Journal of Applied Mechanics and Technical Physics, Vol. 51, No. 1, pp. 74–78, 2010

HYDRODYNAMIC PRESSURE DURING REFLECTION OF A BORE FROM A VERTICAL WALL

V. I. Bukreev

UDC 532.532+532.59

This paper presents the results of experiments in which a nonlinear wave was reflected from a vertical wall. It is shown that the hydrodynamic pressure of the wave depends significantly on the shape of its leading edge. It is found that the highest pressure is reached during reflection of a wave with a cumulative jet at the leading edge.

Key words: *bore, reflection from wall, hydrodynamic pressure, experiment.*

The term bore is used to refer to a moving hydraulic jump [1]. This wave shape is typical of catastrophic waves of various nature, in particular, a tsunami incident on a shelf and a dam-break wave propagating downstream. Five types of bore are distinguished [1]. The main types — a smooth undular bore and a bore with a roller at the head — are described, for example, in [2]. The leading edge of a smooth undular bore can break during evolution. In a certain stage of the breaking process, a cumulative jet having considerable energy can form at the leading edge. Figure 1 gives photographs of the bore head with cumulative jets at the leading edge. The impact of a cumulative jet on an obstacle is accompanied by a significant pressure rise. The dynamic effect of a smooth bore is much weaker, and during the action of a bore with a broken leading edge, the pressure decreases due to air entrainment.

This paper gives some results of the experiments shown schematically in Fig. 2. In a long rectangular channel, 20 cm wide and 25 cm high, with closed butt-ends, an initial depth drop $H = h_- - h_+ > 0$ of a quiescent fluid was produced using a vertical gate 1 cm thick. The gate was at distance L from the left vertical end wall of the channel (see Fig. 2). The origin of a motionless rectangular coordinate system (x, z) is at this cross section. In the region $(-L, x_1)$, the bottom of the channel was horizontal, in the region (x_1, x_2), the bottom rose linearly, and in the region (x_2, x_3), the bottom again became horizontal. Below, the inclined region of the bottom will be called the shelf, and the horizontal region (x_2, x_3) the beach. At the end of the beach there was a vertical wall with pressure sensors with a diameter of 1 cm and an eigenfrequency of approximately 50 kHz. Spectral analysis of the processes performed using the technique described in [3] showed that the sensors did not induce frequency distortions. Static calibration of the sensors was performed directly on the experimental setup by changing the depth of the quiescent fluid when the pressure on the sensor was determined by a hydrostatic law. The static calibration characteristic of the sensor was linear and stable. The root-mean-square random error of the pressure measurement estimated by the results of four to five experiments under the same conditions did not exceed 3%.

At the time $t = 0$, the gate was quickly (in 0.04 sec) lifted upward. As a result, a smooth level-depression wave propagated to the headwater region, and a bore type wave propagated to the tailwater region. The profiles and kinematic characteristics (height, propagation speed, and fluid velocity) of such waves have been studied theoretically (using the first shallow-water approximation) and experimentally [4]. The total force acting on a vertical wall from which a bore is reflected has been investigated in experiments [2, 3]. The present paper considers the local pressure $p(z)$ rather than the total force. In the experiments described here, the parameters $h_- = 20.2$ cm, $L = 360$ cm, $x_1 = 180$ cm, $x_2 = 85$ cm, $x_3 = 210$ cm, and $b = 6.8$ cm were constant, and only the depth h_+ was varied.

Lavrent'ev Institute of Hydrodynamics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090; bukreev@hydro.nsc.ru. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 51, No. 1, pp. 89–93, January–February, 2010. Original article submitted March 2, 2009.

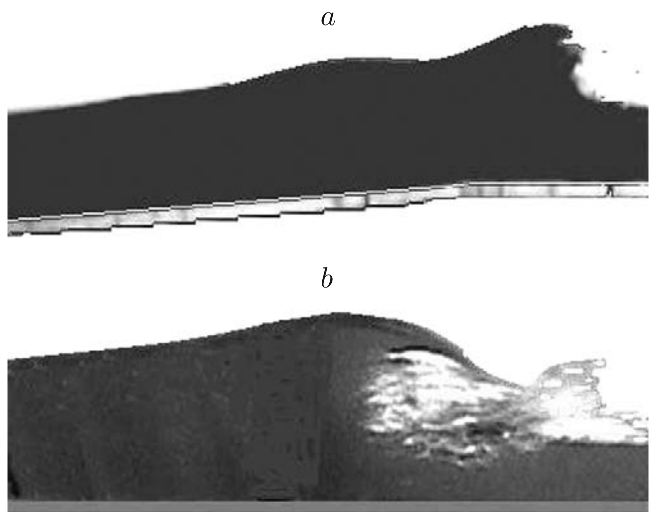

Fig. 1. Formation of cumulative jets during breaking of the bore leading edge on an inclined bottom (a) and horizontal bottom (b).

