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Full Length Research Paper

Determination the Invert Level of a Stilling Basin to Control Hydraulic Jump

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When water is released over the chutes/spillway, the potential energy is converted into kinetic energy at the base of chutes. This energy must be dissipated in order to prevent the possibility of sever scouring of downstream riverbed and the undermining of foundation which may cause failure of spillway and dam. For this purpose energy dissipators must be used which perform the energy reduction by converting the kinetic energy into turbulence and finally into heat. The dissipation of energy can be achieved by means of several methods such as stilling basins. The formation of hydraulic jump in the stilling basin will lead to dissipation of excess energy. In this study we use a simple method to determine stilling basin invert elevation in relation to upstream water elevation, design discharge and downstream water/ tail water elevation. Some solved examples have been provided to exhibit the capabilities of the design procedure.

Key words: Stilling Basin, Hydraulic Jump, Energy Dissipator, Chute, Spillway.

INTRODUCTION

Chutes are used in irrigation canals to convey water from a higher elevation to a lower elevation. They are useful structure for broken high slope to low slope in agricultural projects.

A chute structure may consist of an inlet, a chute section, an energy dissipator, and an outlet transition. The chute section may be pipe as in a pipe chute or an open section as in an open channel chute. Chutes are similar to drops except that they carry the water over longer distances, over flatter slopes, and through greater changes in grade (U.S.B.R., 1978).

The chute section, either pipe or open channel, generally follows the original ground surface and connects to an energy dissipator (stilling basin) at the lower end. Stilling pools or baffled outlets are used as energy dissipators on chute structures. The usual section for an open channel chute is rectangular.

In a stilling pool the water flows down the steep slope section at a velocity greater than the critical velocity. The abrupt change in slope where the flat grade of the stilling pool floor meets the steep slope section forces the water into a hydraulic jump and energy is dissipated in the resulting turbulence. The stilling pool is proportioned to contain the jump. For a stilling pool to operate properly the Froude number should be between 4.5 and 15. Special studies or model testing are required for structures with Froude numbers outside this range. If the Froude number is less than about 4.5 a stable hydraulic jump may not occur. If the Froude number is greater than about 10 a stilling pool may not be the best choice of energy dissipator. Stilling pools require tail water to force the jump to occur where the turbulence can be contained.

Stilling pools usually have a rectangular cross section, parallel walls, and a level floor. The following equations to determine pool invert elevation apply to stilling basin (Figure.1).

