Design Data 16M

American Concrete Pipe Association

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:

$$Q = \frac{1.0}{n} \times A \times R^{2/3} \times S_o^{1/2} \qquad (1)$$

Where:

Q = flow quantity, cubic meters per second
n = Manning's roughness coefficient
A = cross-sectional area of flow, square meters
R = hydraulic radius, meters
S_O = slope, meters 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 [$C_1 = (1/n) \times A \times R^{2/3}$]. 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 meters per second
V_F = the average velocity, flowing full, meters per second
A_F = cross-sectional area of flow, flowing full, square meters

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 1200 mm 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 0.91 meters 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 0.91 meters per second:

$$V_F = \frac{0.91}{0.81}$$

$$V_F = 1.123$$

Entering *Table 1* at a pipe diameter of 1200mm and an *n* value of 0.012, the C_1 value is 44.04 and A_F is 1.167 square meters.

Combining Equations 2 and 3 and solving for S_O:

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

$$S_O = \left[\frac{(1.123)\ (1.167)}{44.04}\right]^2$$

$$S_O = 0.00089 \text{ meters per meter}$$

Answer: The slope requires to maintain a minimum velocity of 0.91 meters per second at on-third full is 0.00089 meters per meter.

EXAMPLE 2

Given: A vertical elliptical concrete sewer is designed to flow ¾ full with a design flow, Q, of 5.66 cubic meters 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 5.66 cubic meters per second:

$$Q_F = \frac{5.66}{0.87}$$

$$Q_F = 6.51 \text{ cubic meters per second}$$

Using *Equation 2*, to calculate C_1 :

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

$$C_1 = \frac{6.51}{(0.01)^{1/2}}$$

$$C_1 = 65.1$$

Entering *Table 2* with C_1 equal to 65.1, and *n* equal to 0.013, the vertical elliptical pipe with a C_1 value equal to, or greater that 65.1 is 1930 x 1219-mm.

Answer: Select a 1930 x 1219mm vertical elliptical pipe.

EXAMPLE 3

Given: A 864 x 1346mm 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 864 x 1346mm and an *n* value of 0.012, the C_1 value is 31.99 and A_F is 0.913 square meters.
From *Equation 2*:

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

$$Q_F = 31.99 \text{ x } (0.10)^{1/2}$$

$$Q_F = 10.12 \text{ cubic meters per second}$$

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

$$V_F = Q_F/A_F$$

$$V_F = 10.12/0.913$$

$$V_F = 11.08 \text{ per second}$$

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:

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

$$V = V_F \text{ x } 1.0$$

$$V = 11.08 \text{ x } 1.0$$

$$V = 11.08 \text{ per second}$$

Answer: The outlet velocity is 11.08 per second.

EXAMPLE 4

Given: A 1016 x 1651mm 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 1016 x 1651mm and an *n* value of 0.012, the C_1 value is 50.47 and A_F is 1.328 square meters.
From Equation 2:

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

$$Q_F = 50.47 \text{ x } (0.10)^{1/2}$$

$$Q_F = 15.96 \text{ cubic meters per second}$$

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

$$V_F = Q_F/A_F$$

$$V_F = 15.96/1.328$$

$$V_F = 12.02 \text{ meters per second}$$

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:

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

$$V = 12.02 \text{ x } 1.04$$

$$V = 12.50 \text{ meters per second}$$

Answer: The outlet velocity is 12.50 meters per second.

