APPENDIX E

COMPUTATIONS FOR THE DESIGN OF A STILLING BASIN

E-l. Introduction. This example is used to illustrate the procedures and guidance provided by this engineering manual for the design of a hydraulic jump-type stilling basin energy dissipator. This stilling basin to be designed for this example is for the spillway crest design example described in Appendix D. This stilling basin design example will include the following:

a. The determination of energy loss from the reservoir to the entrance of the basin.

b. The stilling basin design.

c. The computation of dynamic loads imposed on the stilling basin walls,

d. The exit channel design.

E-2. Computer Programs. The CORPS computer programs are used where applicable for this example and are noted throughout. The design engineer should periodically check the available CORPS programs to determine if additional programs have been added to the system.

E-3. Design Considerations. Site topography and geologic considerations require a 500-foot-long chute between the intersection of spillway face and the drop into the stilling basin (Figure E-l). The site geology will allow the spillway, chute, and stilling basin to be founded on sound rock. Erosional damage to the river banks downstream from the basin is unacceptable. The following data are required for the example:

Spillway design flood tailwater elevation	1,330 feet*
Elevation of the intersection of the spillway face and chute	1,400 feet
Elevation of river channel at the stilling basin location	1,290 feet
Concrete surface roughness	
For velocity computations	0.002 foot
For depth computations	0.007 foot

E-4. Computations.

