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(出版者 / Publisher)
法政大学工学部

(雑誌名 / Journal or Publication Title)
法政大学工学部研究集報 / 法政大学工学部研究集報

(巻 / Volume)
32

(開始ページ / Start Page)
13

(終了ページ / End Page)
17

(発行年 / Year)
1996-03

(URL)
https://doi.org/10.15002/00003809

SUBMERGED JUMPS AT AN ABRUPT DROP

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ABSTRACT

This paper presents an investigation on submerged jumps at an abrupt drop. Three flow conditions on the step have been clarified. At a certain hydraulic condition, the main flow passing over the step can be controlled by changing the step length or the step height. The critical step length obtained by forming the wave from the B-jump does not coincide with the length obtained by forming the B-jump from the wave. The critical step length and the critical submergence factor have been defined.

INTRODUTION

The hydraulic jump is one of the most interesting phenomena in the field of hydraulic engineering and have been studied extensively because of their importance in energy dissipation in hydraulic structures. Experimental investigations have been carried out on both the macroscopic and internal structure of the jumps, but most of these studies have been directed to the macroscopic features. Major contributions to this subject were reviewed by Rajaratnam (1967), McCorquodale (1985) and more recently by Hager (1992). It should be mentioned that most of the papers deal with the free jump on level channel and only a few investigators have considered the hydraulic jumps at abrupt drops, as Moore (1959), Sharp (1974), Rajaratnam (1977), Hager (1986), Ohtsu (1991), but this is a phenomenon often taken place in Mekong Delta where the aprons behind sluice gates, because of some reasons, don't have enough length for submerged jump and eventually the scour holes are formed behind the aprons, the flow passing over the aprons moves the same trend as in the case of the flow passing over the steps.

In Fig.1-a, a hydraulic jump is formed just downstream of a gate which produces a supercritical

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stream with an almost uniform velocity of V_c and depth of h_c. If hydraulic jump is free jump, the tailwater depth h_{tw} is equal to the subcritical sequent depth h_2, given by Belanger equation

$$h_2 = h_c \quad [(1 + 8 F_r^2)^{1/2} - 1] / 2 \qquad (1)$$

where $F_r = V_c / (g h_c)^{1/2}$ is the supercritical Froude number, g is the acceleration due to gravity.

If h_{tw} is greater than h_2, a submerged jump is formed at the gate as shown in Fig.1-a. A submerged jump is characterized by the supercritical Froude number F_r and the submergence factor S, defined as $S = (h_{tw} - h_2) / h_2$ (Rajaratnam, 1965). Obviously, S is equal to zero for the jump at the gate, which we will refer to as the free jump and as S increases above zero, we get submerged jumps of different degrees of submergence. When S becomes large, the submerged jump looks like a plane turbulent jet. If S is very large, it would behave approximately like the classical plane turbulent wall jet (which is a plane turbulent wall jet with an unbounded stagnant ambient and zero longitudinal pressure gradient).

If h_{tw} is less than h_2, the jump would form somewhere downstream and is referred to as a repelled jump.

If a hydraulic jump is formed with a large portion of its length located in the upstream channel, and such a jump is referred to as the A-jump, it should be very similar to the hydraulic jump in a lavel rectangular channel (referred to herein as the classical jump, for convenience) (Rajaratnam and Ortiz,1977).

If the tailwater is progressively lowered, at a certain stage the flow on the step becomes supercritical, also the flow direction passing over the step moves upward and flow changes into a stationary standing wave downstream of the drop, the A-jump is replaced by a maximum wave at the drop. This is characterized by the formation of a large standing eddy just below the drop, and by the flow being a normal open-channel flow at a short distance downstream of the eddy. A further reduction in the tailwater level transforms the maximum wave into a wave train, the main flow after leaving the step flows along the surface and violent undulations propagate far downstream. With further lowering of the tailwater elevation the flow passing over the step always plunges into the water, even if the tailwater elevation is higher than the water surface elevation on the step. This jump with a substantial surface eddy is called maximum B-jump. Lowering the tailwater elevation from the maximum B-jump, minimum B-jump is formed (Ohtsu and Yasuda, 1991).

In this study, the hydraulic jump is formed just downstream of a gate with the step length pretty short to be able dissipate sufficiently energy of motion, so that the maximum velocity continues to decay far downstream of the drop. The flow condition at an abrupt drop changes with Froude number $\mathbf{F_r}$, submergence factor **S**, relative length of step $\mathbf{L / h_c}$ and relative height of step $\mathbf{d / h_c}$.

Note that, regarding hydraulic jump formed a part on step a part behind drop, very little work appears to have been done. Study this hydraulic jump will help to solve the problem of energy dissipation behind the sluice gates in the tidally-affected delta where scour holes behind aprons often exist.

EXPERIMENTS

The experiments were performed in a horizontal plexiglass flume, 20 cm wide, 50 cm high and 400 cm long of Hosei University Hydraulic Laboratory. Water entered this flume from a constant head tank, and flow rate was measured volumetrically using a triangular weir located at the end of the head tank. A plexiglass step of height 10.54 cm and length of 40 cm was installed in the middle portion of the flume and 5 series of experiments were performed with a step height of 1.60 cm, 5 series with a step height of 2.53 cm, 5 series with a step height of 4.11 cm, 5 series with a step height of 6.01 cm and 5 series with a step height of 10.54 cm. These heights were obtained by changing plexiglass pieces of the necessary thickness to the downstream channel.
The water surface along the flume was measured with a point gage with an accuracy of 0.5 mm. The time mean velocity distribution in the supercritical stream on the step was measured with a commercial Prandtl-type Pitot-static tube of 2-mm external diameter. The flow direction passing over the step was observed by moving of particles which were silver-coated glass spheres of 0.01 mm diameter with a density of 1100 kg/m3, giving a vertical sedimentation speed under gravity of approximately 0.1 mm/s. The particles were approximately uniformly dispersed before the gate, they were illuminated with an continuous argon-ion laser in a sheet along the vertical centre-plane of the channel. The sheet was approximately 1mm thick. The particle images were recorded with a video camera system.

