahead of the jump ignoring undulations) was $a/h_- = 0.22$. In the presence of a drop of height $b/h_- = 0.48$, the downstream incident wave also had the shape of one hydraulic jump. The height of the jump depends on x. In Fig. 2 it is evident that compared to the case of an even bottom, upstream of the drop (curve 3, $x/h_- = -2.73$), the jump height is 45% larger, directly on the drop (curve 4, $x/h_- = 0$), this value is 16% smaller, and at a distance downstream of the drop (curve 2, $x/h_- = 8.0$), it is 22% larger. As in the case of an even bottom, undulations occur behind the leading edge of the jump. The relative span of the undulations (the difference in level between the first crest and the first trough normalized by the mean height of the jump) increases downstream: 32% for $x/h_- = -2.73$, 53% for $x/h_- = 0$, and 70% for $x/h_- = 8.0$. The characteristic period of the undulations is $T\sqrt{g/h_-} = 2.70$, and the characteristic length (the distance between adjacent crests) $\lambda/h_- = 2.82$ (g is the acceleration of gravity). For a x, the free-surface level reaches a constant value with time, and in the submerged regime, this value is identical ahead of the drop and behind it (curves 2 and 3 in Fig. 2). In the submerged regime, this value is smaller directly on the drop (curve 4) than ahead of the drop and behind it. By the definition of [14], the regime of tail and head conjugation is called nonsubmerged if downstream processes do not influence upstream processes; otherwise, it is called submerged.

In Fig. 2, the following three characteristic times are indicted on the abscissa axis: t_1 is the travel time of the depression wave to the left open end of the channel, t_2 is the travel time of the breaking wave to the right closed end of the channel, and t_3 is the travel time of the depression wave to the left end wall of the tank, which models the outside harbor of a lock (see Fig. 1). At all these times there are qualitative changes in the wave pattern. In particular, at t_2, there is a high water uprush on the wall [15], and a jump having the shape of an undular boron propagates upstream. From Fig. 2 it follows that the free-surface level corresponding to the undulation crests in the reflected wave, exceeds the initial head-water level, which can cause flow of a large mass of water over the lock side walls [13].

We denote by $h_{\rm as}$ the constant depth behind the jump before the arrival of the reflected wave at the wavemeter. In the interval $x \leqslant 0$, this quantity was measured from the bottom to the drop, and for $x > 0$, from the bottom behind the drop. Figure 3 gives the dependences of $h_{\rm as}$ on h_+ for four values $x \leqslant 0$: at the shield location (curve 4), directly above the drop (curve 1), and at two intermediate points (curves 2 and 3). The depth h_+ was measured from the bottom behind the drop; therefore, its value can be larger than the initial head-water depth h_- (measured from the bottom ahead of the drop) by the height of the drop (see Fig. 1).

From Fig. 3 it follows that for $h_+ \leqslant b$ and all $x \leqslant 0$, the value of $h_{\rm as}$ does not depend on h_+. At the shield location (curve 4), this independence holds over the wider interval $h_+ \leqslant b + 0.138h_-$ (dashed curve 6), and the numerical coefficient is the same (0.138) as in the case of dam break above an even bottom [2]. This is the upper boundary of the nonsubmerged regime. In the case of an even bottom with $h_+ \leqslant b + 0.138h_-$, a depth equal to $4h_-/9$ is established at the shield location [2]. Curve 4 also confirms this theoretical result in the case of a bottom with a drop if the shield is located far away upstream.

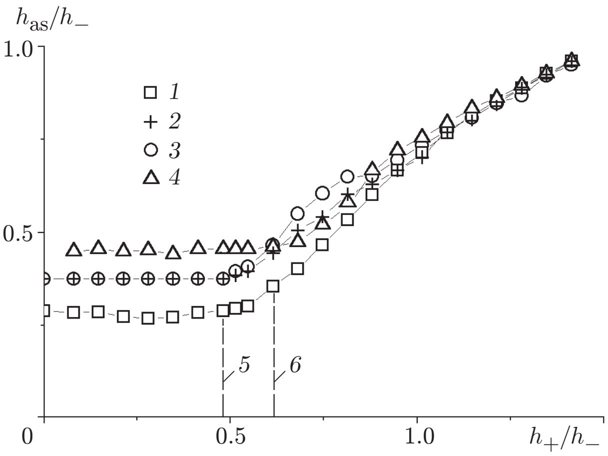

Fig. 3

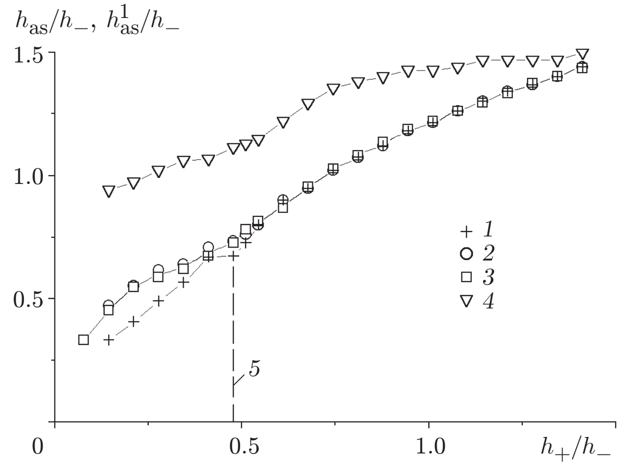

Fig. 4

Fig. 3. Asymptotic depths behind incident waves for $x \leqslant 0$ ($b = 7.2$ cm, $h_- = 15$ cm, and $h_+ - b = 5$ cm): $x = 0$ (1), -11 (2), -41 (3), and -121 cm (4); the drop height and the theoretical upper boundary of the nonsubmerged regime are shown as 5 and 6, respectively.