a. Determine the energy loss on the spillway face and the depth of flow

* All elevations cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

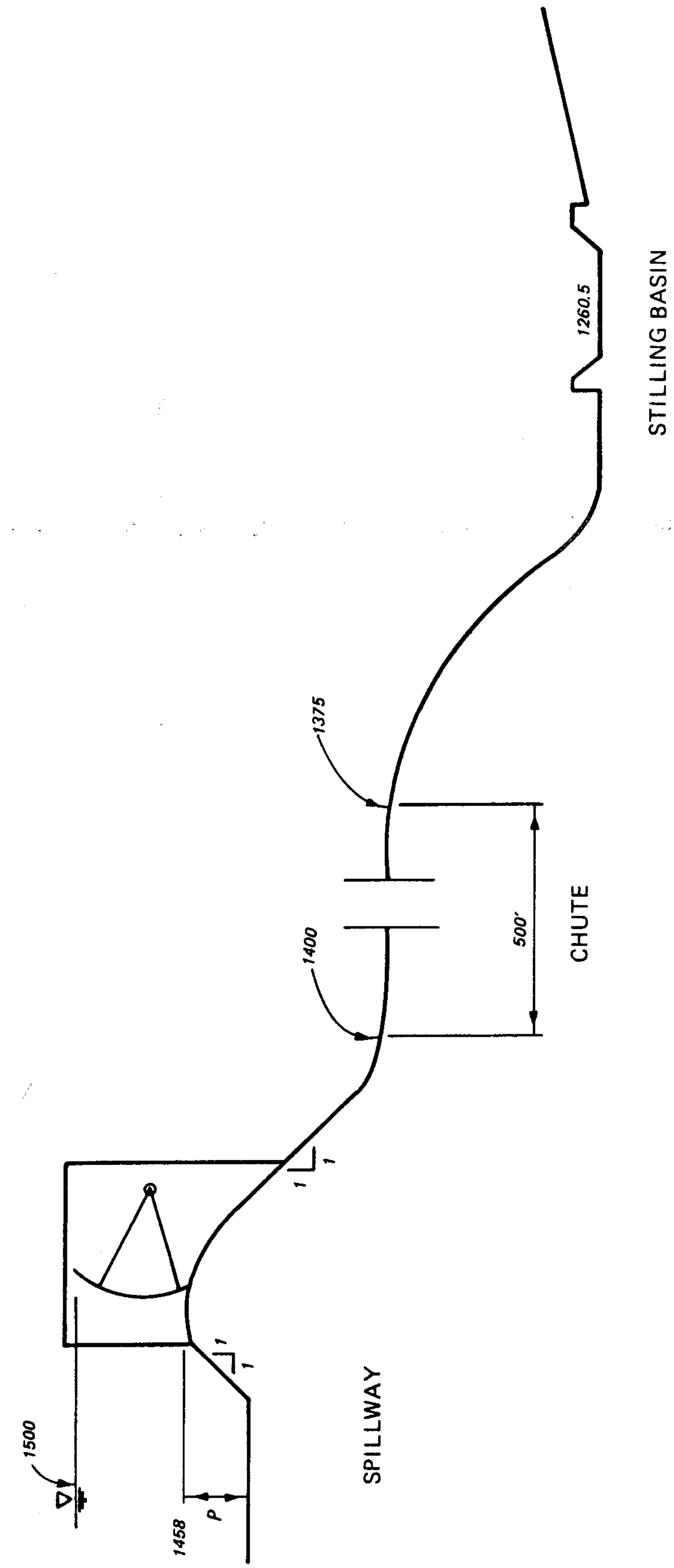

Figure E-1. Stilling basin design problem site geometry at the intersection of the spillway face and the spillway chute using the procedures described in paragraph 2-11.

(1) Boundary geometry computations

(a) The longitudinal length L_c of the curved portion of the spillway crest can be determined using HDC 111-18/1

X = horizontal distance from crest axis to downstream point of tangent from data derived for Appendix D

$$x = 35.61 \text{ feet}$$
$$H_d = 31.57 \text{ feet (from Appendix D)}$$
$$X/H_d = 35.61/31.57 = 1.13$$
$$L_c/H_d = 1.65 \text{ (from HDC 111-18/1)}$$
$$L_c = 1.65(31.57) = 52.1 \text{ feet}$$

(b) Length of tangent L_T, from the spillway tangent point to the spillway toe

$$L_T = (\Delta \text{ elev change})/\sin \alpha$$
$$\alpha = \tan^{-1} 1 = 45 \text{ degrees}$$
$$\text{elev} = \text{elev of tangent point} - \text{elev of toe}$$
$$= 1{,}458 - 19.25 - 1{,}400$$
$$= 38.75 \text{ feet}$$
$$L_T = 38.75/0.707 = 54.8 \text{ feet}$$

(c) Total crest length

$$L = L_c + L_T = 52.1 + 54.8 = 106.9 \text{ feet}$$

(2) Hydraulic computation

(a) Boundary layer thickness

$$\frac{L}{k} = \frac{106.9}{0.002} = 0.535 \times 10^5$$

$$\frac{\delta}{L} = 0.08 \left[\frac{L}{k}\right]^{-0.233} \qquad \text{(Equation 2-19)}$$

$$= 0.08\ (0.535 \times 10^5)^{-0.233}$$

$$= 0.0063$$

$$\delta = 0.0063(106.9) = 0.68 \text{ foot}$$

(b) Energy thickness δ_3

$$\delta_3 = 0.22 \qquad \text{(Equation 2-21)}$$

$$= 0.22(0.68) = 0.15 \text{ foot}$$

(c) Unit discharge q

$q = Q/L_g$

L_g = gross spillway width

= 76 + 12 = 88 feet

$q = 66{,}200/88 = 752\ ft^3/sec$

(d) Potential depth d_p and potential velocity u at toe

$$h_T = d_p \cos\theta + \frac{u^2}{2g} \qquad \text{(Equation 2-22)}$$

$\cos\theta = 0.707$

$h_T = 1{,}500 - 1{,}400 = 100$ feet

By trial:

u ft/sec	$u^2/2g$ feet	$h_T - u^2/2g$ feet	$d_p = \frac{h_T - u^2/2g}{0.707}$ feet	$q = ud_p$ ft^3/sec
75	87.3	12.7	17.9	1,342 > 752
79	96.9	3.1	4.4	348 < 752
77.4	93.0	7.0	9.9	763 ≅ 752

