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Citation	Bulletin of the Disaster Prevention Research Institute (1969), 19(2): 1-17
Issue Date	1969-11
URL	http://hdl.handle.net/2433/124774
Right	
Type	Departmental Bulletin Paper
Textversion	publisher

Generation and Development of a Hydraulic Bore Due to the Breaking of a Dam (1)

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(Manuscript received August 30, 1969)

Abstract

Experiments on the behaviour of the unsteady flow caused by the breaking of a dam were conducted to examine the applicability of the analytical methods to this problem and to find the transitional process of a hydraulic bore in connection with the ratios of initial upstream depth to the downstream one. The breaking of a dam was simulated by the rapid pull-up of a sluice gate installed in a uniform rectangular channel.

As a result of the experiments, it was recognized that four kinds of wave patterns distinguished by the initial relative depth appeared. The characteristics of the hydraulic bore, such as wave profile, wave velocity, wave height and etc. were investigated synthetically. Finally, stability of the undular bore was discussed.

1. Introduction

Hydraulic bores occur due to various sources in the natural world, for example: a) the breaking of a dam, embankment or gate, b) the sudden opening and closure of a valve or gate in an electric system, c) the occurrence of a tsunami, d) a tidal wave penetrating into a river. As each of them shows peculiar features corresponding to its boundary conditions, it is very difficult to deal with all of them systematically.

Regarding the disasters caused by hydraulic bores, the destruction of the Malpasset Dam brought about serious damage to life and property in the lower reaches of the River Reyran in 1959. An extensive landslide which occurred around the Vaiont reservoir in October, 1963, caused the reserved water of 23 million cubic meters to flow over the dam and took a toll of about three thousand lives. In Japan, a crest tainter gate of the Wachi Dam in the Yura River was destroyed in 1967, and this accident led to a reexamination of the safety of all of the gates in Japan and to public sensation with regard to dam construction.

As mentioned above, the occurrence of a hydraulic bore due to a dam breaking always brings about serious damage, so that the construction of a high dam or large reservoir breeds social unrest. Therefore, the unsteady flow caused by the failure of a dam should be further examined to establish a measure of disaster prevention.

In 1892, Ritter[1], who was the first to think of the problem, derived a solution to give a parabolic water profile of the flood caused by the sudden destruction of a dam, using the approximate Saint-Venant equation but ignoring the effects of the channel friction. Ré[2] obtained the solutions of the problem by the graphical method, including the formation of a bore caused in the case of the presence of the initial water depth below the dam. In 1952 and 1954, Dressler[3],[4] offered the solution for the wave front in consideration of the resistance effect and verified it with observed data. Pohle[5] developed the wave theory of the flow caused by the sudden lifting of a gate in 1950, assuming the potential flow by means of Lagrangian coordinates. His work concerned the motions in their early stages after the gate is removed. Stoker[6] showed a comprehensive treatment of the dam-break problem by applying the momentum principle to the formation of the hydraulic bore and the method of characteristics to the shallow water theory. Although, as stated above, various approaches to the dam-break problem have been tried, the nonlinearity of the problem still precludes the development of a consistent method of analysis and the variation of the flow profile corresponding to each boundary condition remains unexplained.

Accordingly, the authors show by the observed data the characteristics of flood caused by the breaking of a dam in connection with the ratio of the initial water depth below the dam to the upstream one and discuss the applicability of Stoker's theory to the hydraulic bore.

2. Experimental Equipment and Procedure

(1) *Experimental equipment*

The experiments were conducted at the Ujigawa Hydraulics Laboratory, Disaster Prevention Research Institute, Kyoto University. The apparatus employed consisted of a rectangular channel 0.5m wide, 0.5m high and 30m long with a horizontal bed. One side wall of the channel consisted of transparent glass so as to be able to observe the phenomena, and the other side wall and the channel bed were made of concrete blocks plastered with watertight mortar. A steel plate was placed at five meters' distance from the upstream end of the channel so that it performed the role of a dam. It was connected with a 30kg weight by wire-rope through a system of pulleys. When the weight falls down, the steel gate swings upwards and goes away from the water surface at a speed of about six meters a second. The vertical pulling up of the plate was presumed to be equivalent to the break of a dam. The installation is shown schematically in Fig. 1.

(2) *Measurement*

The variations of the water surface shown within a range of about six meters around a fixed position were recorded using 16mm and 8mm cinecameras or an automatically rolled-up camera, and analysed by means of the film motion analyzer or projector. Pressure pickups of resistance type were installed in the floor along its center line at half a meter's distance upstream of the gate, and at 0.175m and 16m distances downstream of it, to record the variation of the water level in each section automatically. The velocity measurement was performed at the gate section and at 17 meters' distance downstream of the gate, by photographing the motion of potassium permanganate thrown into the water.

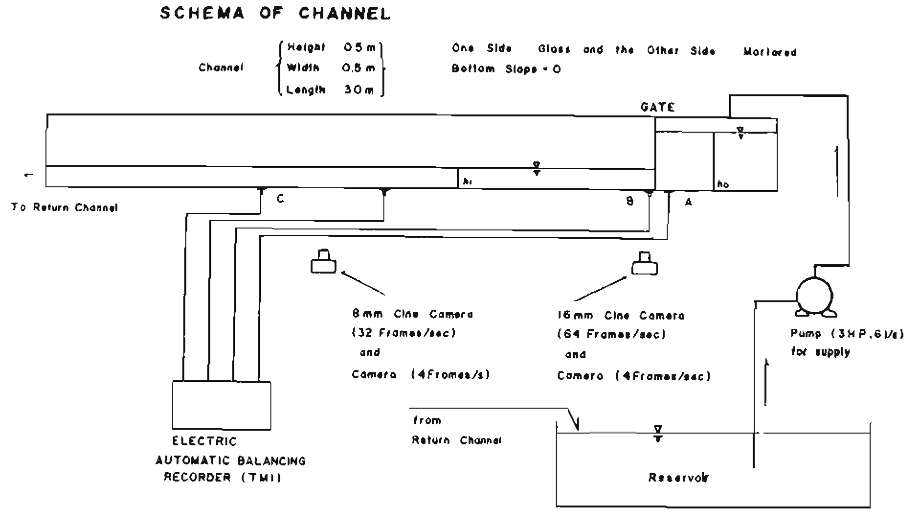


Fig. 1 Experimental apparatus.