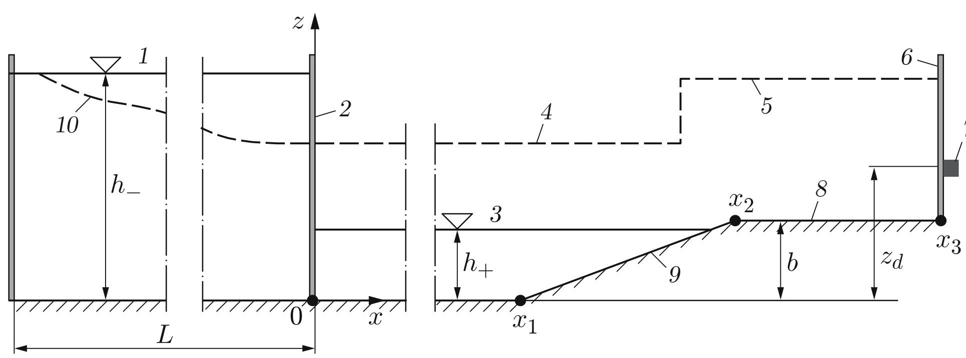

Fig. 2. Diagram of experiment: 1) initial headwater level; 2) gate; 3) initial tailwater level; 4) fluid level behind the direct discontinuous wave; 5) fluid level behind the reflected wave; 6) wall; 7) pressure sensor; 8) beach; 9) shelf; 10) level-depression wave.

According to the first shallow-water approximation, all types of real bore are replaced by a discontinuous wave. At the front of a discontinuous wave, the depth, fluid velocity, and pressure vary in steps. At the moment of reflection of such a model wave, the pressure at the location of the sensor instantaneously takes the value $p_d = \rho g(h_0 + b - z_d)$, where ρ is the fluid density, g is the acceleration due to gravity, and h_0 is the depth above the beach behind the front of the reflected wave; the quantities b and z_d are shown in Fig. 2. The algorithm for calculating h_0 is given in [4]. At $h_+/h_- > 0.1$, the value of h_0 differs only slightly from the value of $h_- - b$ [3].

Figure 3 shows an experimental time dependence of the pressure acting on the sensor. It is evident that the pressure first increases sharply and then takes a constant value. The dimensionless time $t^0 = (g/h_-)^{0.5}t$ is reckoned from the time the gate begins to be lifted. The measured pressure p_d is normalized by the value of the hydrostatic pressure which acts on the sensor placed at the depth $h_- - z_d$ (in Fig. 3, $p^0 = p_d/[\rho g(h_- - z_d)]$) below the free surface level. Figure 3 also shows typical values of the shock pressure $p^0_{\max}$ and the asymptotic pressure p^0_{as}, which are considered below.

Figure 4 shows photographs of the initial stage of reflection of a real wave. In the initial stage of reflection, there is a short-term splash of the fluid on the wall; the splash height depends on the shape of the leading edge of the bore [5]. During reflection of a smooth bore (Fig. 4a), the splash height is greater than that during reflection of

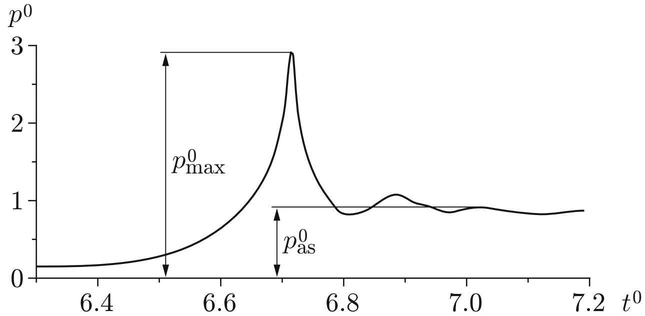

Fig. 3. Time dependence of the local pressure for $h_+ = 11.1$ cm and $z_d = 10$ cm.