A plexiglass gate could move up-down to change the gate opening **a** and could slide on the rails at both sides of the flume to change the step length **L** behind the gate. The vena contracta appeared just behind the gate a distance of **a** and contraction coefficient was calculated by Ansun formula. Downstream water level was controlled by a vertical plate that rises from the bed of the flume. By regulating the downstream level, different submergence conditions could be achieved for any given supercritical Froude number.

On the whole, 125 experiments were made on the flow condition with **d / h**$_c$ varying from 2.17−14.31, **F**$_r$ was varied from 2.17−6.20, **L / h**$_c$ was varied from about 0−41 and **S** was varied from about 0−4.7. The significant details of these experiments are given in Table 1.

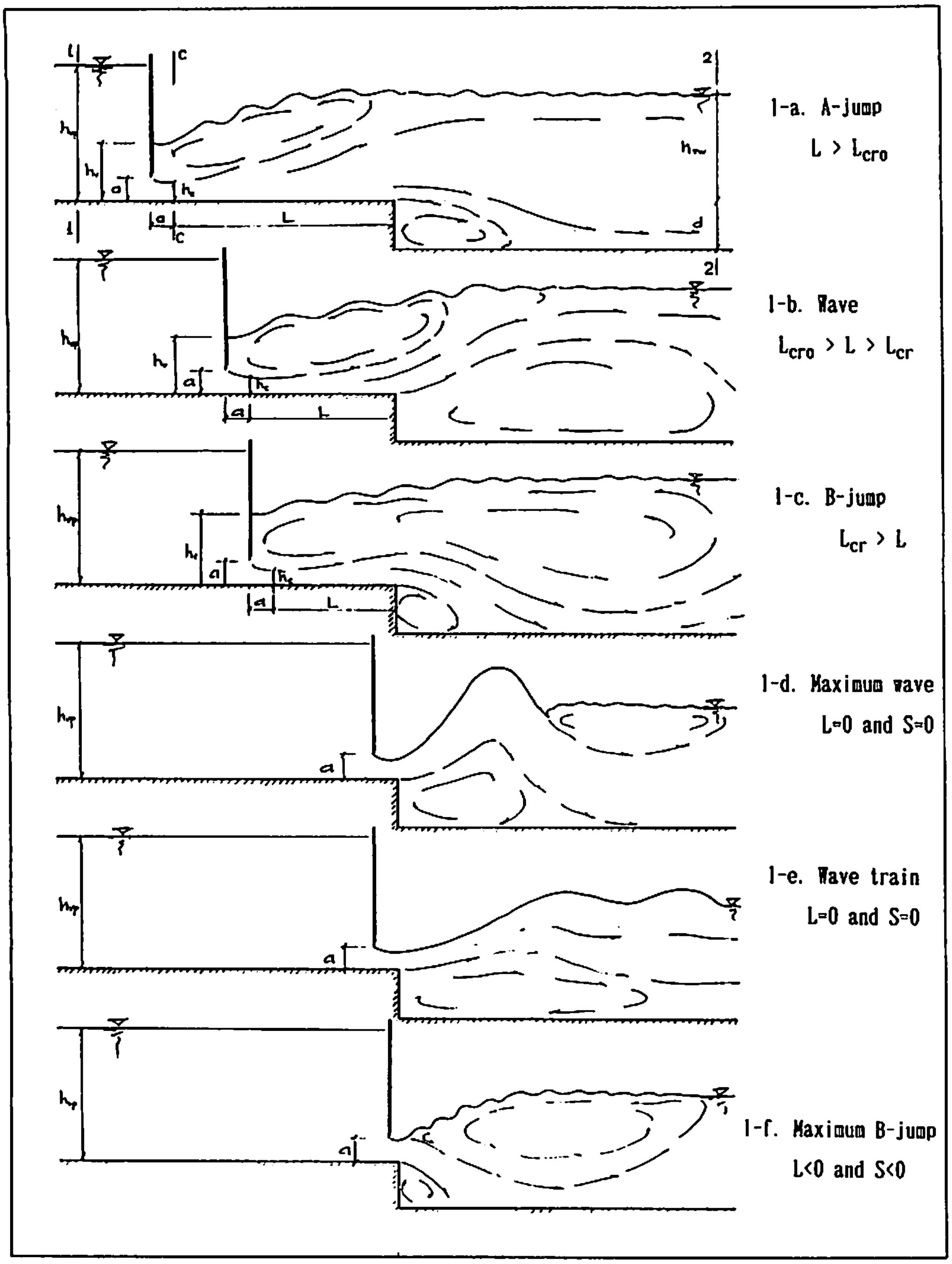

Fig. 1. CLASSIFICATION OF FLOW CONDITIONS

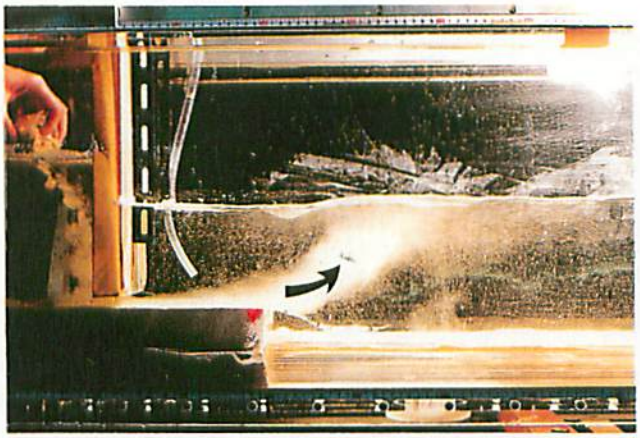

FIG. 1-B. **WAVE**

($\mathbf{F_r}$=4.57, **S**=1.79, $\mathbf{d/h_c}$=4.77, $\mathbf{L/h_c}$=21.25)