The items of experiments and the locations for taking photographs are shown in Table 1.

The time $t=0$ has been defined herein as the moment the gate begins to move upwards. Since it takes 1/10 to 1/20 sec to pull the gate up to the water surface, the maximum error to decide $t=0$ will be about 1/16 sec in the case of the cinecamera with crankspeeds of 8 to 64 frames per second. For the automatically rolled-up camera a maximum error of three or four percent due to the irregularity of the rolling speed was confirmed by the preliminary tests. These errors were cancelled by repeating the experiments under the same conditions.

Regarding the velocity measurement, the diffusion of the tracers caused by the flow turbulence limited the measuring time and made it very short after the gate was removed, especially near the gate section.

3. Experimental Classification of Bores Caused by Dam Breaking

The hydraulic elements given at a moving hydraulic jump and an undular bore are defined in Fig. 2. It was noticed by the photographic observation that three types of the waves corresponding to the ratio of the initial water depth below the dam to the one upstream of the dam appeared due to the breaking of a dam, that is, (a) a parabolic given by Ritter's solution, (b) a moving hydraulic jump, (c) undular bore.

In case (a) $h_1/h_0=0$, a parabolic flow profile with upward concave curve given by the theory agrees with the observed profile except for the front part and the upstream end, as shown in Photo. 1 (a). The wave front has a rounded shape owing to the channel friction as shown in Dressler's analysis. Near the upstream end, the actual profile indicates the upward convex curve contrary to the theoretical one. In case (b) $h_1/h_0=0.1$, the wave of a moving hydraulic jump type, in which a steep front is formed by a surface roller and the water depth above the front is invariable in time, occurs as shown in Photo. 1 (b). The properties of the moving hydraulic jump gradually diminish with an increase of the ratio

Table 1 Experimental items.

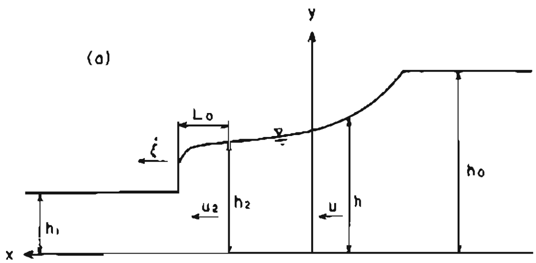
Data No.	Experinental condition			16mm cine-camera		8 mm cine-camera		Camera (1)		Camera (2)		Remarks
	L (m)	h_1 (cm)	h_0 (cm)	x (m)	f/sec	x (m)	f/sec	x (m)	f/sec	x (m)	f/sec	
1	5	0	40	0	32							1) Flow profile 2) Wave height 3) Celerity
2	5	0	40	0	32							
3	5	0	40	0	32	14	32					
4	5	10	40	0	32	14	32					
5	5	20	40	0	32	14	32					
6	5	30	40	0	32	14	32					
7	5	5	40	0	64	14	32					
8	5	10	40	0	64	14	32					
9	5	15	40	0	64	14	32					
10	5	20	40	0	64	14	32					
11	5	25	40	0	64	14	32					
12	5	30	40	0	64	14	32					
13	5	35	40	0	64	14	32					
14	5	17.5	40	0	64	14	32					
15	5	18.5	40	0	64	14	32					
16	5	0	40					0	3.16	14	3.24	1) Flow profile 2) Wave height 3) Celerity
17	5	5	40					0	3.16	14	3.24	
18	5	10	40					0	3.16	14	3.24	
19	5	20	40					0	3.16	14	3.24	
20	5	30	40					0	3.16	14	3.24	
21	5	35	40					0	3.16	14	3.24	
22	5	25	40					0	3.16	14	3.24	
23	5	15	40					0	3.16	14	3.24	
34	5	18	20	0	8			8	3.16			1) Flow profile 2) Wave height 3) Celerity
35	5	16	20	0	8							
36	5	14	20	0	8			8	3.16			
37	5	12	20	0	8			8	3.16			
38	5	10	20	0	8			8	3.16			
39	5	8	20	0	8			8	3.16			
40	5	6	20	0	8			8	3.16			
41	5	4	20	0	8			8	3.16			
42	5	27	30	0	48			8	3.16			
43	5	24	30	0	48			8	3.16			
44	5	21	30	0	64			8	3.16			
45	5	18	30	0	8			8	3.16			

Table 1 Experimental items (continued).

Data No.	Experimental condition			16mm cine-camera		8 mm cine-camera		Camera (1)		Camera (2)		Remarks
	L (m)	h_1 (cm)	h_0 (cm)	x (m)	f/sec	x (m)	f/sec	x (m)	f/sec	x (m)	f/sec	
46	5	15	30	0	8			8	3.16			1) Flow profile
47	5	15	30	0	8			4	3.24	8	3.16	2) Wave height
48	5	16	30	0	8			4	3.24	8	3.16	3) Celerity
49	5	12	30	0	8			4	3.24	8	3.16	
50	5	9	30	0	8			4	3.24	8	3.16	
51	5	6	30	0	8			4	3.24	8	3.16	
52	5	3	30	0	8			4	3.24	8	3.16	
53	5	2	20	0	8			4	3.24	8	3.16	
54	5	0	20	0	8			4	3.24	8	3.16	
55	5	0	30	0	8			4	3.24	8	3.16	
56	5	21	25	0	64			4	3.16	8	3.24	
57	5	18	25	0	64			4	3.16	8	3.24	
58	5	15	25	0	64			4	3.16	8	3.24	
59	5	12	25	0	32			4	3.16	8	3.24	
60	5	9	25	0	64			8	3.16			1) Flow profile
61	5	6	25	0	64			8	3.16			2) Wave height
62	5	3	25	0	64			8	3.16			3) Celerity
63	5	0	25	0	64			8	3.16			
64	5	12	15	0	64			8	3.16			
65	5	10	15	0	64			8	3.16			
66	5	8	15	0	64			8	3.16			
67	5	6	15	0	64			8	3.16			
68	5	4	15	0	64			8	3.16			
69	5	2	15	0	64			8	3.16			
70	5	0	15	0	64			8	3.16			
71	5	30	35	0	64			8	3.16	18	3.24	1) Flow profile
72	5	25	35	0	64			8	3.16	18	3.24	2) Wave height
73	5	20	35	0	64			8	3.16	18	3.24	3) Celerity
74	5	15	35	0	64			8	3.16	18	3.24	
75	5	10	35	0	64			8	3.16	18	3.24	
76	5	5	35	0	64			8	3.16	18	3.24	
77	5	0	35	0	64			8	3.16	18	3.24	

Table 1 Experimental items (continued).

