Partial Flow Conditions For Culverts

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 circular 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 circular 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 foot 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

Tables 1-3 list 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 $S_O^{1/2}$, and C_1 from *Tables 1-3*, 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 of flow, 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. *Figures 1-4* provide such hydraulic element curves for circular, elliptical and arch concrete pipe.

DESIGN METHOD

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

1. Determine the full flow quantity, Q_F, and velocity, V_F, utilizing *Tables 1-3* 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.

EXAMPLE 1

Given: A 48-inch diameter circular concrete pipe storm sewer, with *n* equal to 0.012 and flowing one-third full.

Find: Slope required to maintain a minimum velocity of 3 feet per second.

Solution: Enter *Figure 1* on the vertical scale at Depth of Flow = 0.33 and project a horizontal line to the curved line representing velocity. On the horizontal scale directly beneath the point of intersection read a value of 0.81 which represents the proportional value for full flow:

$$\frac{V}{V_F} = 0.81$$

Since the actual velocity required is 3 feet per second:

$$V_F = \frac{3}{0.81}$$

$$V_F = 3.7$$

Entering *Table 1* at a pipe diameter of 48 inches and an *n* value of 0.012, the C_1 value is 1556 and A_F is 12.566 square feet. Combining Equations 2 and 3 and solving for S_O:

$$S_O = \left[\frac{V_F A_F}{C_1}\right]^2$$

$$S_O = \left[\frac{(3.7)\ (12.566)}{1556}\right]^2$$

$$S_O = 0.00089 \text{ feet per foot}$$

Answer: The slope requires to maintain a minimum velocity of 3 feet per second at on-third full is 0.00089 feet per foot.

EXAMPLE 2

Given: A vertical elliptical concrete sewer is designed to flow 3/4 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 2* 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 0.87 which represents the proportional value for full flow:

$$\frac{Q}{Q_F} = 0.87$$

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

$$Q_F = \frac{200}{0.87}$$

$$Q_F = 230 \text{ cubic feet per second}$$

Using *Equation 2*, to calculate C_1 :

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

$$C_1 = \frac{230}{(0.01)^{1/2}}$$

$$C_1 = 2300$$

Entering *Table 2* with C_1 equal to 2300, and *n* equal to 0.013, the vertical elliptical pipe with a C_1 value equal to, or greater that 2300 is 76 x 48-inch.

Answer: Select a 76 x 48-inch vertical elliptical pipe.

EXAMPLE 3

Given: A 34 x 53-inch horizontal elliptical concrete pipe storm sewer outfall has an *n* value assumed to be 0.012 and is to be installed on a 10 percent slope. To meet future expansion conditions, the pipe will be designed to flow 1/2 full.

Find: The outlet velocity.

Solution: Entering *Table 2* at a horizontal elliptical size of 34 x 53 inches and an *n* value of 0.012, the C_1 value is 1156 and A_F is 10.2 square feet.
From *Equation 2*:

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

$$Q_F = 1156 \times (0.10)^{1/2}$$

$$Q_F = 366 \text{ cubic feet per second}$$

The full flow velocity can be calculated from *Equation 3*:

$$V_F = Q_F/A_F$$

$$V_F = 366/10.2$$

$$V_F = 36 \text{ feet per second}$$

Enter *Figure 3* at 0.5 on the vertical scale and project a horizontal line to the velocity curves. From this intersection, project a vertical line to the horizontal scale. The ratio of partial flow V to full flow V_F is 1.0:

$$\frac{V}{V_F} = 1.0$$

$$V = V_F \times 1.0$$

$$V = 36 \times 1.0$$

$$V = 36 \text{ feet per second}$$

Answer: The outlet velocity is 36 feet per second.

EXAMPLE 4

Given: A 40 x 65-inch arch concrete 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 1/2 full.

Find: The outlet velocity.

Solution: Enter *Table 3* at an arch size of 40 x 65 inches and an *n* value of 0.012, the C_1 value is 1783 and A_F is 14.3 square feet.
From Equation 2:

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

$$Q_F = 1783 \times (0.10)^{1/2}$$

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

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 4* 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.