(e) Spillway energy loss

$$H_L = \frac{\delta_3 u^3}{2gq} \qquad \text{(Equation 2-23)}$$

$$= \frac{0.15(77.4)^3}{2(32.2)(752)} = 1.4 \text{ feet}$$

(f) Energy head at toe of spillway H_{toe}

$H_{toe} = 1{,}500 - 1{,}400 - 1.4$

= 98.6 feet

(g) Depth of flow at toe of spillway d

$$d = d_p + \delta_1 \qquad \text{(Equation 2-24)}$$

$\delta_1 = 0.18\delta$

$$= (0.18)(0.68) = 0.12 \text{ foot}$$

$$d = 9.9 + 0.12$$

$$= 10.0 \text{ feet}$$

b. Calculate Flow Characteristics Throughout the Spillway Chute

(1) Compute flow characteristics (depth, velocity, etc.) throughout the 500-foot-long constant slope portion of the chute using CORPS program H6209, and compute the flow characteristics throughout the trajectory portion of the chute, which immediately precedes the stilling basin. At present there is no CORPS program available for the computation of the flow characteristics on the trajectory slope; however, a number of standard step drawdown programs are available which will handle a variable-sloped channel. The computations for this example were made using the Seattle District program G3722040. Two sets of flow computations for each portion of the chute must be made: the first set, incorporating a relatively low resistance coefficient, will be used to determine design velocities and depths necessary for sizing the stilling basin and the chute floor trajectory shape. The second set, incorporating a relatively high resistance coefficient, will be used for chute wall height design. For brevity, only the first set of computations is included for this example and is found at the end of this appendix.

(2) Resistance Coefficients for Spillway Chute Floor. Paragraph 2-10e recommends effective roughness values of 0.002 foot and 0.007 foot for velocity design and discharge design, respectively. Converting these values to resistance coefficients for use in any of the these energy loss methods described in paragraph 2-10 requires that the hydraulic radius be known. However, since the resistance coefficient is not highly sensitive to the hydraulic radius, a computation of the flow characteristics using a reasonably close approximation of the resistance coefficient will provide a sufficiently accurate hydraulic radius from which to compute the design resistance coefficients. Manning's method (see paragraph 2-10d) was selected to determine the energy loss through the chute, and the first approximation of n value was 0.011. This value resulted in a depth of flow on the 500-foot portion of the chute which ranged between 9 and 10 feet and on the trajectory portion between 6 and 9 feet. A reasonable average hydraulic radius for these depths on the 88-foot-wide chute is

$$R = A/\text{wetted parameter}$$

$$= \frac{88(9.5)}{88 + 2(7.5)} = 7.8 \text{ for the chute}$$

$$= \frac{88(7.5)}{88 + 2(7.5)} = 6.4 \text{ for the trajectory}$$

Using the Colebrook-White equation 2-6

$$f = \left[\frac{1}{2 \log \left(\frac{13.8R}{k} \right)} \right]^2$$

When k = 0.002 and R = 7.8 : f = 0.011

When k= 0.002 and R = 6.4 : f = 0.012

Using equation 2-17

$$n = \frac{f^{1/2} R^{1/6}}{10.8}$$

When f = 0.011 and R = 7.8 : n = 0.014

When f = 0.012 and R = 6.4 : n = 0.014

(3) Parabolic Shape for Chute Invert. The transition for a flatter slope to a steeper slope is discussed in paragraph 4-6 and the equation 4-5 is recommended for this transition. The parabolic invert shape will be used for the entire short portion of the chute between the end of the 500-foot-long constant slope chute and the stilling basin. The equation for the invert is

$$Y = -X \tan \phi - \frac{gX^2}{2(1.25V)^2 \cos^2 \phi}$$

with

$$Y = 78.8 \text{ ft/sec}$$

$$Y = -0.0875X - 0.00167X^2$$

(4) Stilling Basin Design.