Data No.	Experimental condition			16mm cine-camera		8 mm cine-camera		Camera (1)		Camera (2)		Remarks
	L (m)	h_1 (cm)	h_0 (cm)	x (m)	f/sec	x (m)	f/sec	x (m)	f/sec	x (m)	f/sec	
101	5	0	40	0	64							1) Current Velocity
102	5	0	40	0	64							
103	5	10	40	0	64							2) Flow profile
104	5	20	40	0	64							
105	5	30	40	0	64							
106	5	30	40	18	64							
107	5	20	40	18	64							
108	5	10	40	18	64							



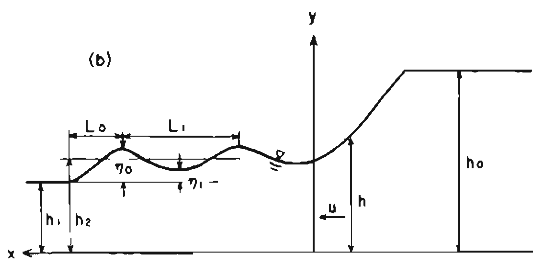


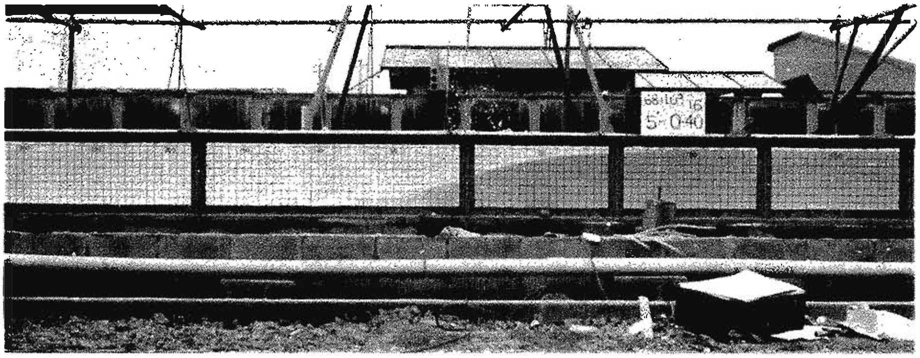
Fig. 2 Definition sketch.

h_1/h_0. When the value of h_1/h_0 becomes more than about 0.4, the front of the bore shows an undulating form. The height and steepness of the undular bore are augmented with the increase of the ratio h_1/h_0 within the range of h_1/h_0 to be less than 0.56. For h_1/h_0 to be above 0.56, the wave height decreases with an increase of the ratio h_1/h_0 and a stable undular bore is formed as seen in Photo. 1 (c).

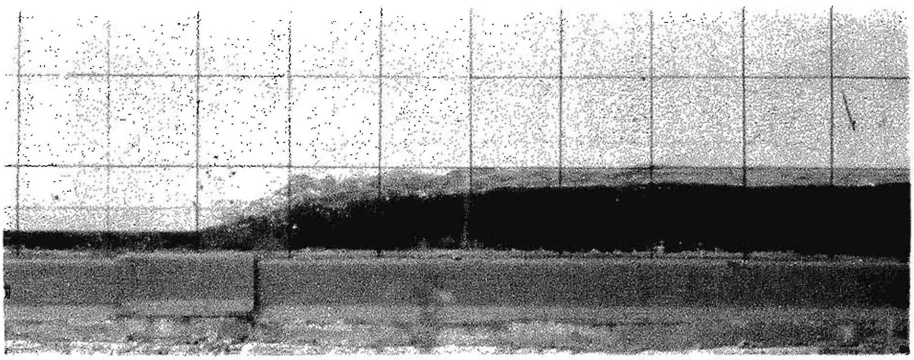
From the results obtained above, it is recognized that the flood waves caused by dam-breaking can be classified into four patterns by the relative water depth initially settled, as follows:

1) $h_1/h_0=0$: a parabolic wave with a rounded front,

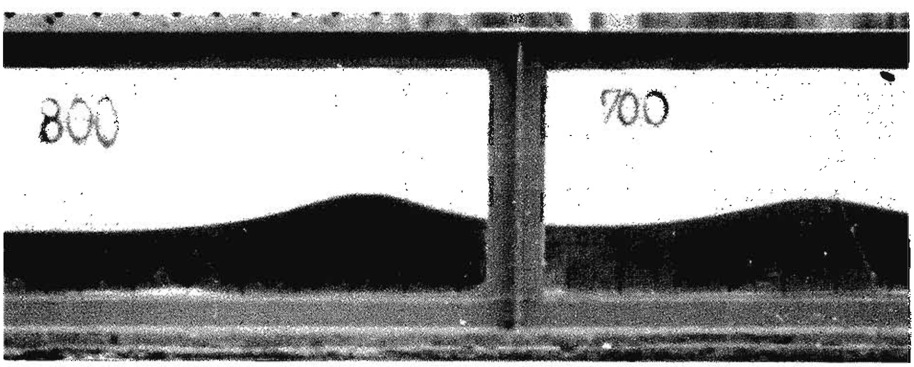
2) $0<h_1/h_0\leq 0.4$: a uniformly progressive wave with a breaking front (moving hydraulic jump),
3) $0.4<h_1/h_0\leq 0.56$: unstable undular bore with a front partly broken, and
4) $0.56\leq h_1/h_0<1.0$: stable undular bore.



(a) $h_1/h_0=0$



(b) $h_1/h_0=0.1$



(c) $h_1/h_0=0.6$

Photo. 1 Wave patterns.

