7 Flumes

A critical depth-flume is essentially a geometrically specified constriction built in an open channel where sufficient fall is available for critical flow to occur in the throat of the flume. Flumes are 'in-line' structures, i.e. their centre line coincides with the centre line of the undivided channel in which the flow is to be measured. The flume cannot be used in structures like turnouts, controls and other regulating devices.

In this chapter the following types of critical-depth flumes will be described: Long-throated flumes (7.1), Throatless flumes with rounded transition (7.2), Throatless flumes with broken plane transition (7.3), Parshall flumes (7.4), H-flumes (7.5). The name 'Venturi flume' is not used in this chapter, since this term is reserved for flumes in which flow in the constriction is sub-critical. The discharge through such a constriction can be calculated by use of the equations presented in Section 1.7.

7.1 Long-throated flumes

7.1.1 Description

Classified under the term 'long-throated flumes' are those structures which have a throat section in which the streamlines run parallel to each other at least over a short distance. Because of this, hydrostatic pressure distribution can be assumed at the control section. This assumption allowed the various head-discharge equations to be derived, but the reader should note that discharge coefficients are also presented for high H_1/L ratios when the streamlines at the control are curved.

The flume comprises a throat of which the bottom (invert) is truly horizontal in the direction of flow. The crest level of the throat should not be lower than the dead water level in the channel, i.e. the water level downstream at zero flow. The throat section is prismatic but the shape of the flume cross-section is rather arbitrary, provided that no horizontal planes, or planes that are nearly so, occur in the throat above crest (invert) level, since this will cause a discontinuity in the head-discharge relationship. Treated in this section will be the most common flumes, i.e. those with a rectangular, V-shaped, trapezoïdal, truncated V, parabolic, or circular throat cross-section. For other shapes see Bos (1985).

The entrance transition should be of sufficient length, so that no flow separation can occur either at the bottom or at the sides of the transition. The transition can be formed of elliptical, cylindrical, or plane surfaces. For easy construction, a transition formed of either cylindrical or plane surfaces, or a combination of both, is recommended. If cylindrical surfaces are used, their axes should be parallel to the planes of the throat and should lie in the cross-section through the entrance of the throat. Their radii should preferably be about 2 H_{1max}. With a plane surfaced transition, the convergence of side walls and bottom should be about 1:3. According to Wells & Gotaas (1956) and Bos & Reinink (1981), minor changes in the slope of the entrance transition will have no effect upon the accuracy of the flume. It is suggested that, where the flume has a bottom contraction or hump, the transitions for the crest and for the sides should be of equal lengths, i.e. the bottom and side contraction should begin at the same point at the approach channel bottom as shown in Figure 7.1.

