8320 old courthouse road • vienna virginia 22180

design data 36

american concrete pipe association

PARTIAL FLOW CONDITIONS ARCH CONCRETE PIPE

Sewers, both sanitary and storm, are designed to carry a peak flow based on anticipated land development. The hydraulic capacity of sewers or culverts constructed of precast arch concrete pipe flowing full under gravity conditions on a known slope is readily calculated from the Manning Formula. Most sewers, however, are designed to operate under partial flow conditions. Culverts operate under either inlet control or outlet control. The type of control under which a particular culvert operates is dependent upon all the hydraulic factors present. Culverts operating under inlet control will always flow partially full while those operating under outlet control can flow full or partially full.

Determination of the depth and velocity of flow in pipe flowing partially full is therefore frequently necessary. This design data presents a method for determining the values of the partial flow depth and velocity in arch concrete pipe through the use of a series of partial flow curves which eliminate tedious trial and error computations.

A complete discussion of the hydraulics of sewers is presented in Design Data 4, and the hydraulics of culverts is presented in Design Data 8.

HYDRAULICS OF CONCRETE PIPE

The most widely accepted formula for evaluating the hydraulic capacity of nonpressure pipe is the Manning Formula. This formula is:

$$Q = \frac{1.486}{n} \times A \times R^{2/3} \times S_o^{1/2} \qquad (1)$$

where

- Q = flow quantity, cubic feet per second
- n = Manning's roughness coefficient
- A = cross sectional area of flow, square feet
- R = hydraulic radius, feet
- S_o = slope, feet of vertical drop per foot of horizontal distance

Table I provides values of $S_o^{1/2}$. *Table II* lists the full flow area, A_F, hydraulic radius, R, and a constant, C_1. For a specific pipe size under full flow conditions, the first three terms of the right hand side of Manning's Formula equal a constant [$C_1 = (1.486/n) \times A \times R^{2/3}$]. Values of C_1 are presented for the more commonly used values, 0.010, 0.011, 0.012, and 0.013, for the roughness coefficient *n* for precast concrete pipe. Utilizing the appropriate value of $S_o^{1/2}$ from *Table I* and C_1 from *Table II*, the full flow quantity, Q_F, may be determined from Manning's Formula conveniently expressed as:

$$Q_F = C_1 \times S_o^{1/2} \qquad (2)$$

Once the full flow quantity, Q_F, has been determined, the average velocity, V_F, for full flow conditions may be calculated from the basic hydraulic relationship:

$$V_F = \frac{Q_F}{A_F} \qquad (3)$$

where

- Q_F = flow quantity, flowing full, cubic feet per second
- V_F = the average velocity, flowing full, feet per second
- A_F = cross sectional area, flowing full, square feet

PARTIAL FLOW HYDRAULIC ELEMENTS

For any size of pipe, curves showing the partial flow relationship of the hydraulic elements, flow quantity, area of flow, hydraulic radius, and velocity of flow in terms of the full flow conditions can be plotted. *Figure 1* provides such hydraulic element curves and *Table II* full flow values for the hydraulic radius for arch concrete pipe.

DESIGN METHOD

To determine the value of any one of the partial flow hydraulic elements for arch concrete pipe, the following three step design method is suggested:

1. Determine the full flow quantity, Q_F, and velocity, V_F, utilizing *Tables I* and *II* or other appropriate methods.
2. Determine the value of the ratio of partial flow to full flow of the known hydraulic elements.
3. Determine the values of the unknown hydraulic elements through the use of the partial flow curves.