4. Analysis of Experimental Results

(1) *Wave velocity*

The actual wave velocities obtained by photographic measurement are plotted against the initial relative depth, h_1/h_0, in Fig. 3. The curve shown in the figure represents the theoretical wave velocity for the rapidly varied unsteady flow derived by Stoker. It was calculated by use of the following equations:-

$$\frac{u_2}{c_1}=\frac{\dot{\xi}}{c_1}-\frac{c_1}{4\dot{\xi}}\left\{1+\sqrt{1+8\left(\frac{\dot{\xi}}{c_1}\right)^2}\right\} \qquad (1)$$

$$\frac{c_2}{c_1}=\left\{\frac{1}{2}\left(\sqrt{1+8\left(\frac{\dot{\xi}}{c_1}\right)^2}-1\right)\right\}^{1/2} \qquad (2)$$

$$\frac{u_2}{c_1}+2\frac{c_2}{c_1}=2\frac{c_0}{c_1} \qquad (3)$$

where the wave propagation speed, c_i, is equivalent to $\sqrt{gh_i}$, and subscripts 0, 1 and 2 indicate the quantities in the zone of the undisturbed reservoir, the constant state at the upstream part of the front and the quiet water downstream of the front, respectively.

In a case where $h_1/h_0=0$, the actual travelling speed of the front becomes considerably smaller than the theoretical value, 2.0, owing to the channel friction. By the fact that values of dimensionless expressions of the velocity vary in proportion to the initial reservoir depth, it is verified that the water of the front moves along the dry channel, according to the resistance law of the

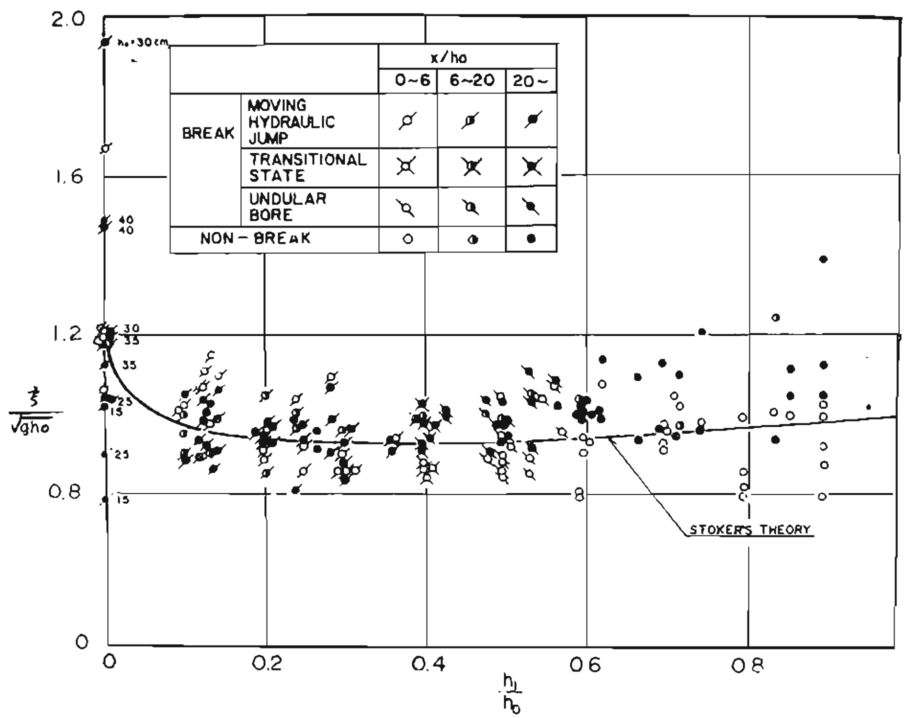


Fig. 3 The wave velocity.

turbulent flow. In the range within which the moving hydraulic jump appears, $0<h_1/h_0<0.4$, it is recognized that at the early stage after a dam breaks the wave travels at a higher speed than that given by the theory, owing to the effect of acceleration, while in the downstream reach the observed velocity agrees with the theoretical curve. When the range of h_1/h_0 is over 0.4, the wave velocity in the downstream reach takes larger values than that in the vicinity of a dam, and the differences between them become larger as the value of h_1/h_0 increases. It seems to be due to the occurrence of the positive surge advancing upstream that the latter takes lower values than those given by Stoker's theory, while the former indicates higher values owing to the development of the undular bore.

(2) *Height of bore*

The variation of the height of a bore corresponding to the relative water depth, h_1/h_0, is indicated in Fig. 4, in which the wave height, h, represents h_2 for a moving hydraulic jump and (η_0+h_1) for an undular bore as defined in Fig. 2.

For the values of h_1/h_0 below 0.4, the undular bore with a very steep front occurs just after the dam breaks, followed by the plunging breaker in the region of $(4\text{-}6)h_0$ downstream from the dam as shown in Photo. 2. Thereafter the wave takes the form of a quasi-steady hydraulic jump and has a height slightly lower than that given by Stoker's theory. This discrepancy is perhaps due to ignoring the effect of the vertical acceleration on applying the nonlinear shallow water theory. Assuming that the velocity in x-direction is represented by the mean velocity, and the velocity component in the vertical direction varies

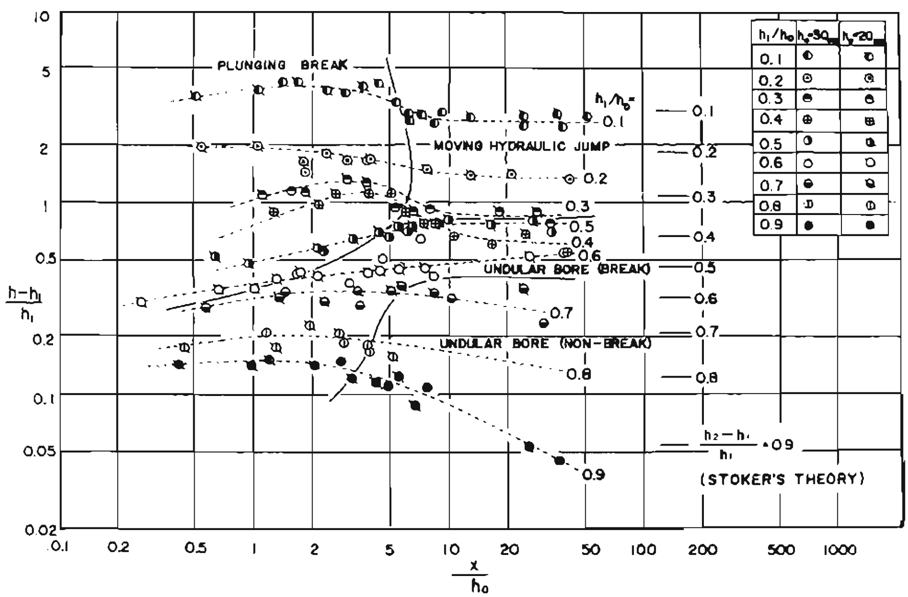


Fig. 4 Development of the bore height.