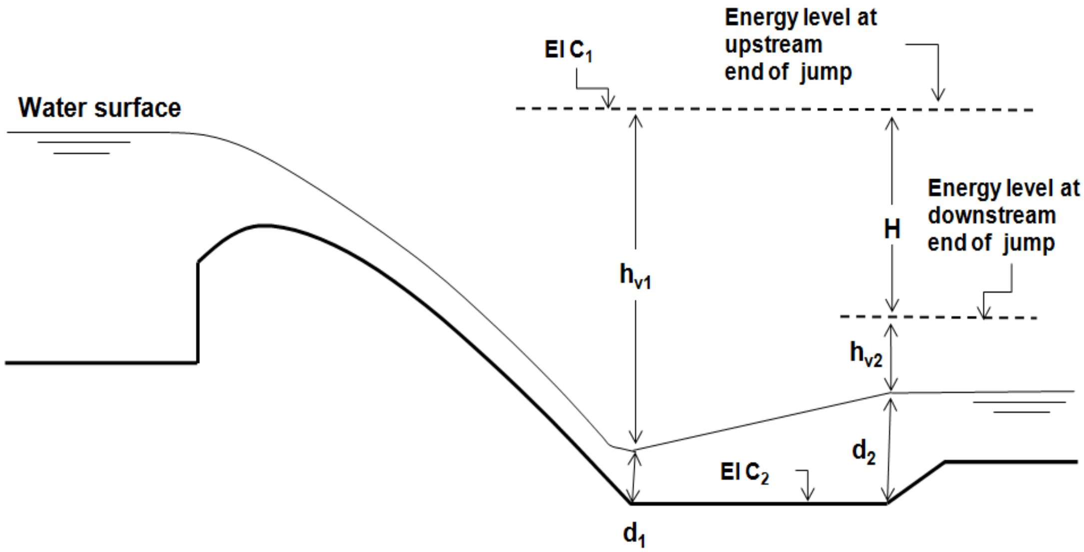

Figure1. Cross section of a chute with hydraulics parameters

$$ElC_1 = ElC_2 + d_1 + h_{V1} = ElC_2 + d_1 + q^2/(2gd_1^2) \quad (1)$$

$$d_2/d_1 = 0.5\left(\sqrt{1+8F_{r1}^{\ 2}} - 1\right) \quad (2)$$

where, g is acceleration due to gravity, d_1 and d_2 are the depth of flow before and after of hydraulic jump respectively, El C_1 is energy level at upstream of chute, El C_2 is stilling basin invert elevation, q is flow rate per unit width ($q = Q/b$) where Q is total discharge, b is the chute width, F_{r1} is Froude number at section before hydraulic jump and defined as: $F_{r1} = V_1/\sqrt{gd_1}$. The average flow velocity (V_1) was calculated as $V_1 = q/d_1$.

Eq. 1 is energy equation between upstream of chute and downstream before hydraulic jump (in stilling basin) and Eq. 2 is a result of combination of momentum and continuity equations. Eq. 2 is name conjugate depth (d_1 and d_2) relation in hydraulic jump. In Eqs. 1, 2 two unknown parameters d_1 and El C_2 must be determine. Note that d_2 is a known parameter from d_2= (energy level at downstream/tail water)-El C_2. So we must solve two non-linear Eqs. 1, 2 by trial and error to obtain two unknown d_1 and El C_2.

In this study we present a simple method for determination of stilling basin invert elevation based on energy at upstream of chute, design discharge, and tail water elevation (from discharge-head curve/rating curve). A number of design examples are presented to demonstrate the application of the algorithm too.

MATERIAL AND METHODS

Solution of system of non-linear equations

Refering to a chute cross section in Figure. 1, we present an example to solve two non-linear Eqs. 1,2 by trial and error to obtain two unknown d_1 and El C_2.

Example 1.

The reservoir level upstream of a 165-m wide spillway for a flow of 1400 m^3/s is at El. 100 m. The downstream river changes to water level for this flow is at El. 95.8 m. Determine the invert level of a stilling basin having the same width as the spillway so that a hydraulic jump is formed in the basin. Assume the losses in the spillway are negligible.

Given:
Q = 1400 m^3/s
B =165 m
Upstream water level = El 100 m.
Downstream water level = El 95.8 m.
Determine:
Stilling basin invert elevation to form the jump?
Solution:
Let El C_2 be the invert elevation of the stilling basin. Then, referring to Figure. 1, d_2 = 95.8– El C_2. Since the losses on the spillway face are negligible, we have:

Table 1. Results of solution non-dimensional Equation. 3 and 4.