(a) Floor Elevation. The basin floor (apron) elevation will be set to develop 100 percent of the conjugate depth d_2 at the spillway design flood discharge of 66,200 ft^3/sec. By a trial procedure which involves assuming a basin elevation and the flow characteristic computations for the trajectory portion of the chute, the entering depth d_1 and velocity V_1 can be determined, from which the entering Froude number F_1 and required tailwater depth d_2 can be determined by equations 2-27 and 2-26, respectively. The required tailwater elevation is then compared to the actual tailwater elevation; when the required and actual elevations coincide, the basin apron elevation is set. Table E-1 illustrates the procedure.

(b) Basin length. The entering Froude number F_1 of 7.7 is sufficiently high to indicate potential cavitation problems around baffles (see paragraph 7-7a); therefore, baffles will not be used in this design.

TABLE E-l

Apron Elevation Computation

Apron Elevation (1)	Y feet (2)	X feet (3)	d_1 feet (4)	V_1 ft/sec (5)	F_1 feet (6)	Required d_2 feet (7)	D_{TW} feet (8)
1,250.0	125.0	248.6	6.5	115.4	8.0	70.4	80.0
1,258.0	117.0	239.8	6.6	113.6	7.8	69.8	72.0
1,260.5	114.5	237.0	6.7	113.0	7.7	69.7	69.5

Notes: (1) Assume apron elevation.
(2) Elevation of Y = 0 at start of parabolic drop (1,375) - apron elevation.
(3) From trajectory equation: $Y = -0.0875X - 0.00167X^2$.
(4)(5) From flow characteristics computation page.
(6) $F_1 = \frac{V_1}{(gd_1)^{1/2}}$.
(7) $d_2 = 0.5d_1 \left[\left(1 + 8 F_1^2\right)^{1/2} - 1\right]$.
(8) Tailwater depth (1,330.0) - apron elevation (1).

$$L_b = Kd_1F_1^{1.5} \quad \text{(Equation 7-1 and Table 7-1)}$$

$$= 1.7(6.7)(7.7)^{1.5}$$

$$= 243 \text{ feet}$$

(c) End Sill

(1) Height = $d_1/2$ or $d_2/12$, whichever (paragraph 7-8) is less

$d_1/2 = 6.7/2 = 3.4$ feet

$d_2/12 = 69.7/12 = 5.8$ feet

use height = 3.5 feet

(2) Top of end sill elev = 1,260.5 + 1,264.0

(3) Shape - upstream face to be sloped
1V:lH to minimize potential for debris trapping

(d) Determine basin wall pressures at X = 100 feet downstream from intersection of chute and basin apron (see paragraph 2-14)

(1) Determine average minimum unit force

$$R_m = 3.75 H_s^{-1.05} \rho V_1 q F_1^{-1.42} \qquad \text{(Equation 2-36)}$$

$$= 3.75(200)^{-1.05} (1.94)(113)(752.3)(7.7)^{-1.42}$$

= 130.9 pounds per foot (lb/ft) of wall

(2) Determine static unit force due to d_2

$$R_s = 0.5 \gamma d_2^2$$

$$= 0.5(62.4)(69.2)^2$$

= 149,400 lb/ft

Assuming the jump length equal to basin length,

$$X/L_b = 100/243 = 0.41$$

(3) Average Unit Force R

$$\frac{R - R_m}{R_s - R_m} = 0.42 \qquad \text{(from Plate 2-4)}$$

R = 0.42 (149,400 - 131) + 131

= 62,800 lb/ft

(4) Minimum Unit Force R_-

$$\frac{R_- - R_m}{R_s - R_m} = 0.19 \qquad \text{(from Plate 2-4)}$$

R_- = 0.19 (149,400 - 131) + 131

= 28,500 lb/ft

(5) Maximum Unit Force R+

$$\frac{R_+ - R_m}{R_s - R_m} = 0.68 \qquad \text{(from Plate 2-4)}$$

R_+ = 0.68 (149,400 - 131) + 131

= 101,600 lb/ft

(6) Maximum Unit Moment M

$Y/d_{TW} = 0.34$ (from Plate 2-5)

$d_{TW} = 1,330 - 1,260.5 = 69.5$ feet

$Y = 0.34\ (69.5) = 23.6$ feet

$M = 101,600(23.6) = 2.4 \times 10^6$ ft/lb

(e) Exit channel design.