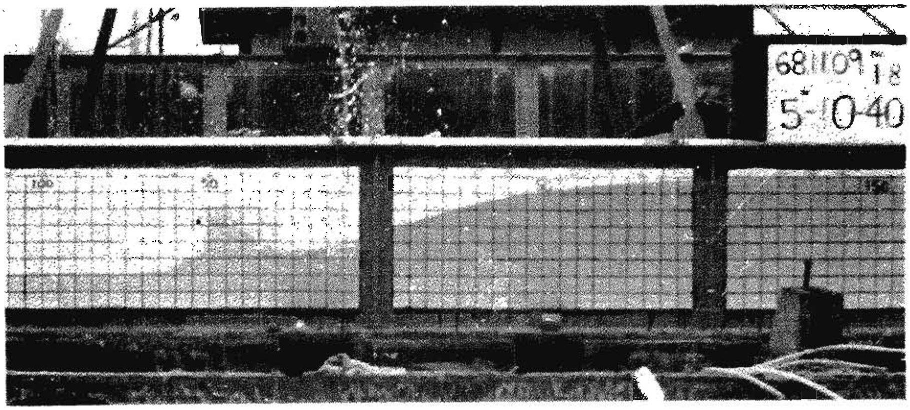


Photo. 2. Plunging break ($h_1/h_0=0.25$, x=0.5m).

linearly from zero at the channel bottom to a definite value at the water surface, the equation of motion for the irrotational flow can be given in dimensionless form by neglecting the infinitesimal terms as follows:

$$\frac{\partial \bar{u}}{\partial \bar{t}}+\bar{u}\frac{\partial \bar{u}}{\partial \bar{x}}+\frac{\partial \bar{\eta}}{\partial \bar{x}}+\frac{1}{3}\frac{\partial^3 \bar{\eta}}{\partial \bar{x}\partial \bar{t}^2}=0 \qquad (4)$$

The last term of the above equation is additional to the first equation of motion given by the nonlinear shallow water theory. Since the water surface gradient takes a negative infinite value at $\bar{t}=0$ and increases gradually with travelling time so that $\partial^3\bar{\eta}/\partial\bar{x}\partial\bar{t}^2$ always takes a negative value, the effect of the water surface gradient makes the water depth smaller. From what is mentioned above, it is concluded that the discrepancy between the calculated bore height and the observed one shown in Fig. 4 is due to the last term on the left hand side of Eq. (4) and increases as the given value of h_1/h_0 becomes smaller.

For the condition that h_1/h_0 ranges from 0.4 to 0.6, the plunging break appears just behind the dam and thereafter develops into the undular bore which the wave crest of the front partly breaks, as seen in Photo 3. The transitional process from a moving hydraulic jump to an undular bore is indicated by the fact that the height of a bore, (η_0+h_1), for $h_1/h_0=0.5$ is larger than

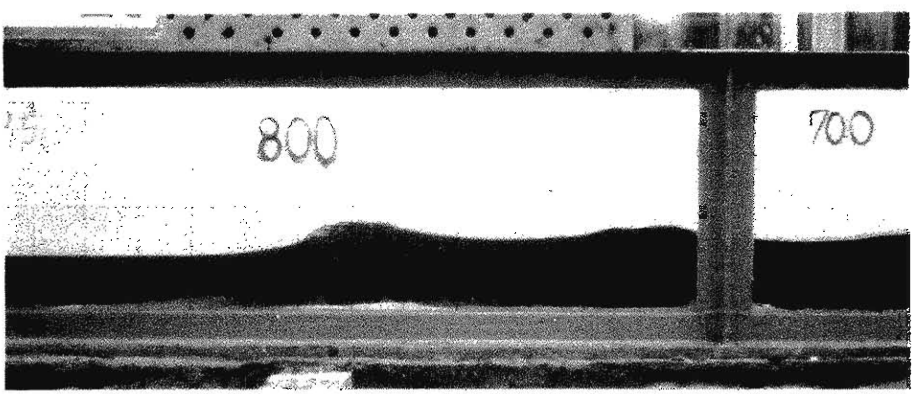


Photo. 3. Undularbore bore with spilling break ($h_1/h_0=0.5$, x=8m).

that for $h_1/h_0=0.4$. In this range the undular bore is unstable and built up towards the flow direction.

When the range of h_1/h_0 is above 0.6, the breaking state which appears just downstream of the dam changes into a stable undular bore at a point about $4h_0$ downstream from the dam. This stable bore has a tendency to decrease its height with travelling due to the frictional resistance of the channel walls.

The maximum heights of the bore in dimensionless expression, $\eta_0/(h_2-h_1)$, which were obtained at a point about eight meters downstream of the dam, are plotted against the relative height, $(h_2-h_1)/h_1$, in Fig. 5. In the figure the critical value for the breaking of a solitary wave obtained by Munk[7], $\eta_0/h_1=0.781$, and that for the formation of the undular bore derived by Keulegan and Patterson[8] are shown together. The experimental curve representing the limit of stability for the undular bore, obtained by Favre, is also indicated in the figure.

If the range h_1/h_0 is smaller than 0.4, uniformly progressive waves with a perfectly broken front appear and the lower limit of $(h_2-h_1)/h_1$ in this range is located just on Munk's critical curve. In the range of $0.4<h_1/h_0<0.6$ in which the crest of a bore front partly breaks, $\eta_0/(h_2-h_1)$ takes the values from 1.0 to 1.5 and its variation shows a good agreement with Munk's curve. Thus, the unstable transitional process from the moving hydraulic jump to the undular bore appears in this range.