Row	H/d_c	K	d_1/d_c	Row	H/d_c	K	d_1/d_c
1	0.05	1.7849	0.7382	301	30	32.9243	0.1214
2	0.1	2.0669	0.6808	302	30.1	33.0006	0.1212
3	0.2	2.4774	0.6146	303	30.2	33.0769	0.1211
4	0.3	2.8052	0.5722	304	30.3	33.1531	0.1209
5	0.4	3.0913	0.5408	305	30.4	33.2292	0.1207
6	0.5	3.3511	0.5157	306	30.5	33.3053	0.1205
7	0.6	3.5923	0.4949	307	30.6	33.3813	0.1203
8	0.7	3.8194	0.4772	308	30.7	33.4573	0.1202
9	0.8	4.0355	0.4617	309	30.8	33.5332	0.1200
10	0.9	4.2425	0.4480	310	30.9	33.6090	0.1198
11	1	4.4419	0.4358	311	31	33.6848	0.1196
12	1.1	4.6348	0.4247	312	31.1	33.7605	0.1194
13	1.2	4.8221	0.4145	313	31.2	33.8361	0.1193
14	1.3	5.0044	0.4053	314	31.3	33.9117	0.1191
15	1.4	5.1824	0.3967	315	31.4	33.9872	0.1189
16	1.5	5.3564	0.3887	316	31.5	34.0627	0.1188
17	1.6	5.5268	0.3813	317	31.6	34.1381	0.1186
18	1.7	5.6939	0.3744	318	31.7	34.2134	0.1184
19	1.8	5.8581	0.3679	319	31.8	34.2887	0.1182
20	1.9	6.0195	0.3617	320	31.9	34.3639	0.1181
21	2	6.1784	0.3559	321	32	34.4391	0.1179
22	2.1	6.3350	0.3505	322	32.1	34.5142	0.1177
23	2.2	6.4893	0.3452	323	32.2	34.5892	0.1176
24	2.3	6.6416	0.3403	324	32.3	34.6642	0.1174
25	2.4	6.7919	0.3356	325	32.4	34.7391	0.1172
26	2.5	6.9404	0.3311	326	32.5	34.8140	0.1171
27	2.6	7.0872	0.3268	327	32.6	34.8888	0.1169
28	2.7	7.2324	0.3227	328	32.7	34.9636	0.1167
29	2.8	7.3760	0.3187	329	32.8	35.0382	0.1166
30	2.9	7.5182	0.3149	330	32.9	35.1129	0.1164
31	3	7.6590	0.3113	331	33	35.1875	0.1162
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
291	29	32.1574	0.1233	591	59	53.0925	0.0886
292	29.1	32.2343	0.1231	592	59.1	53.1569	0.0886
293	29.2	32.3113	0.1229	593	59.2	53.2212	0.0885
294	29.3	32.3881	0.1227	594	59.3	53.2856	0.0884
295	29.4	32.4649	0.1226	595	59.4	53.3499	0.0884
296	29.5	32.5416	0.1224	596	59.5	53.4142	0.0883
297	29.6	32.6183	0.1222	597	59.6	53.4784	0.0882
298	29.7	32.6949	0.1220	598	59.7	53.5427	0.0881
299	29.8	32.7714	0.1218	599	59.8	53.6069	0.0881
300	29.9	32.8479	0.1216	600	59.9	53.6711	0.0880

$$100 = ElC_2 + d_1 + q^2/(2gd_1^2) \Rightarrow ElC_2 = 100 - d_1 - 3.669/d_1^2$$

By calculating Froude number at section before hydraulic jump we have:

$$F_{r1} = V_1/\sqrt{gd_1} \Rightarrow F_{r1}{}^2 = q^2/\left(gd_1{}^3\right)$$

$$F_{r1}{}^2 = (1400/165)^2/\left(9.81 d_1{}^3\right) = 7.338/d_1{}^3$$

Table 2. Design stilling basin invert elevation with different hydraulic parameter

El C_1 (m)	TW* (m)	Q (m^3/s)	b (m)	y_c (m)	y_1 (m)	y_2 (m)	El C_2 (m)
100	95	1400	165	1.943	0.645	4.457	90.543
99.5	95	1400	165	1.943	0.669	4.360	90.640
99	95	1400	165	1.943	0.697	4.254	90.746
98.5	95	1400	165	1.943	0.729	4.138	90.862
98	95	1400	165	1.943	0.767	4.009	90.991
97.5	95	1400	165	1.943	0.813	3.861	91.139
97	95	1400	165	1.943	0.873	3.687	91.313
96.5	95	1400	165	1.943	0.956	3.469	91.531
96	95	1400	165	1.943	1.095	3.154	91.846

*TW is tail water elevation or energy at downstream of canal.