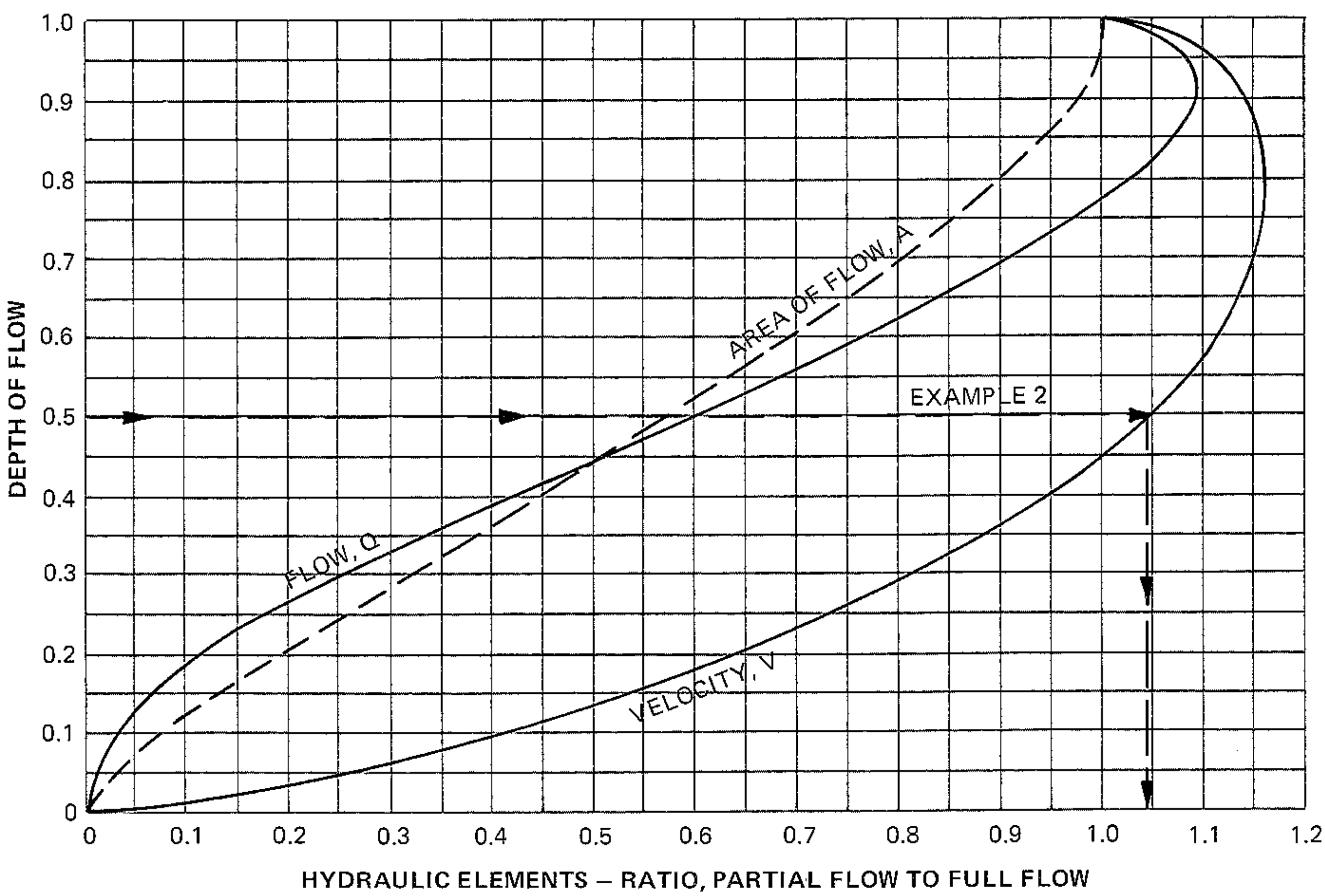
TABLE I: Values of $S_o^{1/2}$ in Manning's Formula.

S	—0	—1	—2	—3	—4	—5	—6	—7	—8	—9
.000	.00000	.01000	.01414	.01732	.02000	.02236	.02449	.02646	.02828	.03000
.001	.03162	.03317	.03464	.03606	.03742	.03873	.04000	.04123	.04243	.04359
.002	.04472	.04583	.04690	.04796	.04899	.05000	.05099	.05196	.05292	.05385
.003	.05477	.05568	.05657	.05745	.05831	.05916	.06000	.06083	.06164	.06245
.004	.06325	.06403	.06481	.06557	.06633	.06708	.06782	.06856	.06928	.07000
.005	.07071	.07141	.07211	.07280	.07348	.07416	.07483	.07550	.07616	.07681
.006	.07746	.07810	.07874	.07937	.08000	.08062	.08124	.08185	.08246	.08307
.007	.08367	.08426	.08485	.08544	.08602	.08660	.08718	.08775	.08832	.08888
.008	.08944	.09000	.09055	.09110	.09165	.09220	.09274	.09327	.09381	.09434
.009	.09487	.09539	.09592	.09644	.09695	.09747	.09798	.09849	.09899	.09950
.010	.10000	.10050	.10100	.10149	.10198	.10247	.10296	.10344	.10392	.10440
.01	.1000	.1049	.1095	.1140	.1183	.1225	.1265	.1304	.1342	.1378
.02	.1414	.1449	.1483	.1517	.1549	.1581	.1612	.1643	.1673	.1703
.03	.1732	.1761	.1789	.1817	.1844	.1871	.1897	.1924	.1949	.1975
.04	.2000	.2025	.2049	.2074	.2098	.2121	.2145	.2168	.2191	.2214
.05	.2236	.2258	.2280	.2302	.2324	.2345	.2366	.2387	.2408	.2429
.06	.2449	.2470	.2490	.2510	.2530	.2550	.2569	.2588	.2608	.2627
.07	.2646	.2665	.2683	.2702	.2720	.2739	.2757	.2775	.2793	.2811
.08	.2828	.2846	.2864	.2881	.2898	.2915	.2933	.2950	.2966	.2983
.09	.3000	.3017	.3033	.3050	.3066	.3082	.3098	.3114	3130	.3146
.10	.3162	.3178	.3194	.3209	.3225	.3240	.3256	.3271	.3286	.3302

TABLE II: Full Flow Coefficient Values Arch Concrete Pipe.