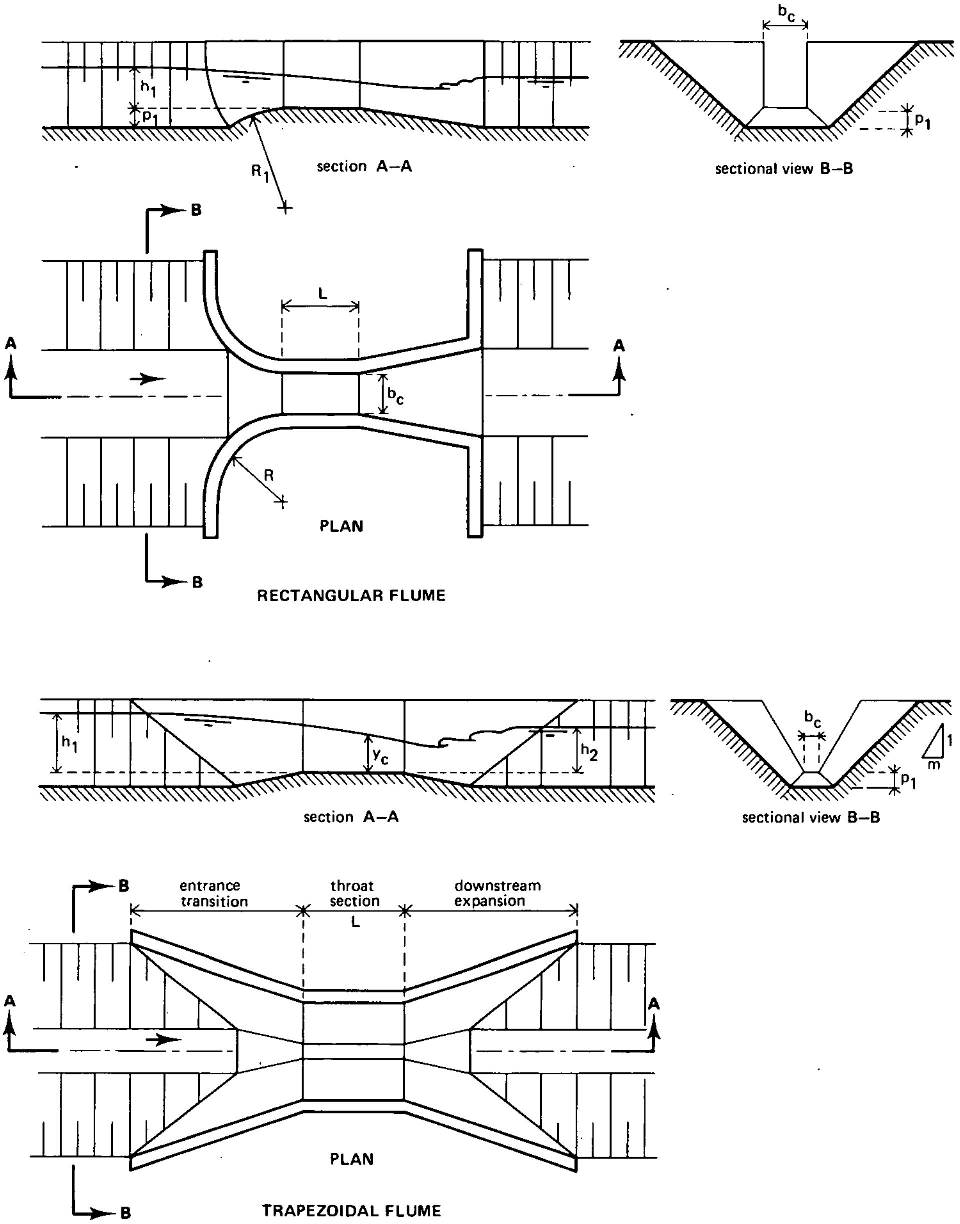


Figure 7.1 Alternative examples of flume lay-out

With flat bottomed flumes, the floor of the entrance transition and of the approach channel should be flat and level and at no point higher than the invert of the throat, up to a distance 1.0 H_{1max} upstream of the head measurement station. This head measurement station should be located upstream of the flume at a distance equal to between 2 and 3 times the maximum head to be measured.

Even if a flume is fitted with a curved entrance transition, it is recommended that the downstream expansion beyond the throat be constructed of plane surfaces. The degree of expansion influences the loss of energy head over the expansion and thus the modular limit of the flume (Section 1.15).

7.1.2 Evaluation of discharge

The basic stage-discharge equations for long-throated flumes with various control sections have been derived in Section 1.9 and are shown in Fig.7.2. As indicated, the reader should use Table 7.1 to find y_c-values for a trapezoïdal flume, and Table 7.2 to find the ratios A_c/d_c^2 and y_c/d_c as a function of H_1/d_c for circular flumes.

For all control sections shown, the discharge coefficient C_d is a function of the ratio H_1/L and is presented in Figure 7.3. The approach velocity coefficient C_v may be read from Figure 1.12 as a function of the dimensionless ratio C_dA^*/A_1.
The error in the product C_dC_v of a well maintained long-throated flume which has been constructed with reasonable care and skill may be deduced from the equation

$$X_c = \pm (3|H_1/L - 0.55|^{1.5} + 4) \qquad (7\text{-}1)$$

The method by which this coefficient error is to be combined with other sources of error is shown in Annex 2.

Photo 1 Long-throated flumes can be portable

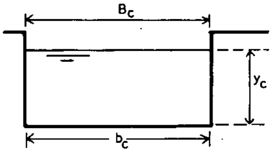
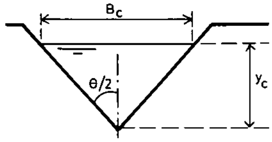
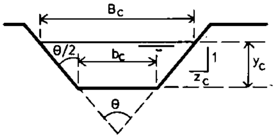
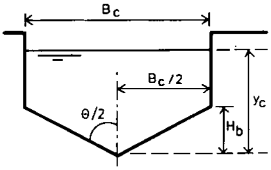
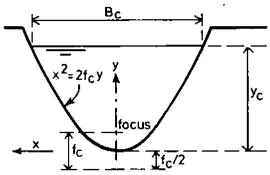
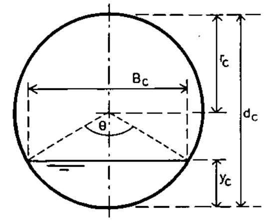
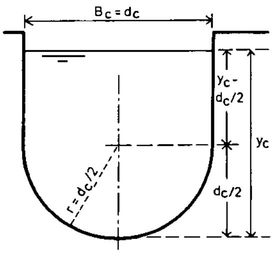
SHAPE OF CONTROL SECTION	HEAD–DISCHARGE EQ. TO BE USED	HOW TO FIND THE y_c - VALUE
	$Q = C_d C_v \frac{2}{3} (\frac{2}{3} g)^{1/2} b_c h_1^{3/2}$	$y_c = \frac{2}{3} H_1$
	$Q = C_d C_v \frac{16}{25} (\frac{2}{5} g)^{1/2} \tan\frac{\theta}{2} h_1^{5/2}$	$y_c = \frac{4}{5} H_1$
	$Q = C_d [b_c y_c + z_c y_c^2][2g(H_1 - y_c)]^{1/2}$	Use Table 3.1
	If $H_1 \leqslant 1.25\ H_b$ $Q = C_d C_v \frac{16}{25} (\frac{2}{5} g)^{1/2} \tan\frac{\theta}{2} h_1^{5/2}$ If $H_1 \geqslant 1.25\ H_b$ $Q = C_d C_v \frac{2}{3} (\frac{2}{3} g)^{1/2} B_c (h_1 - \frac{1}{2} H_b)^{3/2}$	$y_c = \frac{4}{5} H_1$ $y_c = \frac{2}{3} H_1 + \frac{1}{6} H_b$
	$Q = C_d C_v (\frac{3}{4} f_c g)^{1/2} h_1^2$	$y_c = \frac{3}{4} H_1$
	$Q = C_d d_c^{5/2} \sqrt{g}\ [f(\theta)]$ use table 7.2 to find f(θ)	Use Table 7.2
	If $H_1 \leqslant 0.70\ d_c$ $Q = C_d d_c^{5/2} \sqrt{g}\ [f(\theta)]$ use table 7.2 to find f(θ) If $H_1 \geqslant 0.70\ d_c$ $Q = C_d C_v \frac{2}{3} (\frac{2}{3} g)^{1/2} d_c (h_1 - 0.1073 d_c)^{3/2}$	Use Table 7.2 $y_c = \frac{2}{3} H_1 + 0.0358 d_c$

Figure 7.2 Head-discharge relationship for long-throated flumes (from Bos 1985)