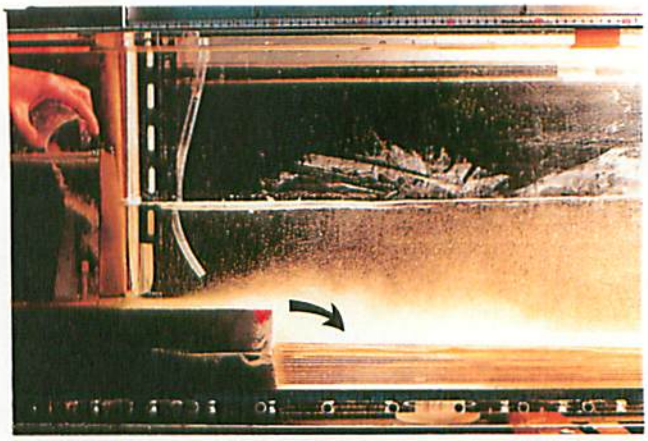

FIG. 1-C. **B-JUMP**

($\mathbf{F_r}$=4.57, **S**=1.79, $\mathbf{d/h_c}$=4.77, $\mathbf{L/h_c}$=21.25)

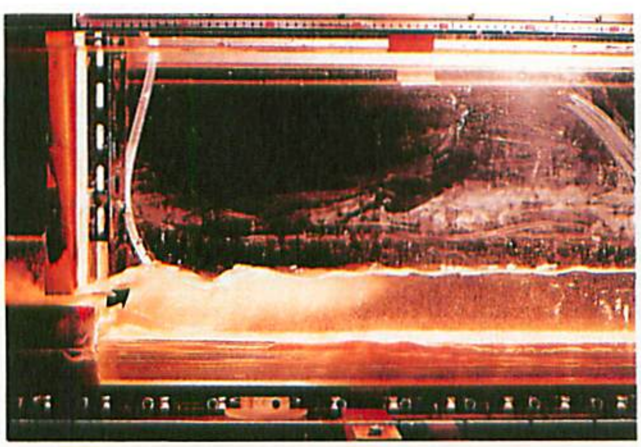

FIG. 1-E. **WAVE TRAIN**

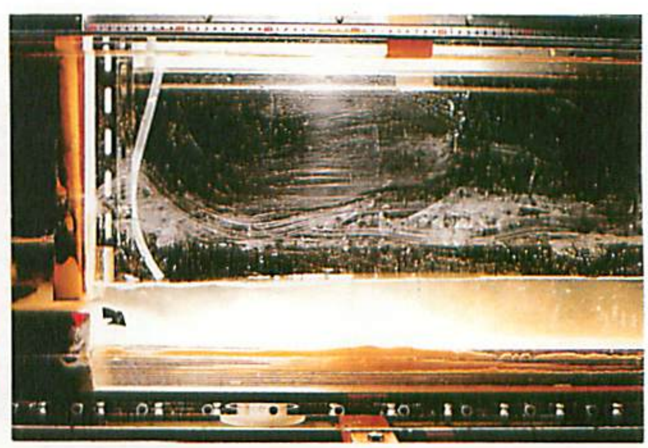

FIG. 1-F. **MAXIMUM B-JUMP**

Table 1. EXPERIMENTAL DATA

Run l/s	Q cm	a cm	h_c cm	d/h_c	F_r	S	L_s/h_c	L_l/h_c
1	2.44	1.2	0.733	2.183	6.207	0.95	31.787	40.655
2			0.734	2.18	6.194	0.688	18.801	32.425
3			0.734	2.18	6.194	0.433	14.714	24.251
4			0.734	2.18	6.194	0.194	11.989	20.163
5			0.735	2.177	6.182	-.143	-0.272	14.694
6	2.13	1.2	0.734	2.18	5.407	1.073	23.569	32.425
7			0.734	2.18	5.407	0.826	18.801	30.381
8			0.734	2.18	5.407	0.579	13.351	22.888
9			0.735	2.177	5.396	0.256	9.932	18.776
10			0.736	2.174	5.385	-.105	-0.951	11.956
11	1.8	1.2	0.734	2.18	4.57	1.642	25.613	40.599
12			0.734	2.18	4.57	1.38	21.526	33.787
13			0.735	2.177	4.56	0.972	14.694	26.939
14			0.738	2.168	4.532	-.109	-0.949	9.214
15	1.33	1.2	0.735	2.177	3.369	2.599	31.701	37.823
16			0.735	2.177	3.369	2.187	27.619	32.381
17			0.737	2.171	3.356	1.287	9.227	22.117
18			0.736	2.174	3.363	1.554	11.957	24.185
19			0.744	2.151	3.309	-.121	-0.941	1.074
20			0.736	2.174	3.363	1.856	11.957	28.261
21	0.86	1.2	0.736	2.174	2.174	4.716	24.185	35.054
22			0.736	2.174	2.174	3.962	16.033	30.978
23			0.738	2.168	2.165	2.801	7.859	20.732
24			0.740	2.162	2.157	1.868	5.135	13.243
25			0.767	2.086	2.044	-.009	-0.913	-0.260
26	0.86	1.2	0.769	3.290	2.036	-.007	-1.560	-0.909
27			0.735	3.442	2.179	4.708	5.850	31.020
28			0.736	3.438	2.174	3.936	3.804	26.902
29			0.738	3.428	2.165	2.775	1.084	18.699
30			0.740	3.419	2.157	1.868	-0.27	10.541
31	2.44	1.2	0.733	3.452	6.207	0.95	16.098	37.926
32			0.734	3.447	6.194	0.671	11.989	28.338
33			0.734	3.447	6.194	0.416	6.540	21.526
34			0.734	3.447	6.194	0.186	1.090	16.076
35			0.735	3.442	6.182	-.135	-0.952	9.252
36	2.13	1.2	0.734	3.447	5.407	1.064	13.351	32.425
37			0.734	3.447	5.407	0.816	9.264	28.338
38			0.734	3.447	5.407	0.550	3.815	20.136
39			0.735	3.442	5.396	0.237	0.408	14.694
40			0.736	3.438	5.385	-.181	-1.630	3.799
41	1.77	1.2	0.734	3.447	4.493	1.702	13.351	36.512
42			0.734	3.447	4.493	1.424	6.540	32.425
43			0.735	3.442	4.484	1.008	6.531	24.218
44			0.736	3.438	4.475	0.440	-0.272	13.315
45			0.738	3.428	4.457	-.139	-1.626	2.436
46	1.33	1.2	0.735	3.442	3.369	2.631	6.531	36.463
47			0.735	3.442	3.369	2.187	3.810	31.020
48			0.736	3.438	3.363	1.284	1.087	17.368
49			0.743	3.405	3.315	-.074	-1.614	0.403
50			0.736	3.438	3.363	1.670	1.766	21.467
51	2.44	1.2	0.733	5.607	6.207	0.950	9.277	31.105
52			0.734	5.599	6.194	0.671	2.452	25.613
53			0.734	5.599	6.194	0.408	0.409	17.439
54			0.734	5.599	6.194	0.186	-0.272	11.989
55			0.735	5.592	6.182	-.176	-0.952	3.129
56	2.14	1.2	0.734	5.599	5.433	1.053	3.134	29.700
57			0.734	5.599	5.433	0.798	1.090	22.888
58			0.734	5.599	5.433	0.542	-0.272	16.076
59			0.735	5.592	5.422	0.231	-0.952	9.252