If the range $\eta_0/(h_2-h_1)$ is over 1.5, an obvious undular bore appears in the entire reach of the channel. In the region $(h_2-h_1)/h_1<0.38$, $\eta_0/(h_2-h_1)$ takes values between 1.5 and 1.8, and its variation shows a different feature from Favre's experimental curve. The limit of stability for the undular bore obtained by the authors is represented by $(h_2-h_1)/h_1=0.38$, while the one given by Favre's experiment takes the value of 0.275. This discrepancy seems to be

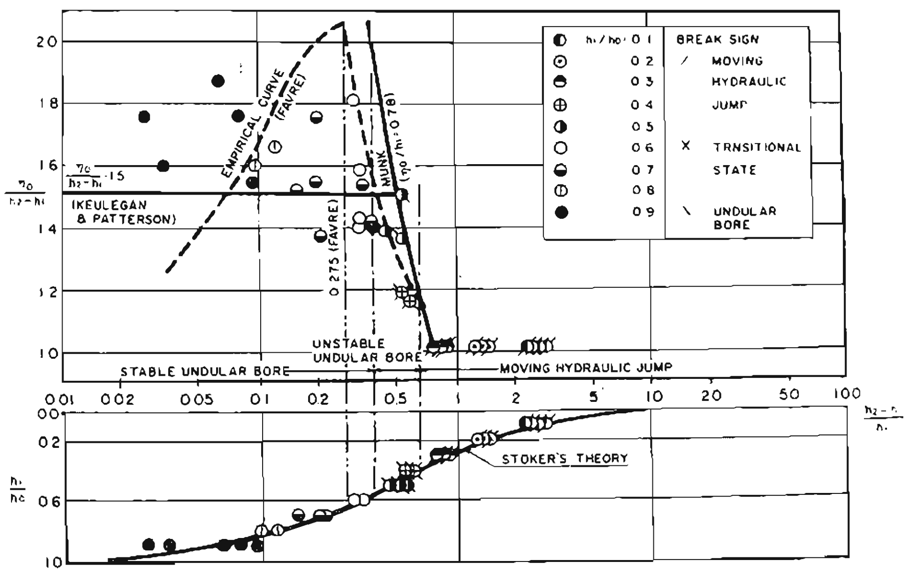


Fig. 5 Maximum height of the bore.

caused by the differences in the mechanism of generation of the bore and in the stability of the bore shown at the measuring point.

(3) *Stability of undular bore*

To study on stability of the undular bore, the time change of the water level recorded at the stations A, B and C are analysed. An example of the records is shown in Fig. 6. At station A, the retrogressive bore is recorded, while at stations B and C the progressive bore is recorded at the early stage, and then followed by the reflected retrogressive bore. It is also noticed from Fig. 6 that the undular bore is transient at station B, but is built up at station C. From the above mentioned, it can be seen that the bore generated by the dam-breaking

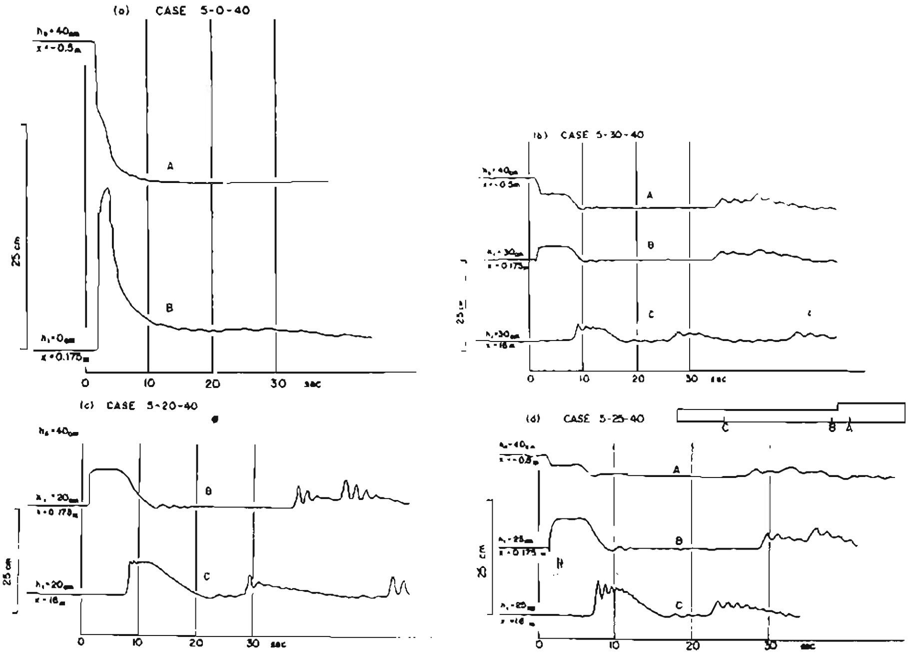


Fig. 6 The time changes of the water level.
(a) $h_1/h_0=0$, (b) $h_1/h_0=0.25$, (c) $h_1/h_0=0.50$, (d) $h_1/h_0=0.75$

tends to become stable as the bore progresses.

The records obtained using pressure pickups should be corrected in consideration of the response characteristics of pressure gauges, when the water level changes periodically and rapidly. However, in this study the correction factor was assumed to be unity for convenience, and the pressure measurements were used to examine the wave velocity and the water level qualitatively. To analyze the bore height quantitatively, photographic records only are applied.

The amplitude of the undular bore defined as $(\eta_0-\eta_1)$ is analyzed and the result is shown in Fig. 7. The most probable relation to be expected will be represented by a curve shown in the figure. In the region of $0.4<h_1/h_0<0.56$, the undular bore partly breaks at the first crest. The amplitude of the first wave rapidly increases and indicates the maximum value at $h_1/h_0=0.56$. And in the region of $0.56<h_1/h_0<1$, the undular bore seems to be stable so that no breaking is found. Favre gave $(h_2-h_1)/h_1=0.275$ from his experiment as the upper limit of the stable undular bore, which is reduced as $h_1/h_0=0.635$ from Stoker's theory. The limit obtained from the authors' experiment, $h_1/h_0=0.56$, which is defined as the boundary value between the existence and nonexistence of any breaking of the weve is different from Favre's limit.