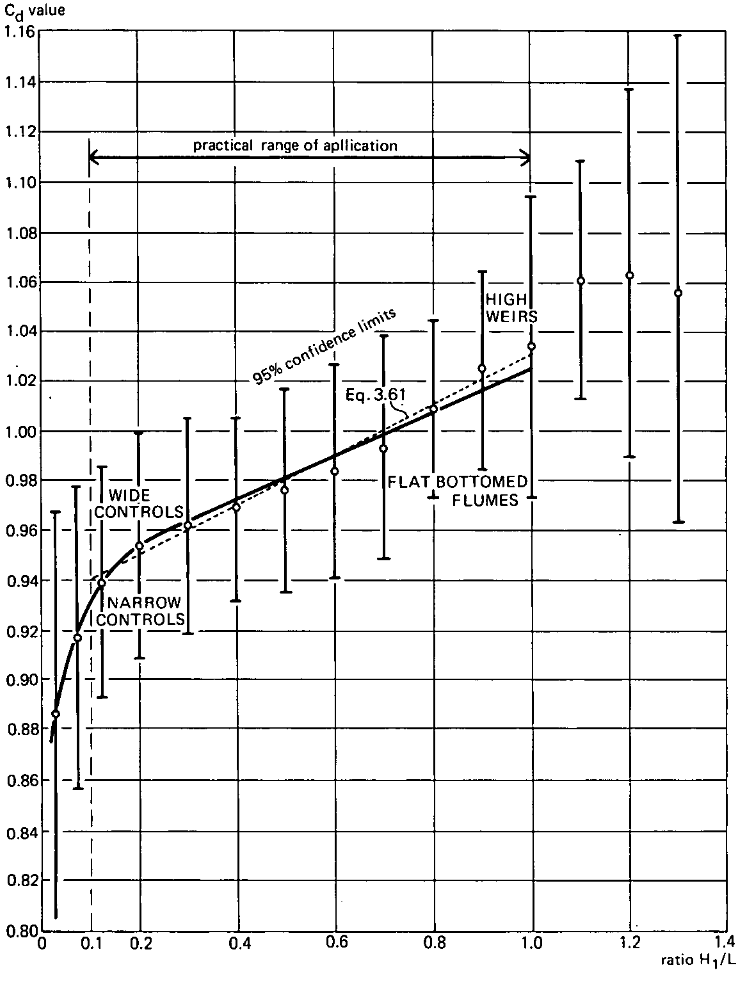


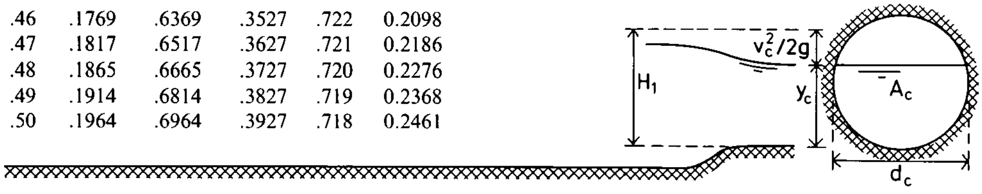
Figure 7.3 C_d values as a function of H_1/L for long-throated flumes of all shapes and sizes (Bos 1985)

Table 7.1 Values of the ratio y_c/H_1 as a function of z_c and H_1/b_c for trapezoïdal control sections

	Side slopes of channel, ratio of horizontal to vertical (z_c:1)									
H_1/b_c	Vertical	0.25:1	0.50:1	0.75:1	1:1	1.5:1	2:1	2.5:1	3:1	4:1
.00	.667	.667	.667	.667	.667	.667	.667	.667	.667	.667
.01	.667	.667	.667	.668	.668	.669	.670	.670	.671	.672
.02	.667	.667	.668	.669	.670	.671	.672	.674	.675	.678
.03	.667	.668	.669	.670	.671	.673	.675	.677	.679	.683
.04	.667	.668	.670	.671	.672	.675	.677	.680	.683	.687
.05	.667	.668	.670	.672	.674	.677	.680	.683	.686	.692
.06	.667	.669	.671	.673	.675	.679	.683	.686	.690	.696
.07	.667	.669	.672	.674	.676	.681	.685	.689	.693	.699
.08	.667	.670	.672	.675	.678	.683	.687	.692	.696	.703
.09	.667	.670	.673	.676	.679	.684	.690	.695	.698	.706
.10	.667	.670	.674	.677	.680	.686	.692	.697	.701	.709
.12	.667	.671	.675	.679	.684	.690	.696	.701	.706	.715
.14	.667	.672	.676	.681	.686	.693	.699	.705	.711	.720
.16	.667	.672	.678	.683	.687	.696	.703	.709	.715	.725
.18	.667	.673	.679	.684	.690	.698	.706	.713	.719	.729
.20	.667	.674	.680	.686	.692	.701	.709	.717	.723	.733
.22	.667	.674	.681	.688	.694	.704	.712	.720	.726	.736
.24	.667	.675	.683	.689	.696	.706	.715	.723	.729	.739
.26	.667	.676	.684	.691	.698	.709	.718	.725	.732	.742
.28	.667	.676	.685	.693	.699	.711	.720	.728	.734	.744
.30	.667	.677	.686	.694	.701	.713	.723	.730	.737	.747
.32	.667	.678	.687	.696	.703	.715	.725	.733	.739	.749
.34	.667	.678	.689	.697	.705	.717	.727	.735	.741	.751
.36	.667	.679	.690	.699	.706	.719	.729	.737	.743	.752
.38	.667	.680	.691	.700	.708	.721	.731	.738	.745	.754
.40	.667	.680	.692	.701	.709	.723	.733	.740	.747	.756
.42	.667	.681	.693	.703	.711	.725	.734	.742	.748	.757
.44	.667	.681	.694	.704	.712	.727	.736	.744	.750	.759
.46	.667	.682	.695	.705	.714	.728	.737	.745	.751	.760
.48	.667	.683	.696	.706	.715	.729	.739	.747	.752	.761
.5	.667	.683	.697	.708	.717	.730	.740	.748	.754	.762
.6	.667	.686	.701	.713	.723	.737	.747	.754	.759	.767
.7	.667	.688	.706	.718	.728	.742	.752	.758	.764	.771
.8	.667	.692	.709	.723	.732	.746	.756	.762	.767	.774
.9	.667	.694	.713	.727	.737	.750	.759	.766	.770	.776
1.0	.667	.697	.717	.730	.740	.754	.762	.768	.773	.778
1.2	.667	.701	.723	.737	.747	.759	.767	.772	.776	.782
1.4	.667	.706	.729	.742	.752	.764	.771	.776	.779	.784
1.6	.667	.709	.733	.747	.756	.767	.774	.778	.781	.786
1.8	.667	.713	.737	.750	.759	.770	.776	.781	.783	.787
2	.667	.717	.740	.754	.762	.773	.778	.782	.785	.788
3	.667	.730	.753	.766	.773	.781	.785	.787	.790	.792
4	.667	.740	.762	.773	.778	.785	.788	.790	.792	.794
5	.667	.748	.768	.777	.782	.788	.791	.792	.794	.795
10	.667	.768	.782	.788	.791	.794	.795	.796	.797	.798
∞		.800	.800	.800	.800	.800	.800	.800	.800	.800