60			0.736	5.584	5.410	-.156	-1.630	2.446
61	1.78	1.2	0.734	5.599	4.519	1.685	1.090	31.063

62			0.734	5.599	4.519	1.420	1.090	26.975
63			0.735	5.592	4.510	0.984	-0.272	20.136
64			0.736	5.584	4.500	0.397	-0.951	9.239
65			0.738	5.569	4.482	-.202	-1.626	0.405
66	1.33	1.2	0.735	5.592	3.369	2.662	1.088	32.381
67			0.735	5.592	3.369	2.187	0.408	24.218
68			0.737	5.577	3.356	1.287	-0.271	13.297
69			0.736	5.584	3.363	1.570	-0.272	16.033
70			0.743	5.532	3.315	-.106	-1.615	0.403
71	0.88	1.2	0.735	5.592	2.229	4.560	1.088	26.939
72			0.736	5.584	2.225	3.831	0.408	22.826
73			0.738	5.569	2.216	2.624	-0.271	13.279
74			0.740	5.554	2.207	1.768	-0.946	6.486
75			0.770	5.338	2.079	-.058	-0.909	-0.909
76	2.44	1.2	0.733	8.199	6.207	0.941	1.091	23.602
77			0.734	8.188	6.194	0.564	-0.272	19.482
78			0.734	8.188	6.194	0.276	-0.954	13.351
79			0.734	8.188	6.194	0.070	-0.954	7.902
80			0.734	8.188	6.194	-.152	-1.635	2.449
81	2.14	1.2	0.734	8.188	5.433	1.063	0.409	21.526
82			0.734	8.188	5.433	0.807	-0.272	17.439
83			0.734	8.188	5.433	0.523	-0.954	11.308
84			0.735	8.177	5.422	0,222	-0.952	5.170
85			0.735	8.177	5.422	-.167	-1.633	1.087
86	1.82	1.2	0.734	8.188	4.620	1.645	-0.272	25.613
87			0.734	8.188	4.620	1.363	-0.272	20.163
88			0.735	8.177	4.611	0.937	-0.952	14.694
89			0.736	8.166	4.601	0.353	-0.951	5.163
90			0.737	8.155	4.592	-.120	-1.628	0.407
91	1.34	1.2	0.735	8.177	3.395	2.647	-0.272	24.218
92			0.735	8.177	3.395	2.160	-0.272	20.136
93			0.736	8.166	3.388	1.234	-0.951	7.870
94			0.736	8.166	3.388	1.549	-0.951	9.239
95			0.742	8.100	3.347	-.146	-2.291	-0.269
96	0.87	1.2	0.735	8.177	2.204	4.659	-0.272	21.497
97			0.736	8.166	2.200	3.869	-0.951	16.033
98			0.738	8.144	2.191	2.672	-0.949	9.214
99			0.740	8.122	2.182	1.779	-1.622	3.784
100			0.773	7.775	2.067	-.082	-2.846	-2.846
101	2.44	1.2	0.733	14.379	6.207	0.941	-0.955	10.641
102			0.733	14.379	6.207	0.671	-0.955	6.540
103			0.734	14.360	6.194	0.416	-0.954	2.452
104			0.734	14.360	6.194	0.169	-1.635	1.090
105			0.735	14.340	6.182	-.193	-2.313	-0.272
106	1.79	1.2	0.734	14.360	4.544	1.692	-0.954	13.351
107			0.734	14.360	4.544	1.395	-0.954	8.583
108			0.735	14.340	4.535	0.972	-1.633	3.810
109			0.736	14.321	4.526	0.388	-1.630	0.408
110			0.738	14.282	4.507	-.161	-2.304	-0.271
111	0.89	1.2	0.736	14.321	2.250	4.493	-1.630	11.972
112			0.736	14.321	2.250	3.968	-1.630	7.880
113			0.738	14.282	2.241	2.552	-1.626	3.794
114			0.740	14.243	2.232	1.707	-2.297	0.405
115			0.762	13.832	2.136	-.001	-2.231	-2.231
116	2.13	1.2	0.734	14.360	5.407	1.073	-0.954	9.264
117			0.734	14.360	5.407	0.816	-0.954	3.815
118			0.734	14.360	5.407	0.512	-1.635	1.771
119			0.735	14.340	5.396	0.218	-1.633	0.408
120			0.736	14.321	5.385	-.152	-2.310	-0.272
121	1.32	1.2	0.735	14.340	3.344	2.709	-1.633	13.333
122			0.735	14.340	3.344	2.197	-1.633	7.891
123			0.736	14.321	3.337	1.592	-1.630	2.446
124			0.736	14.321	3.337	1.256	-1.630	1.085
125			0.743	14.186	3.290	-.034	-2.961	-0.942