(1) Width

$W = W_b + 5$ feet on each side, or $W_b + (0.15)(d_2)$ on each side, whichever is larger (paragraph 7-11b)

$W = 88 + 2(5)$ or $88 + 2\ (0.15)(69.5)$

$= 98$ or 108.8

$W = 110$ feet

(2) Length

Slope = 1V:10H

The channel elevation adjacent to the basin end sill will be set at elevation 1,263.3 or 0.7 foot below top of end sill

$L = 10$ (natural channel elevation - 1,263.3)

$= 10\ (1,290 - 1,263.3)$

$= 267$ feet

(3) Erosion Protection

Velocity over end sill = q/depth

$= 752.3/(1,330 - 1,264)$

$= 11.4$ ft/sec

d_{50}(min) = 1.8 feet (HDC 712-1)

Assuming specific stone weight (γ_s) = 155 lb/ft^3

W_{50} (min) = 500 pounds

W_{100} range = $2W_{50}$ to $5W_{50}$

$$= 1{,}000 \text{ to } 2{,}500 \text{ pounds}$$

$$D_{100} \text{ range} = \left(\frac{6W}{\pi \gamma_s}\right)^{1/3}$$

$$= 2.3 - 3.2 \text{ feet}$$

Thickness $t = 2d_{50}$ or $1.5d_{100}$, whichever is greater

$2d_{50} = 2(1.8) = 3.6$ feet

$1.5d_{100} = 1.5(3.2) = 4.8$ feet

Riprap thickness = 5.0 feet

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**********************************
*  CORPS PROGRAM  #  H6209       *
*  MICRO VERSION  # 83/10/01     *
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INPUT H6209-FLOW PROFILES IN PRISMATIC CHANNEL.

AA-ENTER DESIRED RESISTANCE LAW AS: MANN=MANNING, CHEZ=CHEZY, OR
COLE=COLEBROOK-WHITE.

MANN
AC-ENTER DISCHARGE IN CFS.

66200.
AD-ENTER VALUE OF RESISTANCE COEFFICIENT.

0.014
AE-ENTER CHANNEL INVERT SLOPE IN FT/FT.

0.05
AF-ENTER CHANNEL BOTTOM WIDTH IN FT. ENTER 0.0 IF TRIA. CROSS-SECTION.

88.0
AC-ENTER CHANNEL SIDE SLOPE AS COTANGENT OF ACUTE ANGLE WITH
HORIZONTAL. ENTER 0.0 IF RECTANGULAR SECTION.

0.0
AH-ENTER CHANNEL LENGTH IN FT.

500.0
AI-ENTER INTERVAL FOR WHICH DEPTHS ARE TO BE COMPUTED IN FT.
NOTE: CHANNEL LENGTH/INTERVAL CANNOT EXCEED 500. FURTHERMORE
THE INTERVAL IS AUTOMATICALLY ADJUSTED SMALLER TO OBTAIN
ACCURACY OF 0.01 FT. IN COMPUTED DEPTH.

50.0
AJ-ENTER THE INITIAL DEPTH IN FT.

10.0
AK-ENTER INITIAL DEPTH STATION NUMBER IN FT FROM POINT OF BEGINNING.

35.61
AL-ENTER DIRECTION STATION NUMBERS INCREASING AS DS = DOWNSTREAM
US = UPSTREAM.

DS
AM-ENTER ELEVATION OF CHANNEL INVERT AT INITIAL DEPTH STATION
IN FT ABOVE MSL.