Table 1 Full Flow Coefficient Values Circular Concrete Pipe

D Pipe Diameter (Mm)	A Area (Square Meters)	R Hydraulic Radius (Meters)	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
200	0.032	0.051	0.444	0.403	0.370	0.341
250	0.051	0.064	0.807	0.733	0.672	0.620
300	0.073	0.076	1.314	1.194	1.095	1.011
375	0.114	0.095	2.378	2.162	1.982	1.829
450	0.164	0.114	3.862	3.511	3.218	2.971
525	0.233	0.133	5.821	5.292	4.851	4.478
600	0.292	0.153	8.342	7.584	6.952	6.417
675	0.369	0.171	11.354	10.322	9.461	8.734
750	0.456	0.191	15.098	13.726	12.582	11.614
825	0.552	0.210	19.455	17.686	16.213	14.965
900	0.656	0.229	24.523	22.294	20.436	18.864
1050	0.894	0.267	37.053	33.684	30.877	28.502
1200	1.167	0.305	52.852	48.047	44.043	40.655
1350	1.478	0.343	72.478	65.889	60.398	55.752
1500	1.824	0.381	95.869	87.153	70.891	73.745
1650	2.206	0.419	123.532	112.302	102.944	95.025
1800	2.627	0.457	155.938	141.762	129.949	119.953
1950	3.082	0.495	192.934	175.394	160.778	148.411
2100	3.573	0.533	234.977	213.616	195.814	180.752
2250	4.104	0.572	282.653	256.957	235.544	217.425
2400	4.668	0.610	335.588	305.080	279.657	258.145
2550	5.273	0.648	394.727	358.842	328.939	303.636
2700	5.909	0.686	459.535	417.759	382.946	353.489
2850	6.587	0.724	531.104	482.822	442.586	408.541
3000	7.297	0.762	608.728	553.389	507.273	468.525
3200	8.042	0.800	693.080	630.072	577.566	533.138
3350	8.830	0.838	785.005	713.641	654.171	603.850
3500	9.649	0.876	883.523	803.203	736.269	679.633
3600	10.509	0.915	990.328	900.298	825.273	761.791

Table 2 Full Flow Coefficient Values Elliptical Concrete Pipe

Pipe Size Rise x Span (mm)	Approximate Equivalent Circular Diameter (mm)	A Area (Square Meters)	R Hydraulic Radius (Meters)	Value of C_1 $\frac{1.486}{n}$ x A x $R^{2/3}$			
				n=0.010	n=0.011	n=0.012	n=0.013
355 x 584	450	0.163	0.113	3.815	3.468	3.179	2.935
483 x 762	600	0.289	0.151	8.191	7.446	6.826	6.301
559 x 864	675	0.379	0.176	11.914	10.831	9.928	9.164
610 x 965	750	0.462	0.193	15.447	14.043	12.872	11.882
686 x 1067	825	0.575	0.128	20.847	18.951	17.372	16.036
737 x 1143	900	0.662	0.230	24.866	22.606	20.722	19.128
813 x 1245	975	0.795	0.255	31.996	29.088	26.664	24.613
864 x 1346	1050	0.913	0.272	38.389	34.899	31.991	29.530
965 x 1524	1200	1.155	0.302	51.948	47.225	43.290	39.960
1092 x 1727	1350	1.481	0.344	72.667	66.061	60.556	55.898
1219 x 1930	1500	1.848	0.386	97.948	89.044	81.623	75.345
1346 x 2108	1650	2.228	0.423	125.620	114.200	104.684	96.631
1473 x 2311	1800	2.674	0.465	160.538	145.944	133.782	123.491
1600 x 2489	1950	3.128	0.503	197.713	179.739	164.761	152.087
1727 x 2692	2100	3.651	2.134	605.230	550.209	504.358	465.561
1829 x 2870	2250	4.123	0.574	284.768	258.880	237.307	219.053
1956 x 3073	2400	4.721	0.616	341.911	310.828	284.926	263.008
2083 x 3251	2550	5.319	2.590	1003.066	911.878	835.888	771.589
2210 x 3454	2700	5.995	0.696	470.714	427.922	392.262	362.088
2337 x 3632	2850	6.666	0.733	541.824	492.567	451.520	416.788
2464 x 3835	3000	7.422	0.775	626.205	569.277	521.838	481.696
2692 x 4216	3300	8.914	0.846	797.481	724.983	664.567	613.447
2946 x 4572	3600	10.579	0.921	1001.042	910.038	834.202	770.032