Table 7.2 Ratios for determining the discharge Q of a broad-crested weir and long-throated flume with circular section (Bos 1985)

y_c/d_c	$v_c^2/2gd_c$	H_1/d_c	A_c/d_c^2	y_c/H_1	$f(\theta)$
.01	.0033	.0133	.0013	.752	0.0001
.02	.0067	.0267	.0037	.749	0.0004
.03	.0101	.0401	.0069	.749	0.0010
.04	.0134	.0534	.0105	.749	0.0017
.05	.0168	.0668	.0147	.748	0.0027
.06	.0203	.0803	.0192	.748	0.0039
.07	.0237	.0937	.0242	.747	0.0053
.08	.0271	.1071	.0294	.747	0.0068
.09	.0306	.1206	.0350	.746	0.0087
.10	.0341	.1341	.0409	.746	0.0107
.11	.0376	.1476	.0470	.745	0.0129
.12	.0411	.1611	.0534	.745	0.0153
.13	.0446	.1746	.0600	.745	0.0179
.14	.0482	.1882	.0688	.744	0.0214
.15	.0517	.2017	.0739	.744	0.0238
.16	.0553	.2153	.0811	.743	0.0270
.17	.0589	.2289	.0885	.743	0.0304
.18	.0626	.2426	.0961	.742	0.0340
.19	.0662	.2562	.1039	.742	0.0378
.20	.0699	.2699	.1118	.741	0.0418
.21	.0736	.2836	.1199	.740	0.0460
.22	.0773	.2973	.1281	.740	0.0504
.23	.0811	.3111	.1365	.739	0.0550
.24	.0848	.3248	.1449	.739	0.0597
.25	.0887	.3387	.1535	.738	0.0647
.26	.0925	.3525	.1623	.738	0.0698
.27	.0963	.3663	.1711	.737	0.0751
.28	.1002	.3802	.1800	.736	0.0806
.29	.1042	.3942	.1890	.736	0.0863
.30	.1081	.4081	.1982	.735	0.0922
.31	.1121	.4221	.2074	.734	0.0982
.32	.1161	.4361	.2167	.734	0.1044
.33	.1202	.4502	.2260	.733	0.1108
.34	.1243	.4643	.2355	.732	0.1174
.35	.1284	.4784	.2450	.732	0.1289
.36	.1326	.4926	.2546	.731	0.1311
.37	.1368	.5068	.2642	.730	0.1382
.38	.1411	.5211	.2739	.729	0.1455
.39	.1454	.5354	.2836	.728	0.1529
.40	.1497	.5497	.2934	.728	0.1605
.41	.1541	.5641	.3032	.727	0.1683
.42	.1586	.5786	.3130	.726	0.1763
.43	.1631	.5931	.3229	.725	0.1844
.44	.1676	.6076	.3328	.724	0.1927
.45	.1723	.6223	.3428	.723	0.2012
.46	.1769	.6369	.3527	.722	0.2098
.47	.1817	.6517	.3627	.721	0.2186
.48	.1865	.6665	.3727	.720	0.2276
.49	.1914	.6814	.3827	.719	0.2368
.50	.1964	.6964	.3927	.718	0.2461
.51	.2014	.7114	.4027	.717	0.2556
.52	.2065	.7265	.4127	.716	0.2652
.53	.2117	.7417	.4227	.715	0.2750
.54	.2170	.7570	.4327	.713	0.2851
.55	.2224	.7724	.4426	.712	0.2952
.56	.2279	.7879	.4526	.711	0.2952
.57	.2335	.8035	.4625	.709	0.3161
.58	.2393	.8193	.4724	.708	0.3268
.59	.2451	.8351	.4822	.707	0.3376
.60	.2511	.8511	.4920	.705	0.3487
.61	.2572	.8672	.5018	.703	0.3599
.62	.2635	.8835	.5115	.702	0.3713
.63	.2699	.8999	.5212	.700	0.3829
.64	.2765	.9165	.5308	.698	0.3947
.65	.2833	.9333	.5404	.696	0.4068
.66	.2902	.9502	.5499	.695	0.4189
.67	.2974	.9674	.5594	.693	0.4314
.68	.3048	.9848	.5687	.691	0.4440
.69	.3125	1.0025	.5780	.688	0.4569
.70	.3204	1.0204	.5872	.686	0.4701
.71	.3286	1.0386	.5964	.684	0.4835
.72	.3371	1.0571	.6054	.681	0.4971
.73	.3459	1.0759	.6143	.679	0.5109
.74	.3552	1.0952	.6231	.676	0.5252
.75	.3648	1.1148	.6319	.673	0.5397
.76	.3749	1.1349	.6405	.670	0.5546
.77	.3855	1.1555	.6489	.666	0.5698
.78	.3967	1.1767	.6573	.663	0.5855
.79	.4085	1.1985	.6655	.659	0.6015
.80	.4210	1.2210	.6735	.655	0.6180
.81	.4343	1.2443	.6815	.651	0.6351
.82	.4485	1.2685	.6893	.646	0.6528
.83	.4638	1.2938	.6969	.641	0.6712
.84	.4803	1.3203	.7043	.636	0.6903
.85	.4982	1.3482	.7115	.630	0.7102
.86	.5177	1.3777	.7186	.624	0.7312
.87	.5392	1.4092	.7254	.617	0.7533
.88	.5632	1.4432	.7320	.610	0.7769
.89	.5900	1.4800	.7384	.601	0.8021
.90	.6204	1.5204	.7445	.592	0.8293
.91	.6555	1.5655	.7504	.581	0.8592
.92	.6966	1.6166	.7560	.569	0.8923
.93	.7459	1.6759	.7612	.555	0.9297
.94	.8065	1.7465	.7662	.538	0.9731
.95	.8841	1.8341	.7707	.518	1.0248