DESCRIPTION OF FLOW CONDITION

Observation of the flow condition of the transition from supercritical to subcritical flow at an abrupt drop was carried out by changing submergence factor **S** and step length **L**.

If **L** is large or **S** is small, the flow condition for which the hydraulic jump is entirely formed on the step is called A-jump (Fig.1a). The flow just before leaving the step is subcritical flow and the mean time velocity profile is almost uniform. The flow passing over the step is as the case of a backward-facing step flow (Fig.2) with the following zones: Transient flow zone, mixing layer, recirculation zone, relaxation zone and new wall-boundary layer. This flow has been investigated on both experimental model and mathematical model by many authors as Bradshaw et al. (1972), Narayanan et al. (1974), Armaly et al. (1983), Durst et al. (1983), Nezu et al. (1989),...

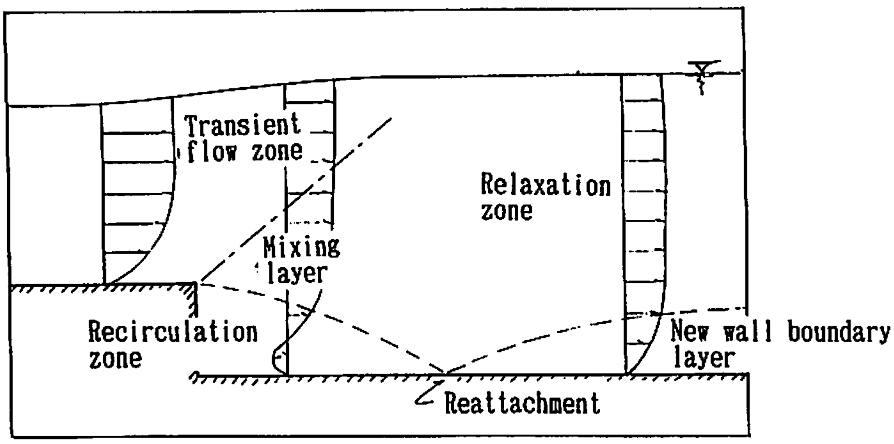

FIG.2. Schematic description of backward-facing step flow

Raising the tailwater elevation or shortening the step length from A-jump condition, at a certain stage, the supercritical flow dispersion is unfinished on the step, the main flow direction passing over the step moves upward, flows along the surface and undulations propagate far downstream. The flow immediately after this change is called wave (Fig. 1b). This is characterized by the formation of two large eddies, one on the hydraulic jump and one just below the drop, and by the reduction of water depth $\mathbf{h_v}$ just behind the gate due to the increase of pressure at the drop.

Applying the momentum equation for sections c-c and 2-2 (Fig.3), the following equation can be obtained.

$$(w/g)\, q\, (v_2 - v_c) = P_c + P_d - P_2 - F_f \qquad (1)$$

Where **q** is discharge per unit width, v_c and v_2 are mean velocties at sections c-c and 2-2 respectively, P_c and P_2 are total pressures at sections c-c and 2-2, P_d is the total pressure on the face of the drop, and F_f is the channel-bed friction. P_c and P_2 can be written as follows:

$$P_c = w\, h_v^2 /2, \qquad P_2 = w\,(h_{tw} + d)^2/2 \qquad (2)$$

For P_d, effect of the curvature of streamline of the main flow passing over the step is taken into consideration, and given by

$$P_d = k\, w\, d\, (h + d/2) \qquad (3)$$

Where **k** is the ratio of the actual pressure on the face of the drop to the hydrostatic pressure. Substituting equations (2) and (3) into equation (1), and expressing in dimensionless form, equation (4) is obtained.

$$2\,(P_d - F_f) / (w\, h_c^2) + (h_v / h_c)^2 = (h_{tw} + d)^2 / h_c^2 - 2\, F_r^2\, (1 - h_c / (h_{tw} + d)) \qquad (4)$$

For given F_r and $(h_{tw} + d) / h_c$, the variation of **k** with changing the depth h_v / h_c is obtained from equation (3) and (4). The experimental results showed in the case of wave, the main flow direction is upward just behind the drop and the depth h_v reduces. This implies P_d must be larger than the hydrostatic pressure, or **k** becomes larger than 1.