Substituting expressions for F_{r1} and d_2 = 95.8– El C_2 into Eq.2, we will have:

$$\frac{95.8-ElC_2}{d_1}=\frac{1}{2}\left(\sqrt{1+8*\frac{7.338}{d_1^{\,3}}}-1\right)$$

$$\frac{95.8-100+d_1+3.669/d_1^{\,2}}{d_1}=\frac{1}{2}\left(\sqrt{1+\frac{58.704}{d_1^{\,3}}}-1\right)$$

Finally *d_1=0.69 m* by trial and error and then, *d_2=4.30 m.* So stilling basin invert elevation is calculated from:
El C_2=95.8-4.30=91.50m.

a) Introducing non-dimension parameters

Using Equation 1 and 2, we can demonstrate the following two non-dimensional equations (U.S.B.R., 1978):

$$\frac{d_1}{d_c}=\sqrt[3]{\frac{2}{K(K+1)}} \qquad (3)$$

$$\frac{H}{d_c}=\frac{(K-1)^3}{4K}\sqrt[3]{\frac{2}{K(K+1)}} \qquad (4)$$

$$d_c=\sqrt[3]{\frac{q^2}{g}} \qquad (5)$$

$$K=\frac{d_2}{d_1}$$

In Eqs. 3 and 4, H is energy loss in hydraulic jump and d_c is critical depth.

With assuming different values for H/d_c from 0.05 to 60 with increment step equal 0.1, and using Excel Solver, we calculated Eqs. 3 and 4 for d_1/d_c and K. Results of these calculations are presented in Table 1.

The Microsoft Office Excel Solver tool uses the Generalized Reduced Gradient (GRG2) nonlinear optimization code (Microsoft Office Excel, 2007). Solver is part of a suite of commands sometimes called tools. With Solver, you can find an optimal value for a formula in one cell-called the target cell-on a worksheet. Solver works with a group of cells that are related, either directly or indirectly, to the formula in the target cell. Solver adjusts the values in the changing cells that you specify-called the adjustable cells-to produce the result that you specify from the target cell formula. You can apply constrained to restrict the values that Solver can use in the model, and the constraints can refer to other cells that affect the target cell formula.

Now we solve example 1 with this method.

$$d_c=\sqrt[3]{\frac{q^2}{g}}=\sqrt[3]{\frac{(1400/165)^2}{9.81}}=1.943\ \ m$$

$$\frac{H}{d_c}=\frac{100-95.5}{1.943}=2.161$$

Then from table 1, for H/d_c=2.2, we find:

$$\frac{d_1}{d_c}=0.3452\Rightarrow d_1=0.67\ \ m$$

$$K=\frac{d_2}{d_1}=6.4893\Rightarrow d_2=4.35\ m$$

Finally we calculate stilling basin invert elevation:

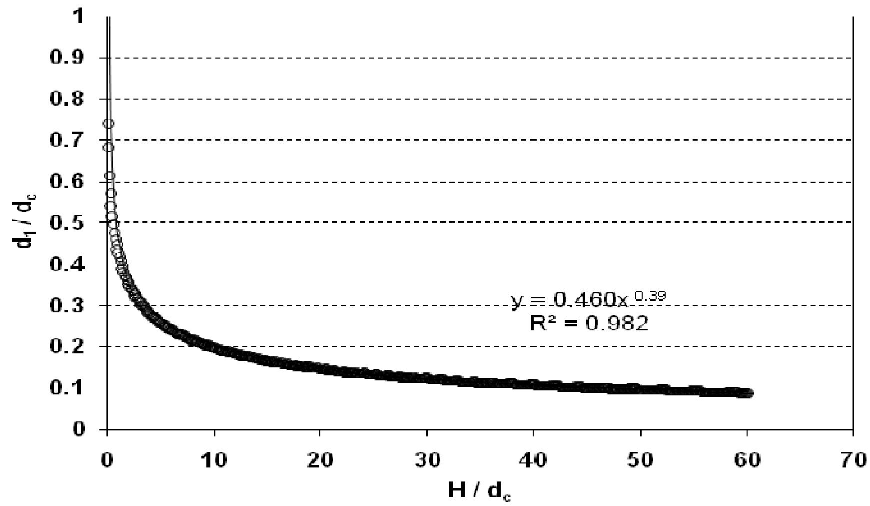

Figure2. Variation of H/d_c against d_1/d_c

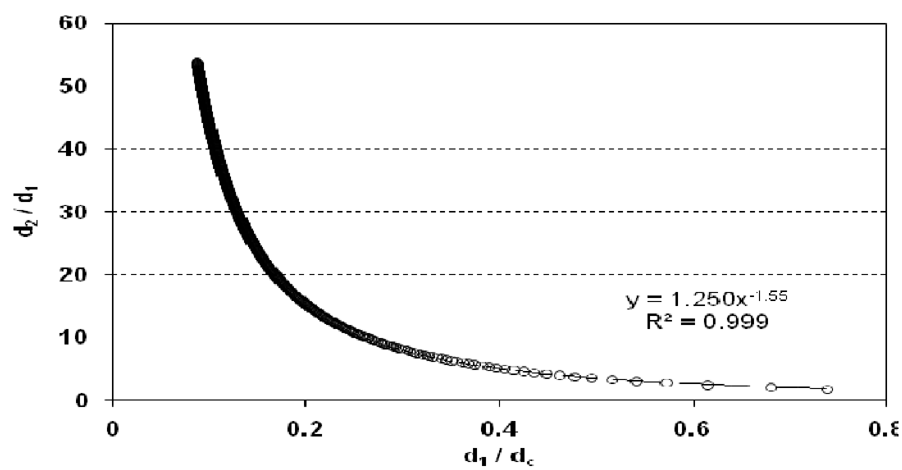

Figure3. Variation of d_1/d_c against d_2/d_1

El C_2=95.8-4.35=91.45m. If we find from table 1, H/d_c=2.161 by interpolation, then *El C_2* will be exactly the same as in previous example; *El C_2=95.8-4.30=91.50 m.*

b) **Regression equations**

From introduced data in table 1, we applied regression analysis to find correlation between H/d_c and d_1/d_c and also between d_1/d_c and d_2/d_1 in another hand. These correlations are shown in Figure. 2 and 3. By selecting different regression equations in Excel software, the following equations were obtained:

$$\frac{d_1}{d_c} = 0.460\left(\frac{H}{d_c}\right)^{-0.39}, R^2 = 0.982 \qquad (6)$$

$$\frac{d_2}{d_1} = 1.250\left(\frac{d_1}{d_c}\right)^{-1.55}, R^2 = 0.999 \qquad (7)$$

To calculate stilling basin invert elevation using Eqs. (6) and (7), we will have :

$$H/d_c = 2.161 \Rightarrow \frac{d_1}{d_c} = 0.46(2.161)^{-0.39} = 0.3406 \Rightarrow d_1 = 0.662\,m$$

$$\frac{d_2}{d_1} = 1.250(0.3406)^{-1.55} = 6.636 \Rightarrow d_2 = 4.393\ m$$

So this example; *El* C_2*=95.8-4.393=91.407 m.*

Some other examples are presented in table 2 with different hydraulic parameter in designing stilling basin invert elevation.

CONCLUSION

A hydraulic jump is the sudden transition from a supercritical open channel flow regime to a subcritical flow motion. The location of a jump in stilling basin may be controlled by providing a number of appurtenances, such as baffle blocks, sill, drop or rise in the channel bottom. For a horizontal rectangular channel and neglecting boundary friction, the energy and momentum principles give stilling basin invert elevation. Thus in this study we applied three method to determine stilling basin invert. They are (a)- energy and momentum equations, (b)- introducing non-dimensional parameters and (c)- regression equations. Solving an example shows the usefulness of methods (b) and (c), because these methods do not need any trial and error calculation.

NOTATION

b chute width;
d_1 depth of flow before hydraulic jump;
d_2 depth of flow after of hydraulic jump;
El C_1 energy at the upstream of chute;
El C_2 stilling basin inverts elevation;
F_{r1} supercritical Froude number, $F_{r1} = V_1/\sqrt{gd_1}$;
g acceleration due to gravity;
H head loss due to hydraulic jump;
h_{v1} velocity head before hydraulic jump;
h_{v2} velocity head after hydraulic jump;
K relative depth defined as: $K=d_2/d_1$;
q discharge per unit width;
Q discharge;
V_1 velocity at the toe of the chute;

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