7.1.3 Modular limit

The modular limit of flumes greatly depends on the shape of the downstream expansion. The relation between the modular limit and the angle of expansion, can be obtained from Section 1.15. Practice varies between very gentle and costly expansions of about 1-to-15, to ensure a high modular limit, and short expansions of 1-to-6. It is recommended that the divergences of each plane surface be not more abrupt than 1-to-6. If in some circumstances it is desirable to construct a short downstream expansion, it is better to truncate the transition rather than to enlarge the angle of divergence (see also Figure 1.35). At one extreme if no velocity head needs to be recovered, the downstream transition can be fully truncated. It will be clear from Section 1.15 that no expanding section will be needed if the tailwater level is always less than y_c above the invert of the flume throat.

At the other extreme, when almost all velocity head needs to be recovered, a transition with a gradual expansion of sides and bed is required. The modular limit of long-throated flumes with various control cross sections and downstream expansions can be estimated with the aid of Section 1.15.

As an example, we shall estimate the modular limit of the flume shown in Figure 7.4, flowing under an upstream head $h_1 = 0.20$ m at a flow rate of $Q = 0.0443\ m^3/s$. The required head loss Δh over the flume, and the modular limit H_2/H_1 are determined as follows

a. Cross-sectional area of flow at station where h_1 is measured equals

$$A_1 = b_1y_1 + z_1y_1^2 = 0.75 \times 0.35 + 1.0 \times 0.35^2 = 0.385\ m^2$$

$$v_1 = Q/A_1 = 0.0443/0.385 = 0.115\ m/s;$$

b. The upstream sill-referenced energy head equals

$$H_1 = h_1 + v_1^2/2g = 0.20 + 0.115^2/(2 \times 9.81) = 0.201\ m;$$

c. The discharge coefficient $C_d = 0.964$;

d. The exponent $u = 1.50$ (rectangular control section);

e. $C_d^{1/u} = 0.964^{1/1.50} = 0.976$;

f. For a rectangular control section $y_c = 2/3\ H_1 = 0.134$ m;

g. The average velocity at the control section is

$$v_c = \frac{Q}{y_cb_c} = \frac{0.0443}{0.134 \times 0.30} = 1.110\ m/s$$

h. With the 1-to-6 expansion ratio the value of ξ equals 0.66;

i. We tentatively estimate the modular limit at about 0.80. Hence, the related h_2-value is $0.80 \times 0.20 = 0.16$ m. Further

$$A_2 = b_2y_2 + z_2y_2^2 = 0.313\ m^2$$

$$v_2 = Q/A_2 = 0.141\ m/s$$

j. $\xi(v_c - v_2)^2/2gH_1 = 0.66(1.110-0.141)^2/(2 \times 9.81 \times 0.201) = 0.157$;

k. The energy losses due to friction downstream from the control section can be found by applying the Manning equation with the appropriate n-value to $L/3 = 0.20$ m of the throat, to the downstream transition length, $L_d = 0.90$ m, and to the canal