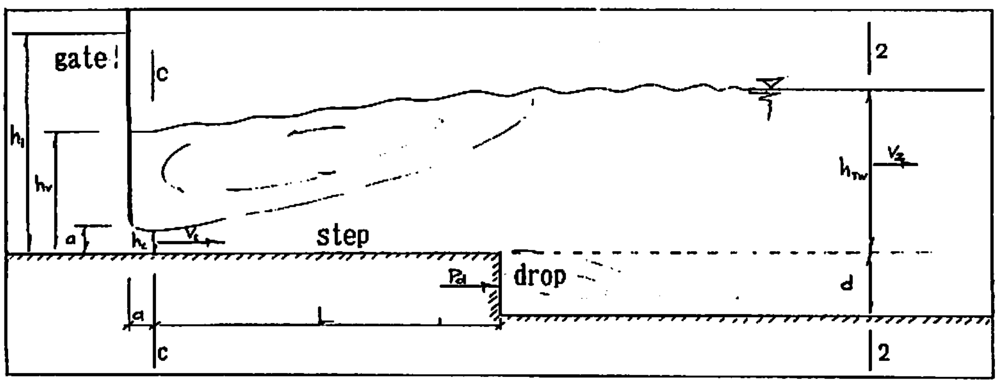

FIG.3. Definition sketch

A further reduction in **L** to a critical step length L_{cr} or a further increase in **S** to a critical submergence factor S_{cr} transforms the wave into a B-jump (Fig. 1c), the main flow passing over the step always plunges into the water. This plunging condition is characterized by the formation of a substantial surface eddy and by the increase of h_v due to the reduction of pressure at the drop P_d. The water surface is flatter, but in the vicinity of the bed, the velocity is higher and eventually the bed shear stress is higher than in the case of wave condition. The critical step length $\mathbf{L_{cr}}$ obtained by transforming the wave through the B-jump, called $\mathbf{L_{l}}$, is longer than that obtained by transforming the B-jump through the wave, called $\mathbf{L_{s}}$, and the critical submergence factor $\mathbf{S_{cr}}$ obtained by lowering the tailwater elevation, called $\mathbf{S_{lo}}$, is smaller than that obtained by raising the tailwater elevation, called $\mathbf{S_{up}}$. So that, the zones:

$\mathbf{L > L_{cro}}$: The flow condition is A-jump

$\mathbf{L_{cro} > L > L_{l}}$: The flow condition is wave
or $\mathbf{S_{lo} > S}$

$\mathbf{L_{l} > L > L_{s}}$: The flow condition may be wave or B-jump, it depends on some outer
or $\mathbf{S_{up} > S > S_{lo}}$ actions, the flow condition is unstable.

$\mathbf{L_{s} > L}$: The flow condition is B-jump
or $\mathbf{S > S_{up}}$

Where $\mathbf{L_{cro}}$ is somewhat less than the length of A-jump $\mathbf{L_{j}}$, $\mathbf{L_{j}}$ can be obtained from studies of Rajaratnam et al. (1995).
In the case of $\mathbf{S} = 0$, and $\mathbf{L} = 0$, the flow direction passing over the step moves upward and flow changes into a stationnary standing wave downstream of the drop, called maximum wave (Fig. 1d). This is characterized by the formation of a large standing eddy just below the drop, and by the flow being a normal open-channel flow at a short distance downstream of the eddy. Or the main flow after leaving the step flows along the surface and violent undulations propagate far downstream, called wave train (Fig. 1e). The wave train and the maximum wave are periodically repeated.

In the case of $\mathbf{S} < 0$, and $\mathbf{L} < 0$, the flow passing over the step always plunges into the water, even if the tailwater elevation is higher than the water surface elevation on the step. This plunging condition with a substantial surface eddy is called maximum B-jump (Fig. 1f).

CRITICAL SUBMERGENCE FACTOR AND CRITICAL STEP LENGTH

Flow condition at an abrupt drop depends on Froude number $\mathbf{F_{r}}$, submergence factor $\mathbf{S}$, relative step length $\mathbf{L / h_{c}}$ and relative step height $\mathbf{d / h_{c}}$. The observation of the flow condition was performed by changing progressively the step length or the tailwater elevation. Experimental results were shown the relation between $\mathbf{S_{cr}}$ and $\mathbf{L_{cr}}$ is pretty linear (Fig. 4), the same trend as in the case of $\mathbf{S_{cr}}$ and $\mathbf{d / h_c}$ (Fig. 5) and the proportion of $\mathbf{S_{cr}}$ to $\mathbf{F_r}$ is logarithm.

The following equation for $\mathbf{S_{lo}}$ and $\mathbf{L_1}$ is obtained:

$$\begin{aligned} S_{lo} = \; & (0.2678 + 0.1347\, d / h_c) - (0.5404 + 0.0462\, d / h_c) \log_n (F_r) \\ & + [(0.1281 + 0.0211\, d / h_c) - (0.0607 + 0.0096\, d / h_c) \log_n (F_r)]\; L_1 / h_c \end{aligned} \qquad (5)$$

And the equation for $\mathbf{S_{up}}$ and $\mathbf{L_s}$ is:

$$\begin{aligned} S_{up} = \; & (-1.7411 + 1.2601\, d / h_c) + (0.8403 - 0.6623\, d / h_c) \log_n (F_r) \\ & + [(-0.4996 + 0.4828\, d / h_c) + (0.2608 - 0.2482\, d / h_c) \log_n (F_r)]\; L_s / h_c \end{aligned} \qquad (6)$$

Note that, in the case of $\mathbf{d / h_c} < 0.5 - 1.5$ and $\mathbf{F_r} > 2.5 - 3.0$, the main flow direction passing over the step is always downward ($\mathbf{k} < 1$) as the study of Ohtsu et al. (1991). In this case, the flow condition approaches the A-jump on the horizontal channel.