Pipe Size R x S (Inches)	Approximate Equivalent Circular Diameter (Inches)	A Area (Square Feet)	R Hydraulic Radius (Feet)	Value of $C_I = \frac{1.486}{n} \times A \times R^{2/3}$			
				n = 0.010	n = 0.011	n = 0.012	n = 0.013
11 x 18	15	1.1	0.25	65	59	54	50
13½ x 22	18	1.6	0.30	110	100	91	84
15½ x 26	21	2.2	0.36	165	150	137	127
18 x 28½	24	2.8	0.45	243	221	203	187
22½ x 36¼	30	4.4	0.56	441	401	368	339
26⅝ x 43¾	36	6.4	0.68	736	669	613	566
31⁵⁄₁₆ x 51⅛	42	8.8	0.80	1125	1023	938	866
36 x 58½	48	11.4	0.90	1579	1435	1315	1214
40 x 65	54	14.3	1.01	2140	1945	1783	1646
45 x 73	60	17.7	1.13	2851	2592	2376	2193
54 x 88	72	25.6	1.35	4641	4219	3867	3569
62 x 102	84	34.6	1.57	6941	6310	5784	5339
72 x 115	90	44.5	1.77	9668	8789	8056	7436
77¼ x 122	96	51.7	1.92	11850	10770	9872	9112
87⅛ x 138	108	66.0	2.17	16430	14940	13690	12640
96⅞ x 154	120	81.8	2.42	21975	19977	18312	16904
106½ x 168¾	132	99.1	2.65	28292	25720	23577	21763

FIGURE 1: Relative Velocity and Flow in Arch Pipe for Any Depth of Flow.



EXAMPLE 1

Given: An arch concrete sewer is designed to flow ¾ full with a design flow, Q, of 200 cubic feet per second. The slope is 0.01 and *n* is equal to 0.013.

Find: The required pipe size.

Solution: Enter *Figure 1* at a depth of flow of 0.75 on the vertical scale. Project a line to the flow curve, Q, and from the intersection, project a vertical line to the horizontal scale and read a value of 0.98 which represents the proportional value for full flow:

$$\frac{Q}{Q_F} = 0.98$$

Since the actual flow required is 200 cubic feet per second:

$$Q_F = \frac{200}{0.98}$$

$$Q_F = 204 \text{ cubic feet per second}$$

From *Table I*, the value of $S_o^{1/2}$ is 0.1, and using Equation 2, to calculate C_1:

$$C_1 = \frac{Q_F}{S_o^{1/2}}$$

$$C_1 = \frac{204}{0.1}$$

$$C_1 = 2040$$

Entering *Table II* with C_1 equal to 2040, and *n* equal to 0.013, the arch pipe with a C_1 value equal to, or greater than 2040 is 45 × 73-inch.

Answer: Select a 45 × 73-inch arch pipe.

EXAMPLE 2

Given: A 40 × 65-inch arch concrete pipe storm sewer outfall has an *n* value assumed as 0.012 and is to be installed on a 10 percent slope. To meet future expansion conditions, the pipe will be designed to flow ½ full.

Find: The outlet velocity.

Solution: Entering *Table II* at an arch size of 40 × 65 inches and an *n* value of 0.012, the C_1 value is 1783 and A_F is 14.3 square feet. From *Table I*, $S_o^{1/2}$ is 0.3162. From Equation 2:

$$Q_F = C_1 S_o^{1/2}$$

$$Q_F = 1783 \times 0.3162$$

$$Q_F = 564 \text{ cubic feet per second}$$

The full flow velocity can be calculated from Equation 3:

$$V_F = Q_F/A_F$$

$$V_F = 564/14.3$$

$$V_F = 39 \text{ feet per second}$$

Enter *Figure 1* at 0.5 on the vertical scale and project a horizontal line to the velocity curve, V. From this intersection, project a vertical line to the horizontal scale. The ratio of partial flow V to full flow V_F is 1.04:

$$\frac{V}{V_F} = 1.04$$

$$V = 39 \times 1.04$$

$$V = 41 \text{ feet per second}$$

Answer: The outlet velocity is 41 feet per second.