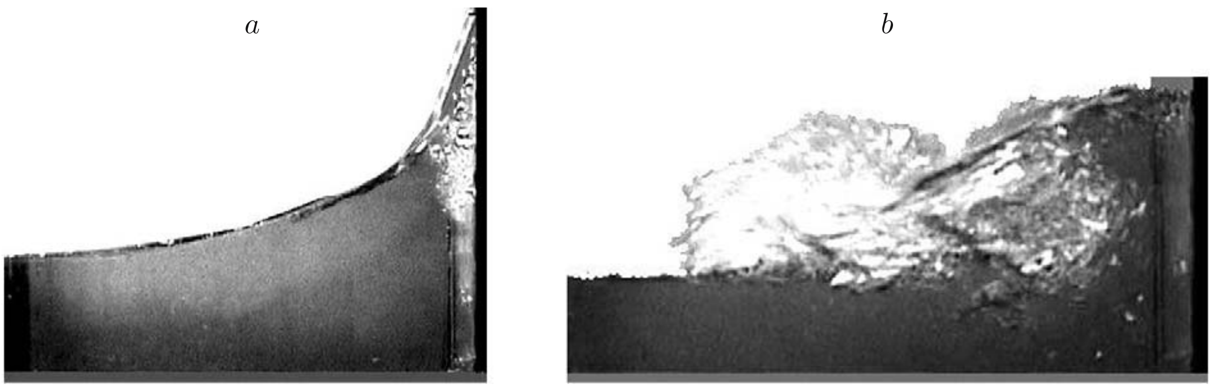

Fig. 4. Initial stages of reflection of a smooth bore (a) and a bore with a cumulative jet at the leading edge (b).

a bore with a roller. For these shapes of the leading edge, the shock pressure is due to the splash of the fluid. During reflection of a wave with a broken leading edge (Fig. 4b), the shock pressure is due to the action of a cumulative jet.

Figure 5 gives experimental data on the asymptotic pressure for various values of the coordinate z_d. The dimensionless initial difference between the headwater and tailwater depths $h^0_+ = 1 - h_+/h_- \geqslant 0$ is plotted on the abscissa. The characteristic linear size is the difference $h_- - h_+$ which describes the energy input to the waves normalized to the unit volume of the moving fluid. In Fig. 5 it is evident that, in the examined range of h^0_+, the dimensionless asymptotic pressure $p^0_{\rm as}$ differs from the value $p^0_{\rm as} = 1$ by no more than 5%. Hence, in the indicated range, the asymptotic pressure can be determined by a hydrostatic law and by the depth of the examined point below the initial free-surface level in the headwater region with an error not worse than 5%.

The shock pressure can considerably exceed the asymptotic value. Figure 6 gives the corresponding experimental data for various values of the coordinate z_d. The maxima of the curves in Fig. 6 correspond to the value of h^0_+ at which a wave with a cumulative jet at the leading edge was incident on the wall. For smaller values of h^0_+, the incident wave broke before approaching the wall, and for larger values of h^0_+, the incident wave was smooth. The greatest maximum (curve 2 in Fig. 6) is reached when the sensor is in the zone of action of the cumulative jet. In this case, the shock pressure is almost 18 times higher than the asymptotic pressure.

Figure 7 gives experimental data on the shock pressure distribution along the vertical coordinate for various values of the parameter h^0_+. The quantity z^0 in Fig. 7 is determined from the formula $z^0 = (z_d - b)/(h_- - b)$. At $h^0_+ = 0.65$ (curve 1) a wave with a broken leading edge was incident on the wall, at $h^0_+ = 0.41$ (curve 2) the incident wave was smooth, and at $h^0_+ = 0.48$ (curve 3) the incident wave had a cumulative jet. The maximum of curve 3 corresponds to the impact of a cumulative jet on the pressure sensor at $z^0 = 0.54$.