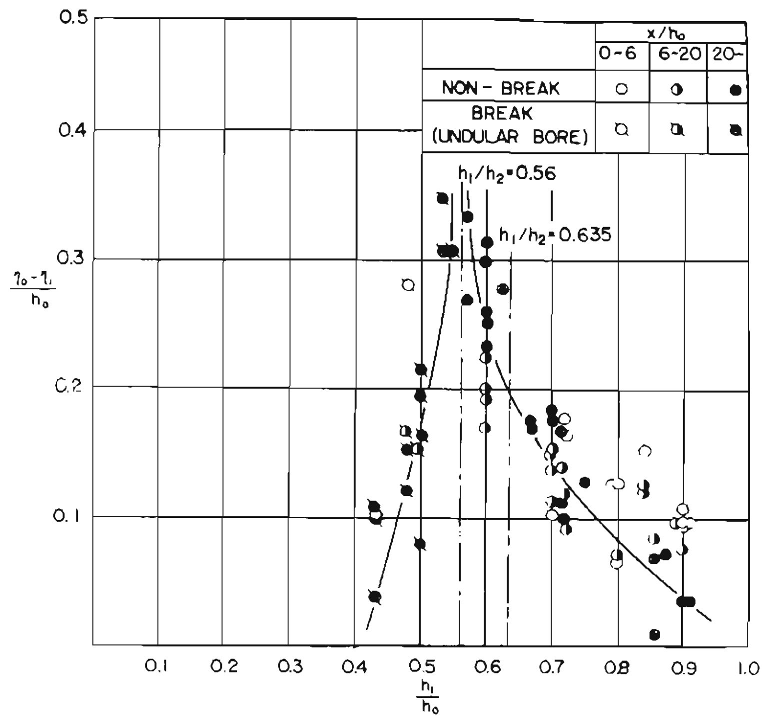


Fig. 7 The amplitude of the bore.

Murota[9] has shown that the value of σ becomes 1.5 for the stable undular bore, where $\sigma=\{(\eta_0-\eta_1)/2+h_2-h_1\}/(h_2-h_1)$. The authors' analyses show that σ takes an approximately constant value, 1.5, for $1.0>h_1/h_0>0.67$ and that the value of σ is maximum at the limit of the stable undular bore, decreasing to zero at $h_1/h_0=0.4$. For $0<h_1/h_0<0.4$ it becomes almost zero, because the bore is not undular but uniformly progressive. The variation of σ against the value of h_1/h_0 is shown in Fig. 8. The characteristics of the undular bore obtained by the authors' experiment seems to be similar to that of Murota's results when the bore is fully developed. The development of the undular bore was studied numerically with consideration of the vertical acceleration by Peregrine[10].

The relation between the wave length L_1 and the mean wave height is shown in Fig. 9. It is recognized from the figure that the wave length is shorter in the neighbourhood of the dam, that is, at a generating stage of the bore and

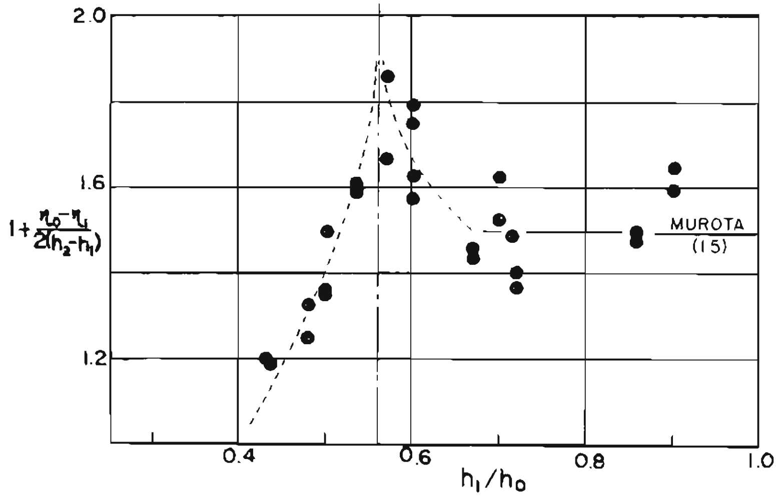


Fig. 8 Relative amplitude of the bore.

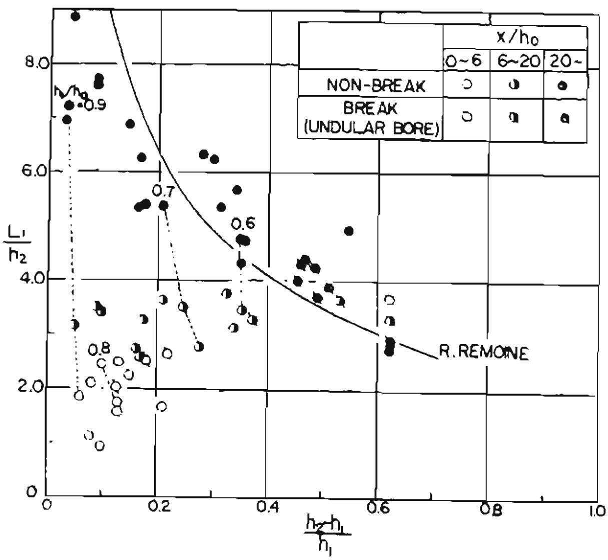


Fig. 9 The relationship between L_1 and mean wave height.

becomes larger as the bore develops, approaching the limit given by Remoine[11].

Fig. 10 shows the variation of the wave steepness of the undular bore against the mean wave height. It is obvious that the steepness $(\eta_0-\eta_1)/L_1$ varies with the relative depth and the travelling time. In the stable region, the value of steepness which is large in the vicinity of the dam decreases gradually through the development of the bore. In the unstable region, the values of the steepness are large as a whole, but they scatter because in this region the bore is not fully stable but in a developing stage. The value of steepness has a tendency to approach the real line shown in Fig. 10 with the build-up of the bore.