Fig. 4. Asymptotic depths behind incident waves h_{as} (curves 1–3) and behind the reflected wave h^1_{as} (curve 4) for $x > 0$ ($b = 7.2$ cm, $h_- = 15$ cm, and $h_+ - b = 5$ cm): $x = 40$ (1), 80 (2) and $x = 150$ cm (3 and 4); the drop height is shown as 5.

The depth above the drop is smaller than the depth at the shield location for all values of h_+. According to the data given in Fig. 3, in the interval $h_+ \leqslant b$, the ratio of these depths is constant and equal to 3/4. Thus, the experiments showed that in an infinitely long channel at sufficiently large times and $h_+ \leqslant b$, the flow is determined by two characteristic depths: the critical depth $h_* = 4h_-/9$ at the shield location and the depth $h^0_* \approx h_*/1.33$ above the drop if the distance from the shield to the drop is large enough. The experiments of [12] also showed that if the shield is located directly above the drop, the so-called second critical depth $h_{**} \approx h_*/1.3$ is established there.

Figure 4 gives plots of the function $h_{as}(h_+)$ for three values $x > 0$ (behind the drop) and a plot of the function $h^1_{as}(h_+)$ for $x = 150$ cm (h^1_{as} is the average depth behind the reflected wave). For $h_+/h_- > b/h_-$, the experimental points for various values of x for incident waves lie on a universal curve, indicating the existence of a self-similar flow regime. For $h_+/h_- < b/h_-$, the experimental points corresponding to $x = 40$ cm are located below the points corresponding to large values of x. This is a consequence of the local depth reduction due to the jet flow incident from the drop onto the channel bottom. For reflected waves, self-similarity held for all values $0.27 \leqslant x/h_- \leqslant 10$. Figure 4 gives data only for $x/h_- = 10$.

According to theory [3, 4] and experimental data [12], for the case of the shield location directly above the drop, breaking waves with one or two jumps moving one after another can propagate behind the sill. The same wave shapes were observed in the present experiments with the shield location upstream of the drop. For this case, as a first approximation, the boundary separating the regions of existence of these wave shapes can be determined by the algorithm described in [3, 4] or by the plot given in [12, p. 68].

The dependences of the propagation speed of the wave leading edge D on the depth behind the shield h_+ for two values of x are given in Fig. 5. For $x < 0$, the dependence is almost the same as that for the case of an even bottom [16]. In particular, for $h_+ < b$, the wave on the segment $x < 0$ propagates over the dry bottom. In this case, according to theory [2], $D = 2\sqrt{gh_-}$. As in the case of an even bottom [16], in the present experiments, a smaller value close to the maximum propagation speed of solitary waves was obtained: $D \approx c_{**} = 1.3\sqrt{gh_-}$. The measurement error D is shown by a section of a vertical straight line. On the segment $x < 0$, this speed is constant. For $h_+ > b$, the wave on the segment $x < 0$ propagates over the flooded bottom. In this case, experimental data are in fairly good agreement with theoretical data [2].

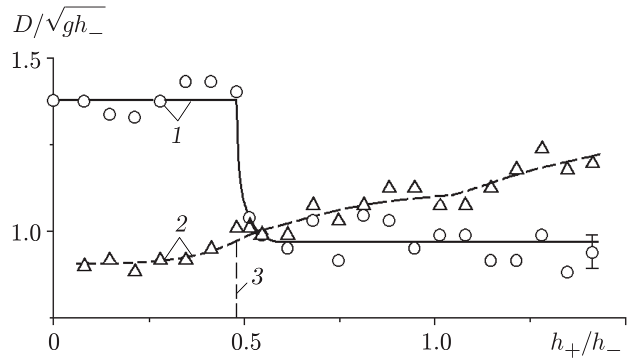

Fig. 5. Propagation speed of the leading edge of the incident wave versus the initial depth behind the drop for $b = 7.2$ cm, and $h_- = 15$ cm: $x = -26$ (1) and 135 cm (2); the drop height is shown as 3.

For rather large $x > 0$ and $h_+ > b$, the data obtained for $D(h_+)$ also differ only slightly from theoretical and experimental results for the case of the shield location above the drop [12]. For $h_+ < b$, the location of the shield has a significant effect on D. When the shield is located directly above the drop, the propagation speed of the wave leading edge increases more considerably with decrease in h_+ than in the experiments discussed here.

Conclusions. Experimental data were obtained for values of x and t such that the friction on the walls has an insignificant effect on wave processes. Therefore, conversion from the model to a full-scale object can be performed using the Froude criterion. In the example considered, the parameters h_- and b in the scale 1 : 100 correspond to the parameters of the ship lock of the Novosibirsk hydroelectric power station. The obtained data show that in the accident described above, the first free-surface elevation in the incident wave taking into account undulations reaches 5.8 m. The second rise in the level in the reflected wave is even larger and reaches 7.8 m taking into account undulations. Continuous flow over the chamber sides is also possible.

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