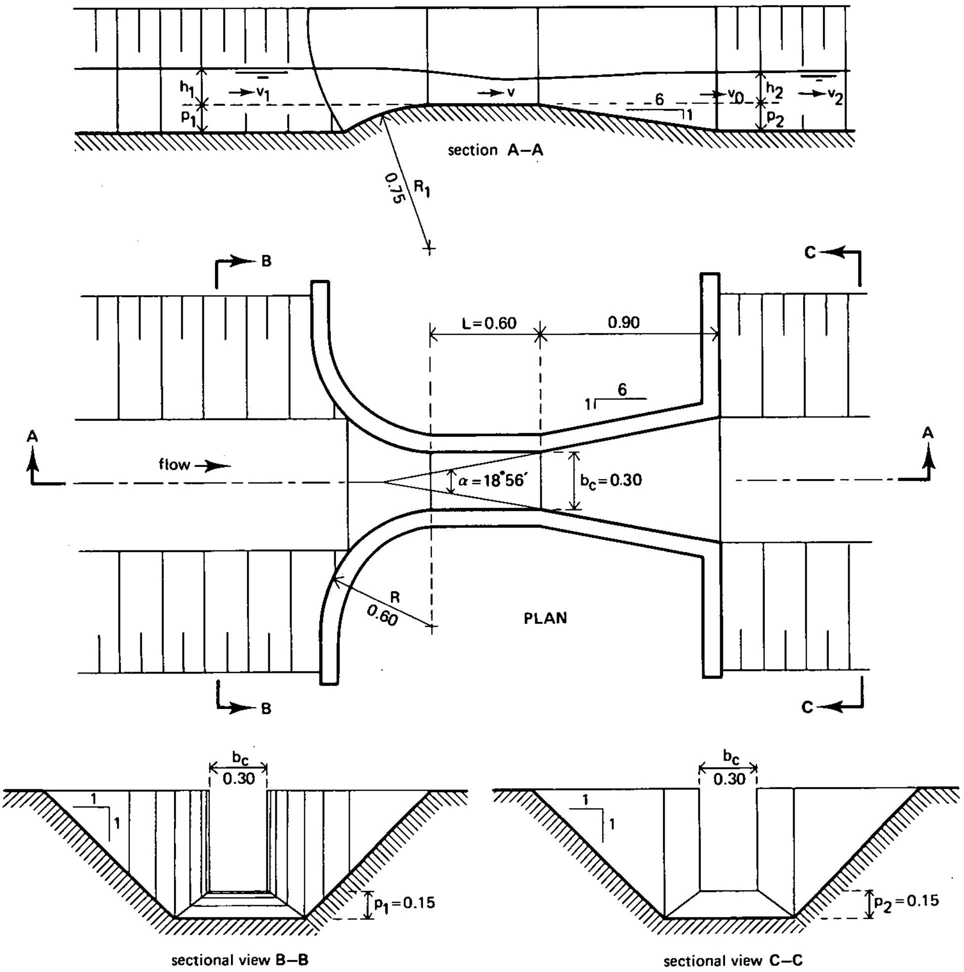


Figure 7.4 Long-throated flume dimensions (example)

up to the h_2 measurement section. The latter length equals (Bos 1984)

$$L_e = 10\,(p_2 + L/2) - L_d = 10\,(0.15 + 0.30) - 0.90 = 3.60\,\text{m}$$

Using a Manning n-value of 0.016 for the concrete flume and canal the friction losses are

$$\Delta H_{\text{throat}} = \frac{L}{3}\left(\frac{n\,v_c}{R_c^{2/3}}\right)^2 = 0.00239\,\text{m}$$

$$\Delta H_{\text{trans}} = L_d\left[\frac{n(v_c + v_2)}{2R_{\text{trans}}^{2/3}}\right]^2 = 0.00057\,\text{m}$$

$$\Delta H_{\text{canal}} = L_e\left(\frac{n\,v_2}{R_2^{2/3}}\right)^2 = 0.00016\,\text{m}$$

Hence $\Delta H_f \simeq 0.003$ m. It should be noted that for low h_1-values and relatively long transitions, the value of ΔH_f becomes significantly more important. The value of ΔH_f is relatively insensitive for minor changes of the tailwater depth y_2. Hence, for a subsequent pass through this step in the procedure the same ΔH_f-value may be used;

l. Calculate $\Delta H_f/H_1 = 0.003/0.201 = 0.015$;

m. The downstream sill-referenced energy head at the tailwater depth used at Step i equals

$$H_2 = h_2 + v_2^2/2g = 0.16 + 0.14^2/(2 \times 9.81) = 0.161 \text{ m}$$

n. The ratio H_2/H_1 equals then 0.801;

o. Substitution of the values of steps e, j, l, and n into Equation 1.125 gives at modular limit H_2/H_1

$$0.801 = 0.976 - 0.015 - 0.157 = 0.804$$

which is almost true. Hence, $h_1 - h_2 = 0.04$ m for this flume if $h_1 = 0.20$ m.

Once some experience has been acquired a close match of Equation 1.125 can be obtained in two to three iterations. Since the modular limit varies with the upstream head, it is advisable to estimate the modular limit at both minimum and maximum anticipated flow rates and to check if sufficient head loss is available.

The computer program FLUME (Clemmens et al. 1987) calculates the modular limit and head loss requirement for broad-crested weirs and long-throated flumes.

7.1.4 Limits of application

The limits of application of a long-throated flume for reasonably accurate flow measurements are:

a. The practical lower limit of h_1 is related to the magnitude of the influence of fluid properties, boundary roughness, and the accuracy with which h_1 can be determined. The recommended lower limit is 0.07 L;

b. To prevent water surface instability in the approach channel the Froude number $Fr = v_1/(gA_1/B_1)^{1/2}$ should not exceed 0.5;

c. The upper limitation on the ratio H_1/L arises from the necessity to prevent streamline curvature in the flume throat. Values of the ratio H_1/L should be less than 1.0;

d. The width B_c of the water surface in the throat at maximum stage should not be less than L/5;

e. The width at the water surface in a triangular throat at minimum stage should not be less than 0.20 m.

7.2 Throatless flumes with rounded transition

7.2.1 Description

Throatless flumes may be regarded as shorter, and thus cheaper, variants of the long-throated flumes described in Section 7.1. Although their construction costs are lower,