Table 1 Full Flow Coefficient Values Circular Concrete Pipe

D Pipe Diameter (Inches)	A Area (Square Feet)	R Hydraulic Radius (Feet)	Value of $C_1 \frac{1.486}{n} \times A \times R^{2/3}$			
			n=0.010	n=0.011	n=0.012	n=0.013
8	0.349	0.167	15.8	14.3	13.1	12.1
10	0.545	0.208	28.4	25.8	23.6	21.8
12	0.785	0.205	46.4	42.1	38.6	35.7
15	1.227	0.312	84.1	76.5	70.1	64.7
18	1.767	0.375	137	124	114	105
21	2.405	0.437	206	187	172	158
24	3.142	0.500	294	267	245	226
27	3.976	0.562	402	366	335	310
30	4.909	0.625	533	485	444	410
33	5.940	0.688	686	624	574	530
36	7.069	0.750	867	788	722	666
42	9.621	0.875	1308	1189	1090	1006
48	12.566	1.000	1867	1698	1556	1436
54	15.904	1.125	2557	2325	2131	1967
60	19.635	1.250	3385	3077	2821	2604
66	23.758	1.375	4364	3967	3636	3357
72	28.274	1.500	5504	5004	4587	4234
78	33.183	1.625	6815	6195	5679	5242
84	38.485	1.750	8304	7549	6920	6388
90	44.170	1.875	9985	9078	8321	7684
96	50.266	2.000	11850	10780	9878	9119
102	56.745	2.125	19340	12670	11620	10720
108	63.617	2.250	16230	14760	13530	12490
114	70.882	2.375	18750	17040	15620	14420
120	78.540	2.500	21500	19540	17920	16540
126	86.590	2.625	24480	22260	20400	18830
132	95.033	2.750	27720	25200	23100	21330
138	103.870	2.875	31210	28370	26010	24010
144	113.100	3.000	34960	31780	29130	26890

Table 2 Full Flow Coefficient Values Elliptical Concrete Pipe

Pipe Size R x S (HE) S x R (VE) (Inches)	Approximate Equivalent Circular Diameter (Inches)	A Area (Square Feet)	R Hydraulic Radius (Feet)	Value of $C_1 \frac{1.486}{n} \times A \times R^{2/3}$			
				n=0.010	n=0.011	n=0.012	n=0.013
14 x 23	18	1.8	0.367	138	125	116	108
19 x 30	24	3.3	0.490	301	274	252	232
22 x 34	27	4.1	0.546	405	368	339	313
24 x 38	30	5.1	0.613	547	497	456	421
27 x 42	33	6.3	0.686	728	662	607	560
29 x 45	36	7.4	0.736	891	810	746	686
32 x 49	39	8.8	0.812	1140	1036	948	875
34 x 53	42	10.2	0.875	1386	1260	1156	1067
38 x 60	48	12.9	0.969	1878	1707	1565	1445
43 x 68	54	16.6	1.106	2635	2395	2196	2027
48 x 76	60	20.5	1.229	3491	3174	2910	2686
53 x 83	66	24.8	1.352	4503	4094	3753	3464
58 x 91	72	29.5	1.475	5680	5164	4734	4370
63 x 98	78	34.6	1.598	7027	6388	5856	5406
68 x 106	84	40.1	1.721	8560	7790	7140	6590
72 x 113	90	46.1	1.845	10300	9365	8584	7925
77 x 121	96	52.4	1.967	12220	11110	10190	9403
82 x 128	102	59.2	2.091	14380	13070	11980	11060
87 x 136	108	66.4	2.215	16770	15240	13970	12900
92 x 143	114	74.0	2.340	19380	17620	16150	14910
97 x 151	120	82.0	2.461	22190	20180	18490	17070
106 x 166	132	99.2	2.707	28630	26020	23860	22020
116 x 180	144	118.6	2.968	36400	33100	30340	28000