Table 3 Full Flow Coefficient Values Arch Concrete Pipe

Pipe Size R x S (mm)	Approximate Equivalent Circular Diameter (mm)	A Area (Square Meters)	R Hydraulic Radius (Meters)	Value of C_1 $\frac{1.486}{n}$ x A x $R^{2/3}$			
				n=0.010	n=0.011	n=0.012	n=0.013
279 x 457	375	0.102	0.076	1.837	1.670	1.531	1.413
343 x 559	450	0.149	0.091	3.017	2.743	2.514	2.321
394 x 660	525	0.204	0.110	4.684	4.259	3.904	3.603
457 x 724	600	0.260	0.137	6.918	6.289	5.765	5.322
572 x 908	750	0.409	0.171	12.578	11.434	10.481	9.675
676 x 1111	900	0.595	0.207	20.823	18.930	17.353	16. 018
803 x 1299	1050	0.818	0.244	31.908	29.007	26.590	24.545
914 x 1486	1200	1.059	0.274	44.712	40.647	37.260	34.394
1016 x 1651	1350	1.328	0.308	60.568	55.062	50.473	46.591
1143 x 1854	1500	1.644	0.344	80.795	73.450	67.329	62.150
1371 x 2235	1800	2.378	0.411	131.569	119.609	109.641	101.207
1575 x 2591	2100	3.214	0.479	196.653	178.776	163.878	151.272
1829 x 2921	2250	4.134	0.539	273.969	249.063	228.307	210.745
1962 x 3099	2400	4.803	0.585	336.034	305.486	280.029	258.488
2213 x 3505	2700	6.131	0.661	465.453	423.139	387.878	358.041
2461 x 3912	3050	7.599	0.738	620.377	563.979	516.981	477.213
2705 x 4286	3350	9.206	0.808	798.479	725.890	665.399	614.214