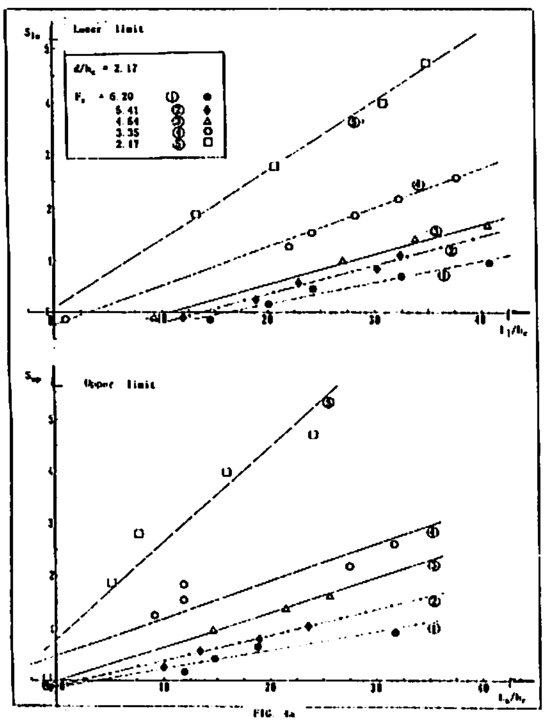

Fig. 4a

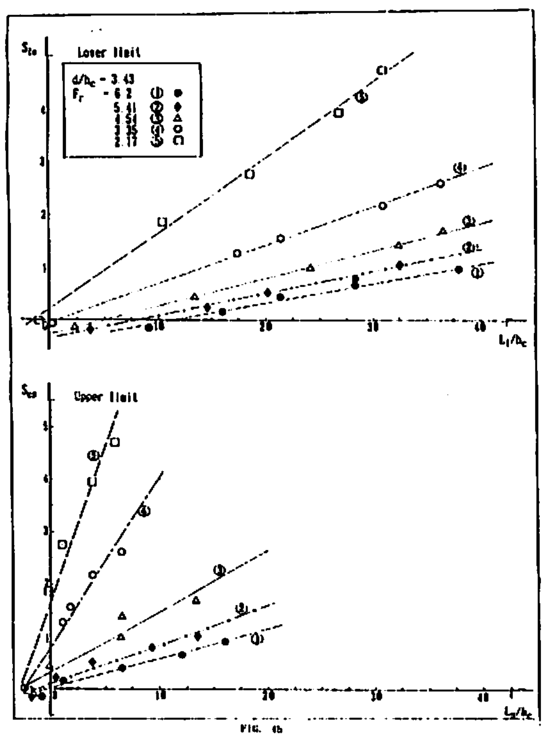

Fig. 4b

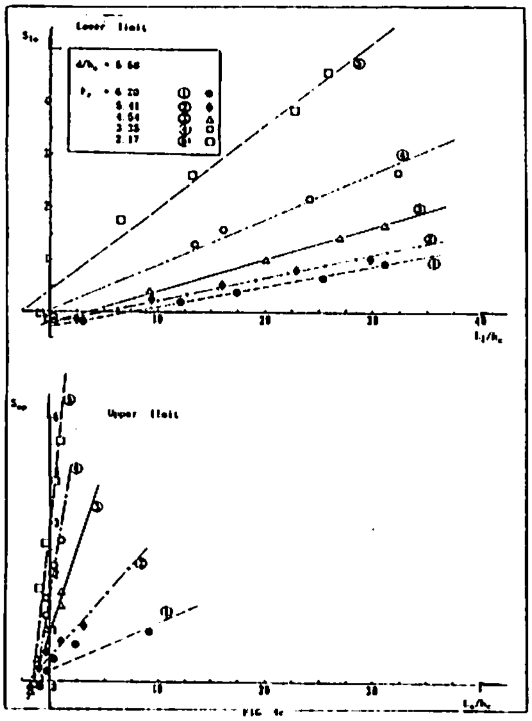

Fig. 4c

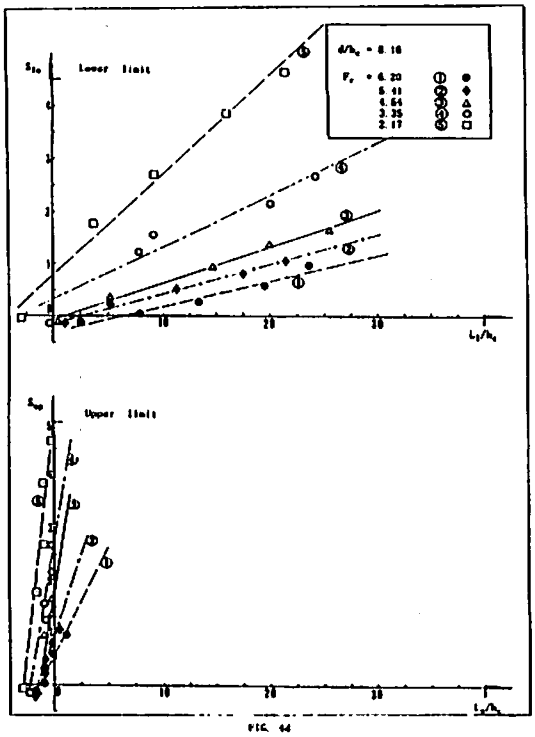

Fig. 4d

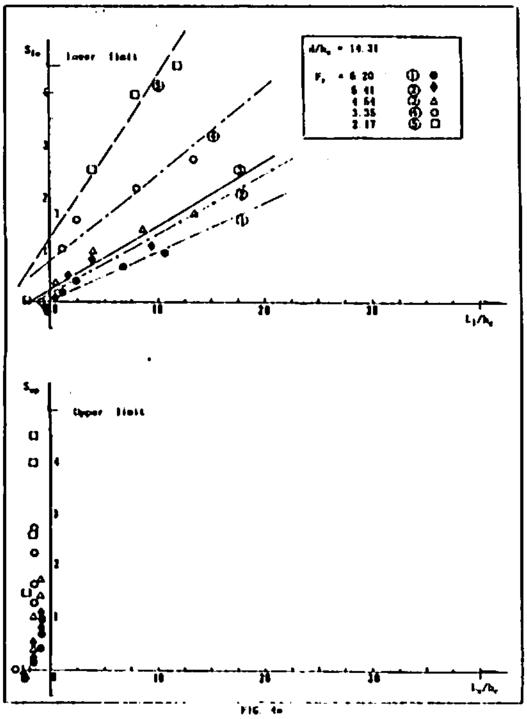

Fig. 4e

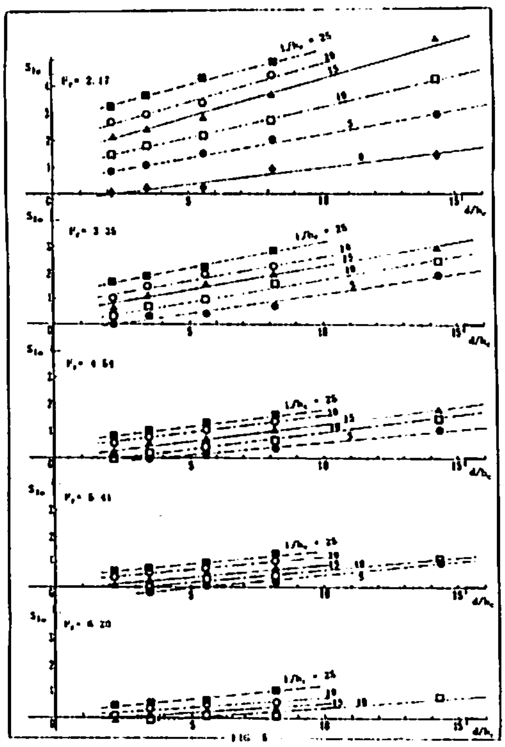

Fig. 5

CONCLUSIONS

Based on an experimental study on the submerged jumps at an abrupt drop for the supercritical Froude number $\mathbf{F_r}$ from 2.17− 6.20, the relative step height $\mathbf{d / h_c}$ from 2.17−14.31, the relative step length $\mathbf{L / h_c}$ from 0−41 and the submergence factor $\mathbf{S}$ from 0−4.7, the following conclusions are drawn:

1. The flow condition of a flow passing over a step in certain hydraulic conditions can be controlled by changing the step length **L**, or the step height **d**. This is especially significant for designing the aprons behind sluice gates in tidally-affected lowlands where there is always submerged jump and submergence factor changes progressively following the vibration of tidal elevation. In A-jump type, the maximum velocity decay in submerged jump is slower than in free jump and the submerged jump length is longer than the free jump length, the proportion of jump length to submergence factor is linear. So that, an apron for submerged A-jump is often uneconomic. There are three main flow conditions: One is A-jump-like, a hydraulic jump is formed with a large portion of its length located on the step. One is B-jump-like, the main flow passing over step always plunges into the water. The water surface is flatter, but the intensity of attack on the downstream channel by the plunging jet is rather high, eventually the high shear stress exists on a long distance of the bed. This flow condition is suitable for weirs on good foundation in the vicinity of hydropower stations, docks,... And one is wave-like, the main flow after leaving the step flows along the surface and violent undulations propagate far downstream. The water surface is rough, the wave's main disadvantage appears to be its excessive height, which might cause overtopping of the downstream channel banks. But the shear stress on the bed is insignificant. This flow condition is suitable for weirs on weak foundation and downstream of weirs is a large water surface area.