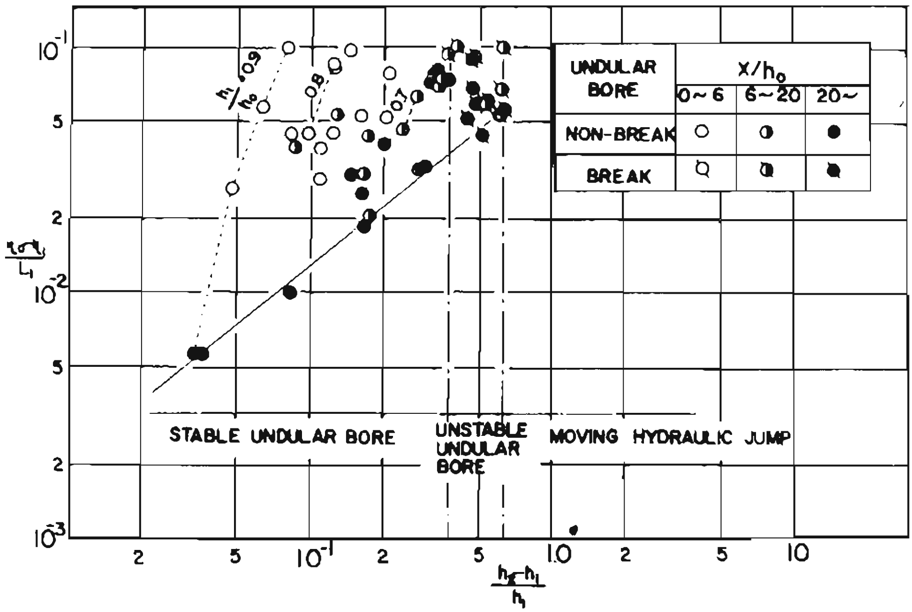


Fig. 10 The relationship between the mean wave height and $(\eta_0-\eta_1)/L_1$.

The value of η_0/L_0 is also analyzed and shown in Fig. 11. The plotted values are for $h_0=20$ cm and 30 cm, and for the range of 5 to 8 m of x. The length L_0 corresponds to the length from the toe to the first crest of the wave and η_0 is the height of the first wave measured from the still water level in the downstream section. For the stable undular bore, the relationship between η_0/L_0 and $(h_2-h_1)/h_1$ is given approximately by the following equation:-

$$\frac{\eta_0}{L_0}=\left\{\frac{(h_2-h_1)}{h_1}\right\}^n \tag{5}$$

where the value of n is unity as an approximation. For the region of the unstable undular bore, $0.38\leq(h_2-h_1)/h_1<0.63$, η_0/L_0 becomes larger than 0.15. As seen above, the steepness of the bore generated by dam-breaking takes the maximum value at the upper limit of the unstable region. For the moving hydraulic jump, the value of η_0/L_0 is 0.3 at most and decreases gradually with the increase of the value of $(h_2-h_1)/h_1$.

5. Conclusion

The present paper is to describe synthetically the characteristics of floods caused by dam-breaking by means of experiments in which various conditions for the initial upstream and downstream water depths are given.

The conclusions obtained from this study are summarized as follows:-

(1) The flood waves caused by dam-breaking distinctly show four patterns corresponding to the relative water depth initially settled.

(2) The wave velocity in the downstream reach gives good agreement with

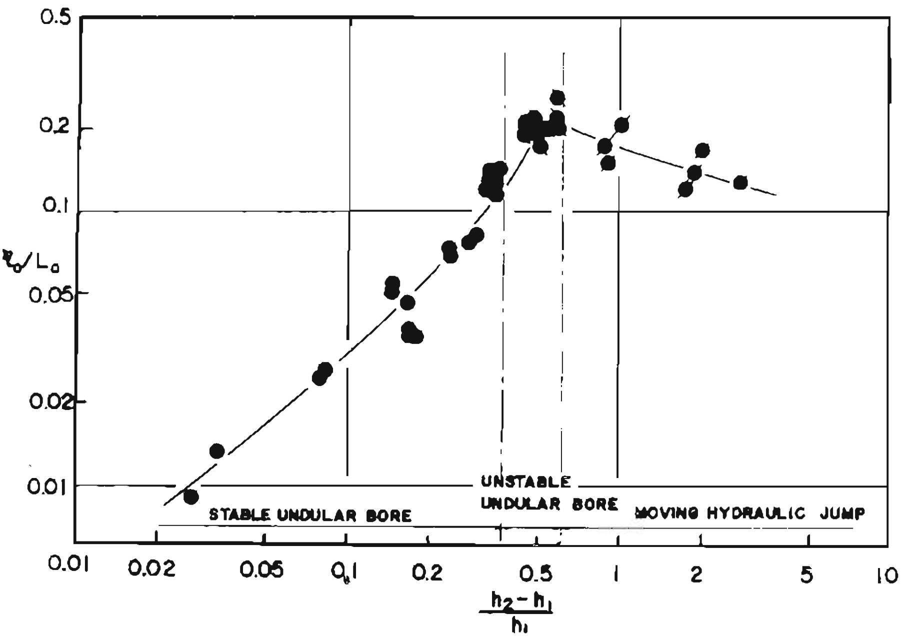


Fig. 11 The variation of η_0/L_0.

the theoretical one for $0<h_1/h_0<0.4$, while for $h_1/h_0>0.4$ it shows a higher value due to the development of the undular bore.

(3) The height of the bore for the moving hydraulic jump is smaller than that given by Stoker's theory in the downstream reach, due to the effect of vertical acceleration. The plunging break of the wave which occurs at the early stage is a peculiar phenomenon for any condition of dam-breaking.

(4) In the transitional region in which the unstable undular bore occurs, the height of the bore gradually increases with the travelling distance due to the development of the bore. For the stable undular bore its height decreases with progression owing to the frictional resistance of the channel.

(5) The stable undular bore was obtained in the region of $h_1/h_0>0.56$, while the experimental result obtained by Favre indicated this limit to become 0.635. This discrepancy between them may be caused by differences in the mechanism used to generate the bore.

(6) The steepness of the bore front increases in proportion to the value of $(h_2-h_1)/h_1$ in the stable and unstable bore regions, and shows its maximum value at the upper limit of the unstable region, while it decreases in the region of the moving hydraulic jump with the increase of $(h_2-h_1)/h_1$.

From the above investigations, the transformation of the bore which appears at the early stage after dam-breaking is considerably complicated and it performs important role in the discussion of the development of the bore.

In view of this, the authors have conducted the numerical analysis of the flood profile in consideration of the vertical accelerations. The results of this research will be reported in a subsequent paper.

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