Table 3 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 $C_1 \frac{1.486}{n} \times A \times R^{2/3}$			
				n=0.010	n=0.011	n=0.012	n=0.013
11 x 18	15	1.1	0.25	65	59	54	50
$13^{1/2}$ x 22	18	1.6	0.30	110	100	91	84
$15^{1/2}$ x 26	21	2.2	0.36	165	150	137	127
18 x $28^{1/2}$	24	2.8	0.45	243	221	203	187
$22^{1/2}$ x $36^{1/4}$	30	4.4	0.56	441	401	368	339
$26^{5/8}$ x $43^{3/4}$	36	6.4	0.68	736	669	613	566
$3^{15/18}$ x $51^{1/8}$	42	8.8	0.80	1125	1023	938	866
36 x $58^{1/2}$	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
63 x102	84	34.6	1.57	6941	6310	5784	5339
72 x 115	90	44.5	1.77	9668	8789	8056	7436
$77^{1/4}$ x 122	96	51.7	1.92	11850	10770	9872	91122
$87^{1/8}$ x 138	108	66.0	2.17	16430	14940	13690	12640
$96^{7/8}$ x 154	120	81.8	2.42	21975	19977	18312	16904
$106^{1/2}$ x $168^{3/4}$	132	99.1	2.65	28292	25720	23577	21763

Figure 1 Relative Velocity and Flow in Circular Pipe for Any Design Depth or Flow