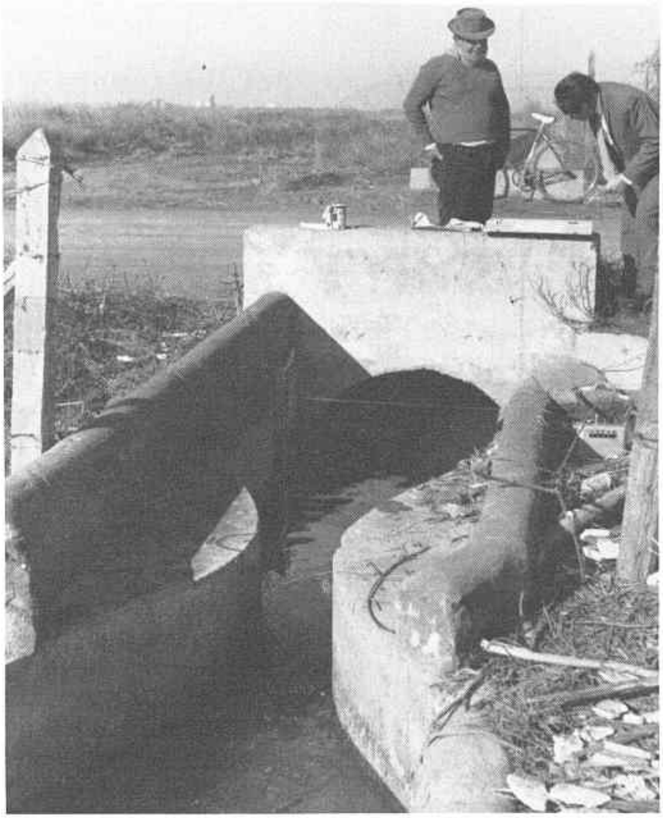


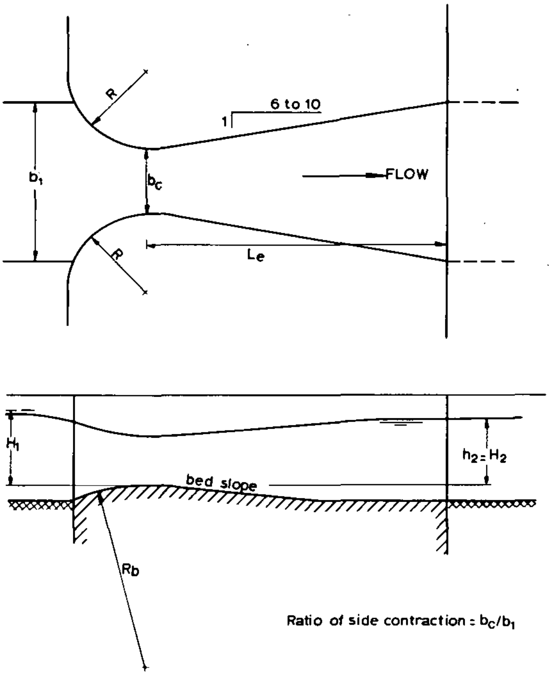
Photo 2 Throatles flume with rounded transaction

throatless flumes have a number of disadvantages, compared with long-throated flumes. These are:

- The discharge coefficient C_d is rather strongly influenced by H_1 and because of streamline curvature at the control section also by the shape of the downstream transition and by H_2;
- The modular limit varies with H_1 and has a lower value;
- The control section can only be rectangular;
- In general, the C_d-value has a rather high error of about 8 percent.

Two basic types of throatless flumes exist, one having a rounded transition between the converging section and the downstream expansion, and the other an abrupt (broken plane) transition. The first type is described in this section, the second in Section 7.3.

A throatless flume with rounded transition is shown in Figure 7.5. In contradiction to its shape, the flow pattern at the control section of such a flume is rather complicated and cannot be handled by theory. Curvature of the streamlines is three-dimensional, and a function of such variables as the contraction ratio and curvature of the side walls, shape of any bottom hump if present, shape of the downstream expansion, and



Ratio of side contraction : b_c/b_1

Figure 7.5 The throatless flume

the energy heads on both ends of the flume. Laboratory data on throatless flumes are insufficient to determine the discharge coefficient as a function of any one of the above parameters.

The Figure 7.6 illustrates the variations in C_d. Laboratory data from various investigators are so divergent that the influence of parameters other than the ratio H_1/R is evident.

7.2.2 Evaluation of discharge

The basic head-discharge equation for flumes with a rectangular control section equals

$$Q = C_d C_v \frac{2}{3}\sqrt{\frac{2}{3}}\, g\, b_c\, h_1^{3/2} \qquad (7\text{-}2)$$

From the previous section it will be clear that a C_d-value can only be given if we introduce some standard flume design. We therefore propose the following:

- The radius of the upstream wing walls, R, and the radius, R_b, of the bottom hump, if any, ranges between 1.5 H_{1max} and 2.0 H_{1max};
- The angle of divergence of the side walls and the bed slope should range between 1-to-6 and 1-to-10. Plane surface transitions only should be used;
- If the downstream expansion is to be truncated, its length should not be less than $1.5(B_2-b_c)$, where B_2 is the average width of the tailwater channel.

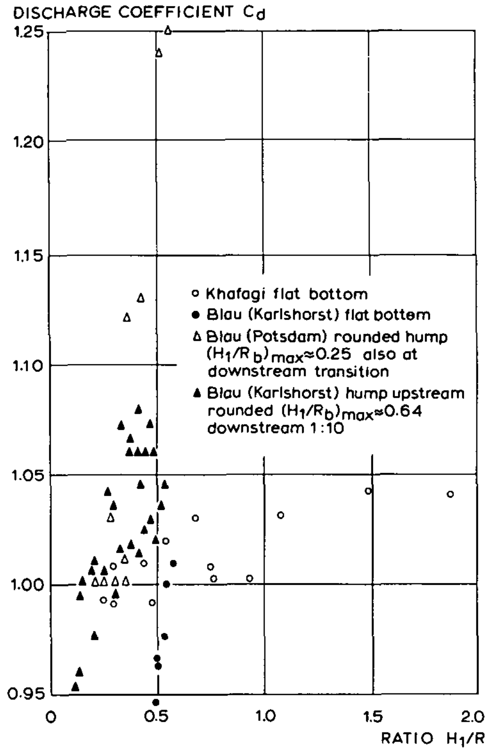


Figure 7.6 C_d-values for various throatless flumes

If this standard design is used, the discharge coefficient C_d equals about unity. The appropriate value of the approach velocity coefficient, C_v, can be read from Figure 1.12 (Chapter 1).

Even for a well-maintained throatless flume which has been constructed with reasonable care and skill, the error in the above indicated product C_dC_v is rather high, and can be expected to be about 8 percent. The method by which this coefficient error is to be combined with other sources of error is shown in Annex 2.

7.2.3 Modular limit

Investigating the modular limit characteristics of throatless flumes is a complex problem and our present knowledge is limited. Tests to date only scratch the surface of the problem, and are presented here mainly to illustrate the difficulties. Even if we take the simplest case of a flume with a flat bottom, the plot of H_2/H_1 versus H_1/b_c, presented in Figure 7.7 shows unpredictable variation of the modular limit for different angles of divergence and expansion ratios b_c/B_2.