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

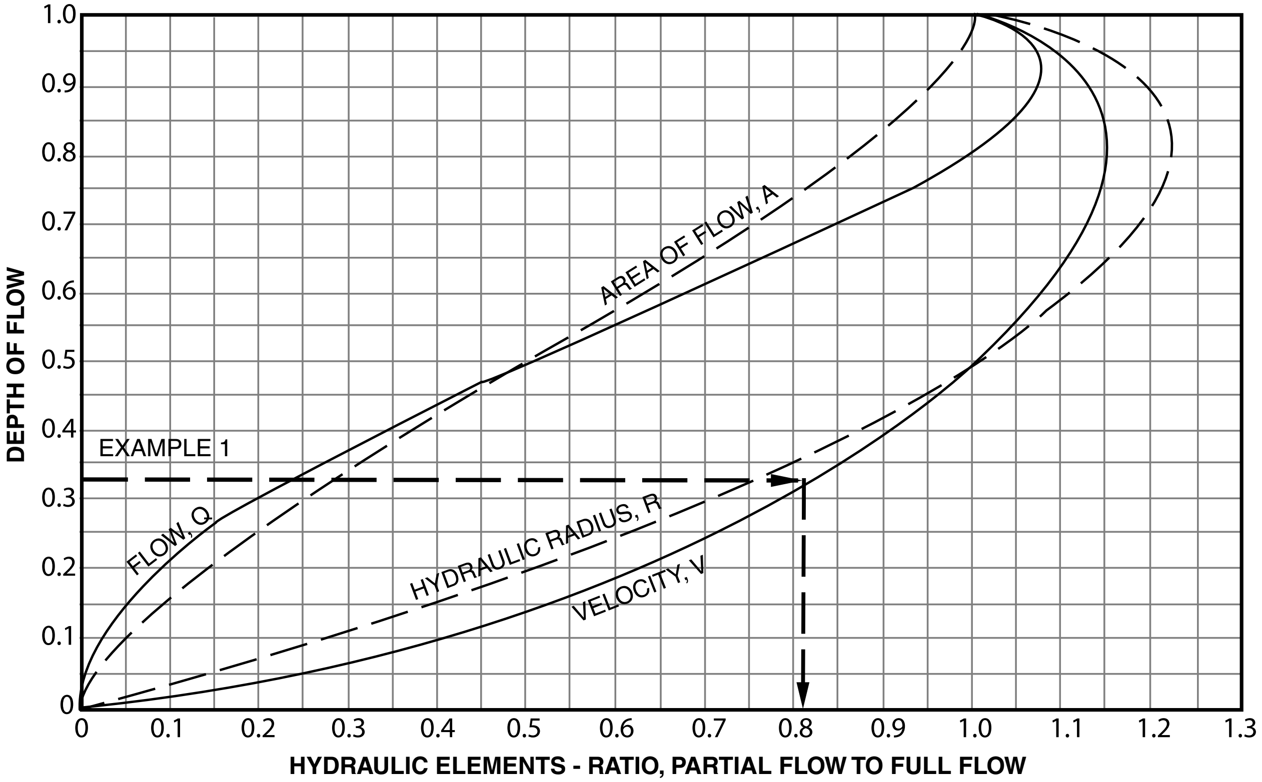

Figure 2 Relative Velocity and Flow in Vertical Elliptical Pipe for Any Depth of Flow