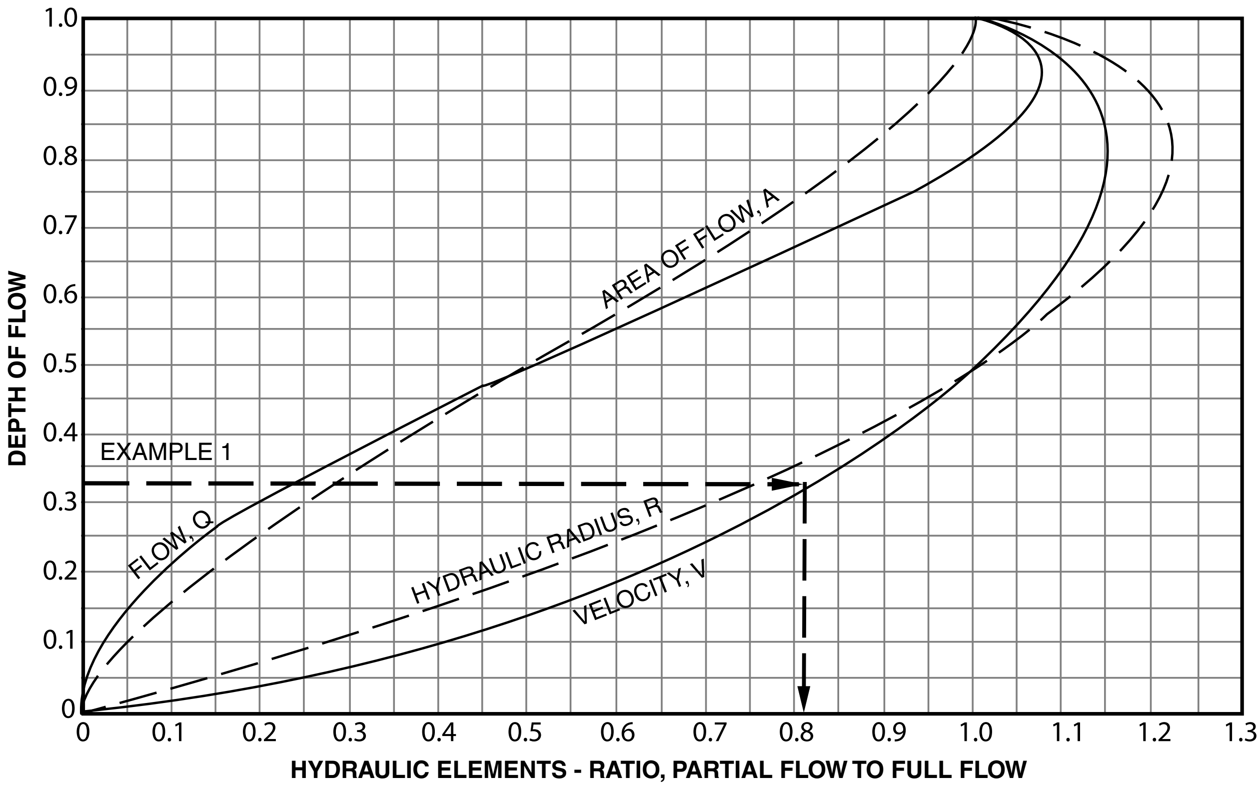

Figure 2 Relative Velocity and Flow in Vertical Elliptical Pipe for Any Depth of Flow

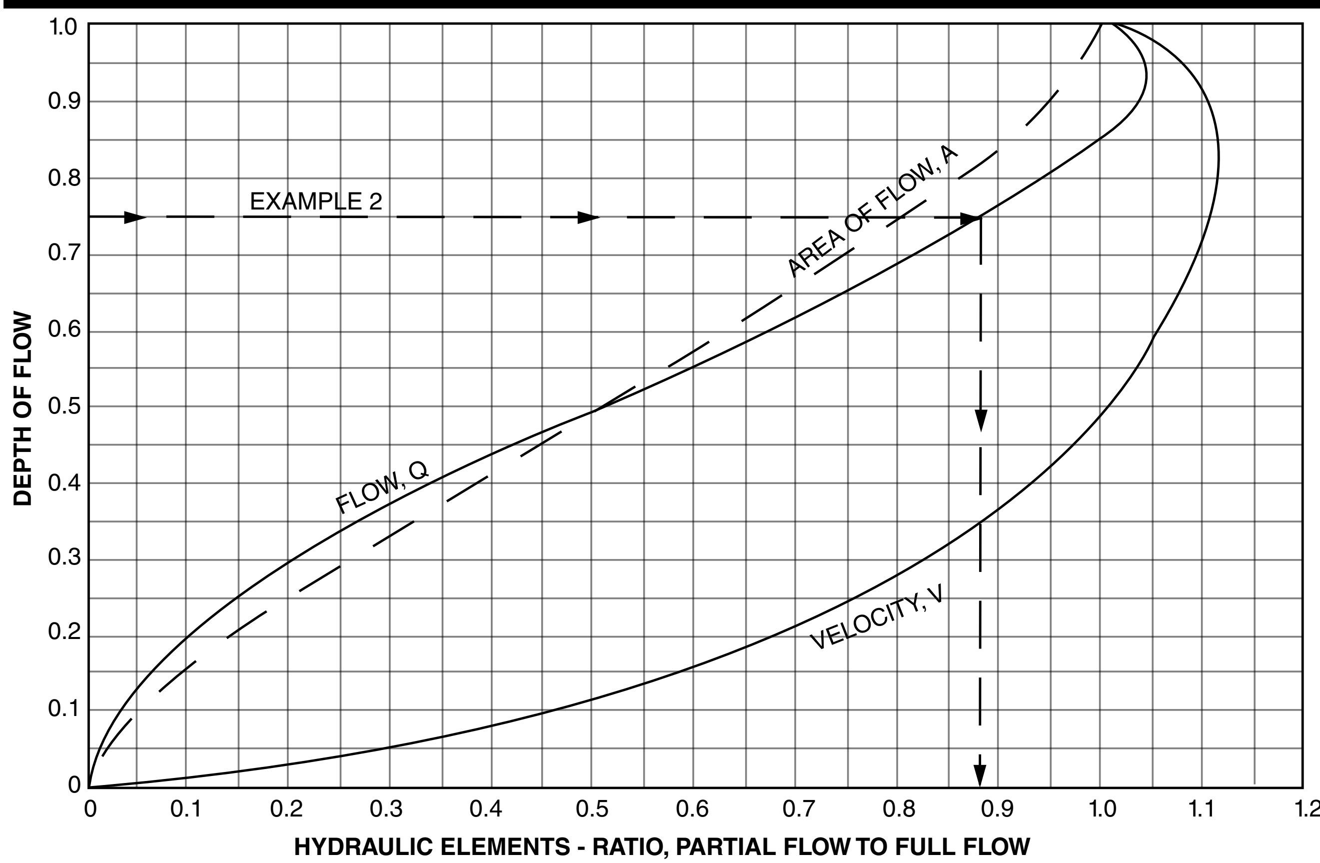

Figure 3 Relative Velocity and Flow in Horizontal Elliptical Pipe for Any Depth of Flow