It may be noted that Khafagi (1942) measured a decrease of modular limit with increasing expansion ratio b_c/B_2 for 1-to-8 and 1-to-20 flare angles. For long-throated flumes this tendency would be reversed and in fact Figure 7.7 shows this reversed

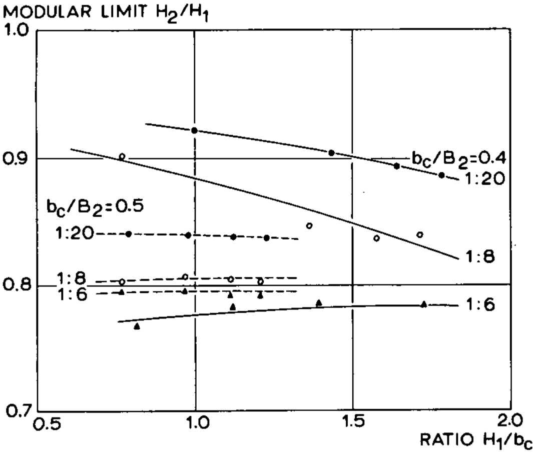


Figure 7.7 Modular limit conditions of flat bottomed throatless flumes (after Khafagi 1942)

trend for a 1-to-6 flare angle. The modular limits shown in Figure 7.7 are not very favourable if we compare them with long-throated flumes having the same b_c/B_2 ratio and an abrupt ($\alpha = 180°$) downstream expansion. The modular limit of the latter equal 0.70 if $b_c/B_2 = 0.4$ and 0.75 if $b_c/B_2 = 0.5$.

The variation in modular limit mentioned by Khafagi is also present in data reported by Blau (1960). Blau reports the lowest modular limit for throatless flumes, which equals 0.5; for $H_1/b_c = 0.41$, $A_c/A_2 = 0.21$, $b_c/B_2 = 0.49$, wingwall divergence and bed slope both 1-to-10.

There seems little correlation between the available data, which would indicate that the throatless flume is not a suitable modular discharge measurement structure if the ratio H_2/H_1 exceeds about 0.5.

7.2.4 Limits of application

The limits of application of a throatless flume with rounded transition for reasonably accurate flow measurements are:

a. Flume design should be in accordance with the standards presented in Section 7.2.2;
b. The practical lower limit of h_1 depends on the influence of fluid properties, boundary roughness, and the accuracy with which is h_1 can be determined. The recommended lower limit is 0.06 m;
c. To prevent water surface instability in the approach channel the Froude number $Fr = v_1/(gA_1/B_1)^{1/2}$ should not exceed 0.5;
d. The width b_c of the flume throat should not be less than 0.20 m nor less than H_{1max}.

7.3 Throatless flumes with broken plane transition

7.3.1 Description

The geometry of the throatless flume with broken plane transition was first developed in irrigation practice in the Punjab and as such is described by Harvey (1912). Later, Blau (1960) reports on two geometries of this flume type. Both sources relate discharge and modular limit to heads upstream and downstream of the flume, h_1 and h_2 respectively. Available data are not sufficient to warrant inclusion in this manual.

Since 1967 Skogerboe et al. have published a number of papers on the same flume, referring to it as the 'cutthroat flume'. In the cutthroat flume, however, the flume discharge and modular limit are related to the piezometric heads at two points, in the converging section (h_a) and in the downstream expansion (h_b) as with the Parshall flume. Cutthroat flumes have been tested with a flat bottom only. A dimension sketch of this structure is shown in Figure 7.8.

Because of gaps in the research performed on cutthroat flumes, reliable head-discharge data are only available for one of the tested geometries ($b_c = 0.305$ m, overall length is 2.743 m). Because of the non-availability of discharge data as a function of h_1 and h_2 (or H_1 and H_2) the required loss of head over the flume to maintain modularity is difficult to determine.

In the original cutthroat flume design, various discharge capacities were obtained by simply changing the throat width b_c. Flumes with a throat width of 1, 2, 3, 4, 5, and 6 feet (1 ft = 0.3048 m) were tested for heads h_a ranging from 0.06 to 0.76 m. All flumes were placed in a rectangular channel 2.44 m wide. The upstream wingwall had an abrupt transition to this channel as shown in Figure 7.8.

Obviously, the flow pattern at the upstream piezometer tap is influenced by the ratio b_c/B_1. Eggleston (1967) reports on this influence for a 0.3048 m wide flume. A variation of discharge at constant h_a up to 2 percent was found. We expect, however, that this variation will increase with increasing width b_c and upstream head. Owing to the changing entrance conditions it even is possible that the piezometer tap for

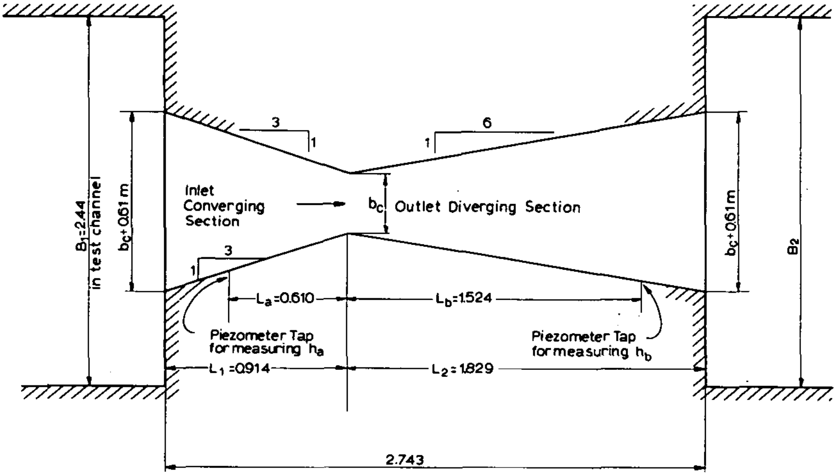


Figure 7.8 Cutthroat flume dimensions (after Skogerboe et al. 1967)