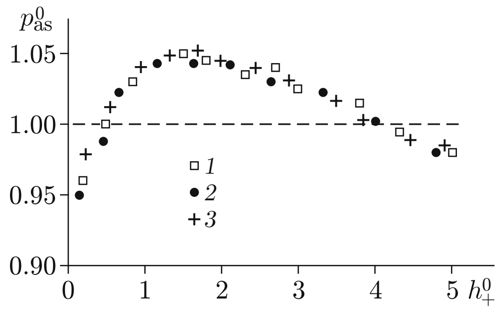

Fig. 5

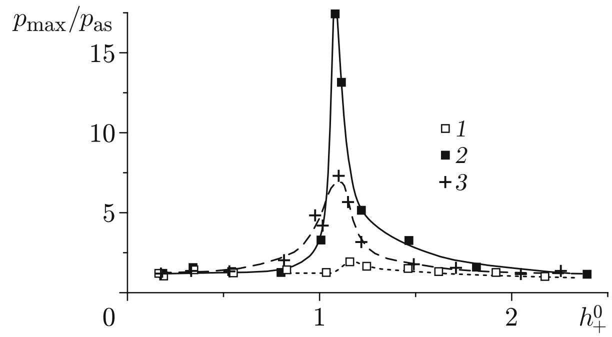

Fig. 6

Fig. 5. Asymptotic pressure versus initial tailwater depth for $z_d = 13$ (1), 14 (2), and 17 cm (3); the dashed curve refers to $p^0_{\rm as} = 1$.

Fig. 6. Ratio of the shock pressure to the asymptotic pressure versus initial tailwater depth for $z_d = 13$ (1), 14 (2), and 17 cm (3).

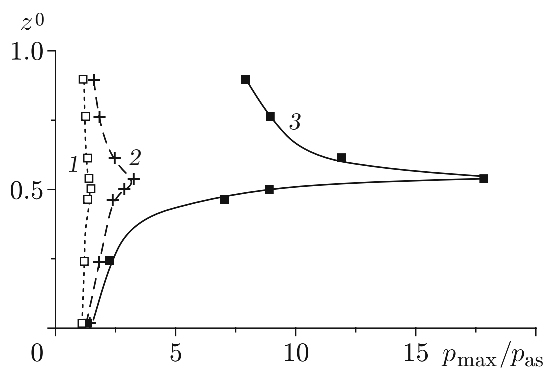

Fig. 7. Shock pressure versus vertical coordinate for $h^0_+ = 0.65$ (1), 0.41 (2), and 0.48 (3).

Using the formula $u_c = (2p_{\rm max}/\rho)^{0.5}$, the fluid velocity in this jet can be estimated from the maximum shock pressure of the cumulative jet. In the experiments performed, the greatest value was $u_c = 4.45$ m/sec. According to the results of [4], the fluid velocity in the incident wave is equal to $u_* = 0.66$ m/sec for the same values of the given parameters as in the experiments. The dynamic pressure at the flow stagnation point is given by the formula $p_* = \rho u_*^2/2$. In the experiments, the ratio $p_{\rm max}/p_* = (u_c/u_*)^2$ reached the value $p_{\rm max}/p_* = 45.5$.

In the case of breaking of a high dam or a tsunami propagating in shallow water, the velocity u_* can reach 20 m/sec or more. The cumulative jets formed during breaking of such waves has a great destructive force. However, a tsunami wave breaks before approaching the coastal line, whereas a dam-breaking wave breaks at a distance no more than 100 m downstream. In this case, there is little probability that any engineering facility will be affected by cumulative jets. As a rule, in such cases, obstacles are subjected to waves with already broken leading edge, and the dynamic pressure differs little from the asymptotic pressure (see [3] and Fig. 6). Cumulative jets formed during breaking of high wind waves are much more dangerous. In educational films, one can see pictures of cumulative jets formed on a shelf even at a weak wind, and examples where hurricane generated waves break through the gate of a ship.

This work was supported by the Russian Foundation for Basic Research (Grant No. 07-01-00015) and Integration Project of the Russian Academy of Sciences No. 14.2.

REFERENCES

1. Chow Ven Te, *Open-Channel Hydraulics*, McGraw HillBook, New York (1959).
2. V. I. Bukreev, "Dependence of force action of a water wave on the shape of its leading front," *Fluid Dyn.*, **43**, No. 6, 909–914 (2008).
3. V. I. Bukreev, "Force action of discontinuous waves on a vertical wall," *J. Appl. Mech. Tech. Phys.*, **50**, No. 2, 278–283 (2009).
4. V. I. Bukreev, A. V. Gusev, and V. V. Ostapenko, "Waves in an open channel formed by removal of a gate ahead of a rough bottom of the type of a shelf," *Vod. Res.*, **31**, No. 5, 540–545 (2004).
5. V. I. Bukreev, "Water impingement on a vertical wall due to discontinuity decay above a drop," *J. Appl. Mech. Tech. Phys.*, **44**, No. 1, 59–63 (2003).