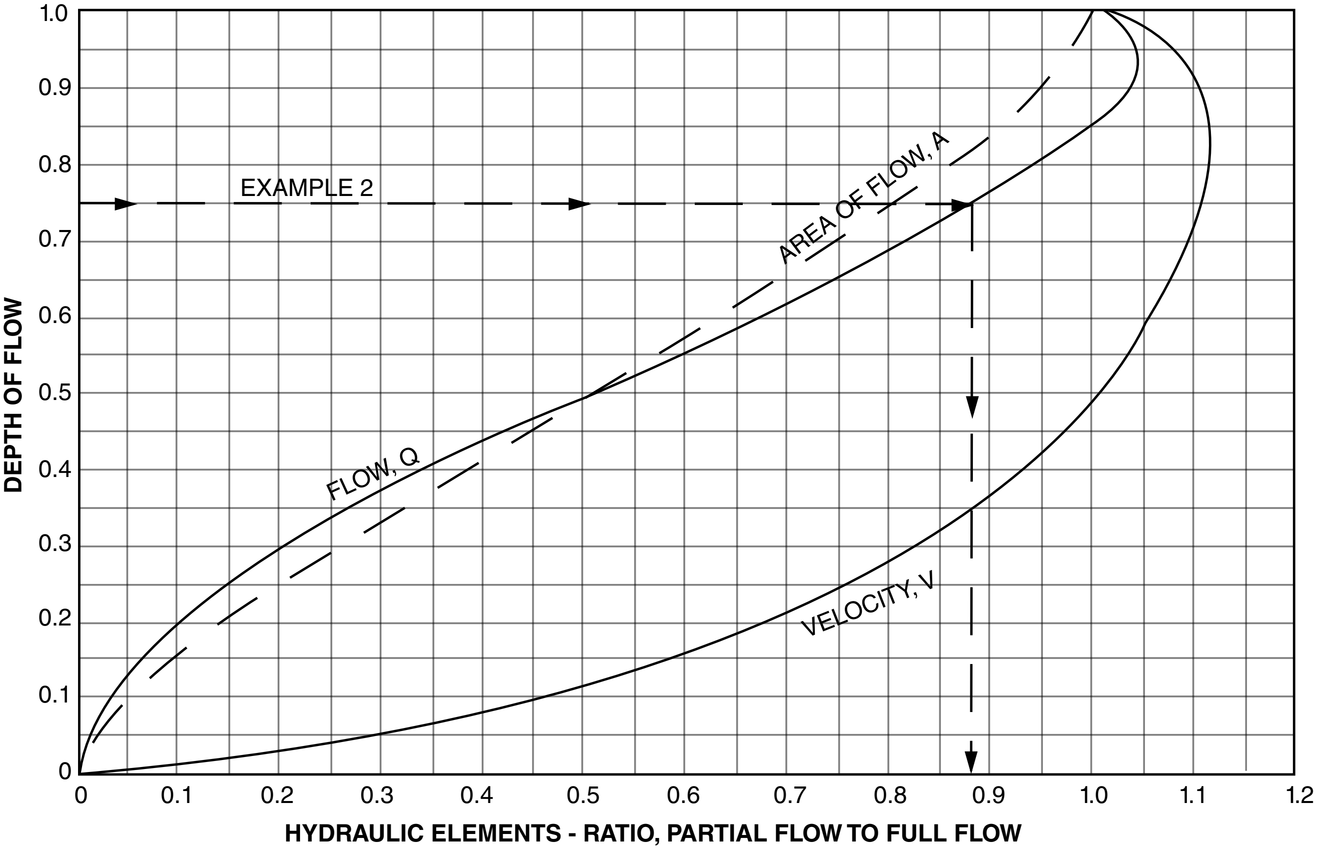

Figure 3 Relative Velocity and Flow in Horizontal Elliptical Pipe for Any Depth of Flow

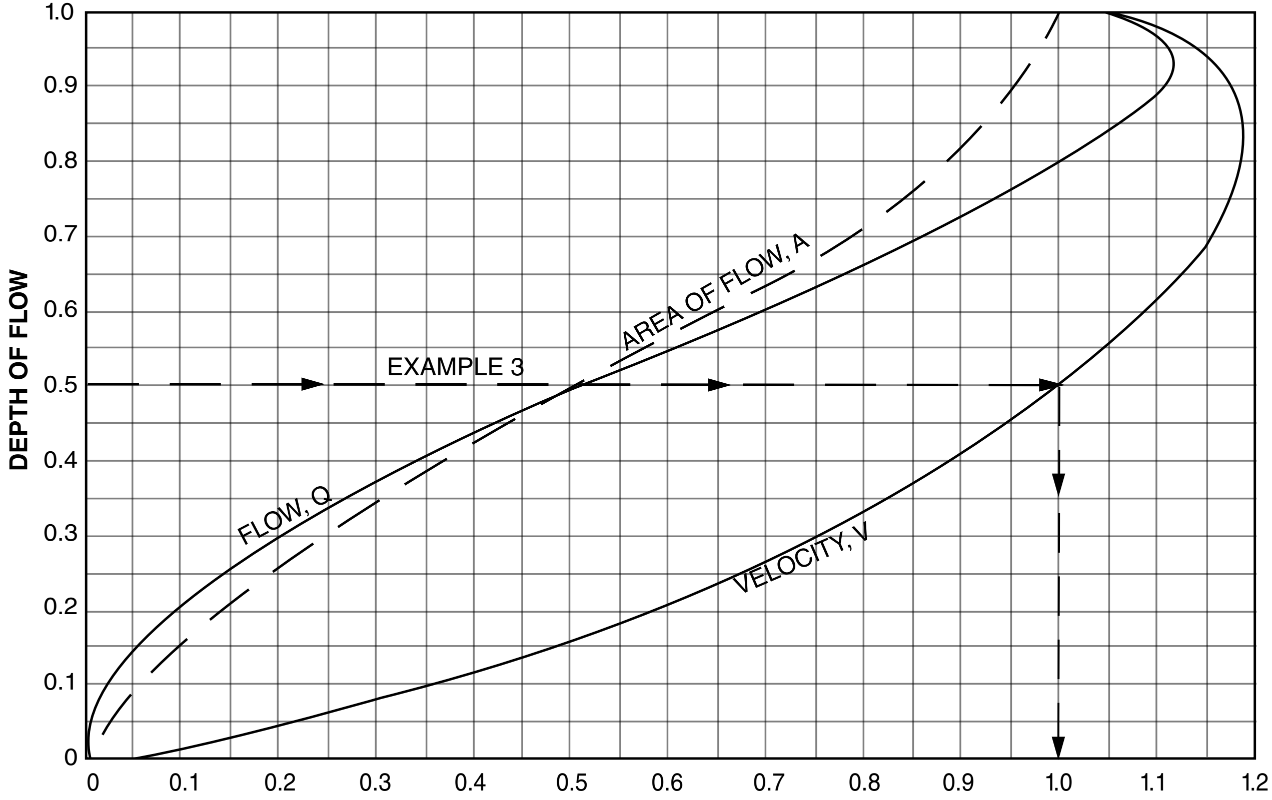

Figure 4 Relative Velocity and Flow in Arch Pipe for Any Depth of Flow