1400.0
AN-ENTER ENERGY COEFFICIENT (ALPHA).

1.0
AO-STORE OUTPUT FOR GRAPHICS AND/OR OTHER USE?
ENTER Y OR N
N
CHANGE ANY INPUT BEFORE RUN?

ENTER Y OR N
N
OUTPUT-H6209

FLOW PROFILE IN RECT CHARNEL USING MANN RESISTANCE LAW WITH THE FOLLOWING GIVEN DESIGN DATA.

DISCHARGE: 66200.00 CFS
CHANNEL WIDTH: 88.00 FT.
INVERT SLOPE: .05000 FT/FT.
SIDE SLOPE: .00H:lV
RESISTANCE COEF: .01400
CHARNEL LENGTH: 500.00 FT.
ALPHA: 1.00

FLOW PROFILE WITH FOLLOWING CHARACTERISTICS:

CHANNEL SLOPE CLASSIFICATION: STEEP
ZONE DESIGNATION: 52
CURVE TYPE: DRAWDN
FLOW TYPE: SUPERC

NORMAL DEPTH: 8.54 FT.
CRITICAL DEPTH: 26.00 FT.
CRITICAL SLOPE: .001782 FT/FT.

STATION NO.	INVERT ELEV (MSL)	WATER DEPTH (FT)	WATER SURF ELEVATION (MSL)	FLOW VELOCITY (FPS)	VELOCITY HEAD (FT)	SPECIFIC ENERGY (FT)
0+35.61	1400.000	10.000	1410.000	75.227	87.875	97.875
0+85.61	1397.500	9.942	1407.443	75.663	88.895	98.838
1+21.22	1395.719	9.903	1405.623	75.964	89.603	99.507
1+71.22	1393.219	9.850	1403.069	78.374	so.573	100.423
2+21.22	1390.719	9.799	1400.519	76.769	91.515	101.314
2+71.22	1388.219	9.751	1397.970	77.152	92.428	102.179
3+21.22	1385.719	9.704	1395.424	77.521	93.315	103.019
3+71.22	1383.219	9.660	1392.879	77.878	94.176	103.836
4+21.22	1380.719	9.617	1390.337	78.222	95.011	104.628
4+71.22	1378.219	9.576	1387.796	78.555	95.822	105.398
5+21.22	1375.719	9.537	1385.257	78.877	96.608	106.145
5+35.61	1375.000	9.526	1384.526	78.967	96.830	106.356

ENTER END OR RERUN

END
stop - Program terminated.

EXAMPLE PROBLEM

DISCHARGE= 66200.
DEPTH SUPPLIED
STATION BOTTOM ELEVATION
0. 1375.

BOTTOM WIDTH	CHAN S.S.	BED SLOPE	N-COEF ROUGH
88.00	0.00	0.050000	0.014

DEPTH	VELOCITY	FRI(SLOPE	ENERGY G.L.)
9.50000	79.18660	0.035902	1481.87

STA	WSEL	CBE	DEPTH	SLOPE	VEL	F SLOPE	W B C	Z
25.	1381.24	1371.77	9.39	0.12920	80.15	0.0373	88.0	0.00
51.	1375.63	1366.24	9.17	0.21280	82.02	0.0400	88.0	0.00
75.	1368.44	1359.12	8.91	0.29640	84.47	0.0439	88.0	0.00
100.	1359.77	1350.63	8.62	0.33960	87.30	0.0486	88.0	0.00
125.	1347.33	1338.05	8.23	0.50320	91.45	0.0562	88.0	0.00
150.	1333.41	1324.38	7.86	0.54680	95.68	0.0647	88.0	0.00
175.	1317.56	1308.62	7.50	0.63040	100.30	0.0750	88.0	0.00
200.	1299.66	1290.81	7.15	0.71240	105.2?	0.0872	88.0	0.00
225.	1279.67	1270.88	6.82	0.79720	110.37	0.1014	88.0	0.00
250.	1257.60	1248.86	6.50	0.88080	115.70	0.1177	88.0	0.00
275.	1233.45	1224.75	6.21	0.96440	121.13	0.1361	88.0	0.00