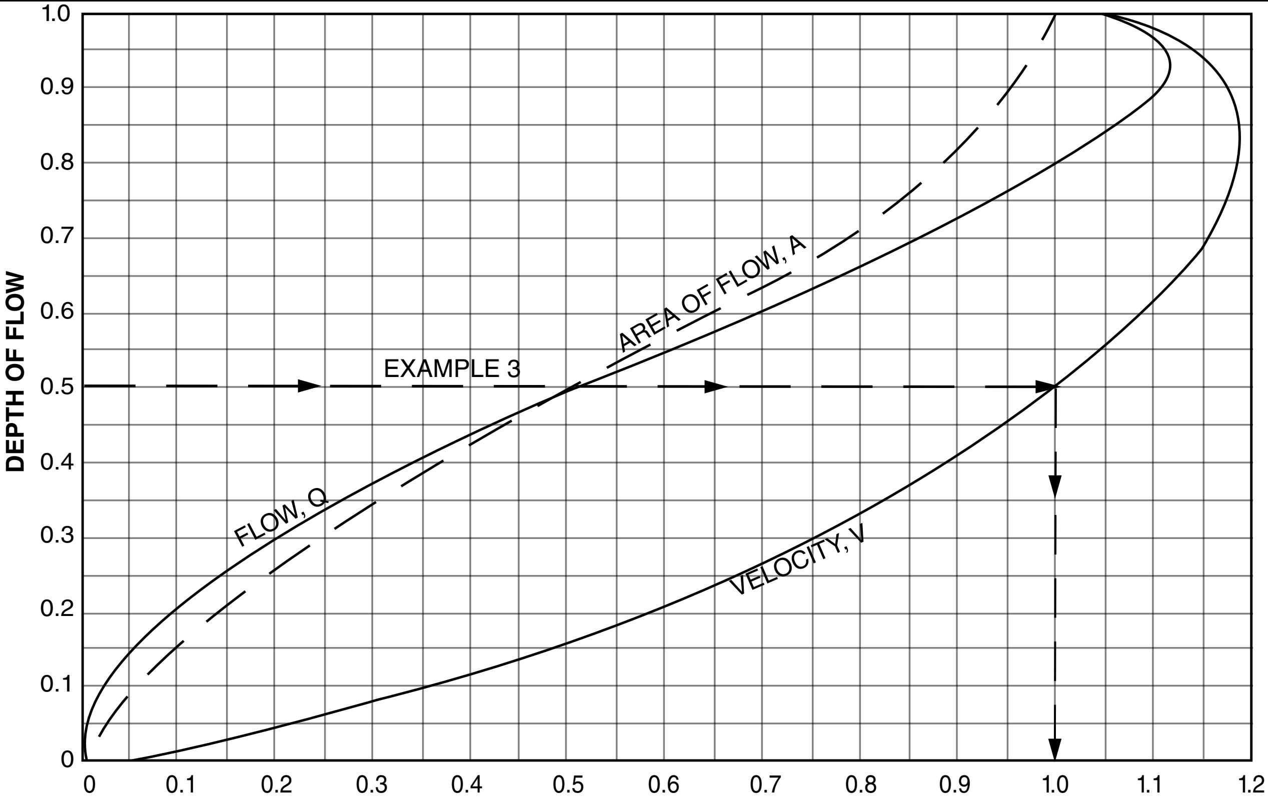

Figure 4 Relative Velocity and Flow in Arch Pipe for Any Depth of Flow