2. In the case of wave, the pressure on the face of the drop is higher, eventually the water depth just behind the gate is lower and the discharge capacity of the sluice gate is better than those in the case of B-jump or A-jump.

3. The critical submergence factor or the critical step length transforms the wave into the B-jump and the critical submergence factor or the critical step length transforms the B-jump into the wave do not coincide. In the critical zone, the fow condition may be wave or B-jump, it depends on some outer actions.

4. The proportion of the critical submergence factor to the step length and the step height is linear. Whereas the critical submergence factor decreases in proportion to logarithm of Froude number.

NOTATIONS

a gate opening
d step height
F_f channel bed friction
F_r supercritical Froude number on the step
g gravitational acceleration
h_c contraction depth
h_2 subcritical sequent depth of h_c
h_{tw} tailwater depth
h_v water depth just behind the gate
k ratio of the actual pressure on the face of the drop to the hydrostatic pressure
L step length
L_{cr} critical step length
L_j length of A-jump
L_l L_{cr} obtained by transforming the wave through the B-jump
L_s L_{cr} obtained by transforming the B-jump through the wave
P_c total pressure at section c-c
P_d total pressure on the face of the drop
P_2 total pressure at section 2-2
Q discharge
S submergence factor
S_{cr} critical submergence factor
S_{lo} S_{cr} obtained by transforming the wave through the B-jump
S_{up} S_{cr} obtained by transforming the B-jump through the wave
v_c mean velocity of supercritical flow at section c-c
v_2 mean velocity at section 2-2
w unit weight of water

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