Appendix B: Collection System Information

FILE

CALCULATION COVER PAGE

Metcalf & Eddy	**JOB NO.** 60001707	**DEPARTMENT/ DISCIPLINE/ TECHNOLOGY** Engineering	**REVISION NO.** 0

SUBJECT/ TITLE

Honokaa PER Validation Calculation for Partial Flow in Circular Pipes

REV. NO.	ORIGINATOR SIGNATURE / DATE	REVIEWER SIGNATURE / DATE
0	Bert Saito, August 31, 2005	Martin Nakasone

CALCULATION DESCRIPTION

The purpose of this calculation is to validate an Excel spreadsheet for the calculations of full flow vs. partial flow in a circular pipe. The validation calculations also include the calculation of critical depth in a partial flow circular pipe. A check of the calculation will be made by comparing results with the ISCO Open Channel Flow Measurement Handbook.

CALCULATION METHODOLOGY/ ASSUMPTIONS

Use Manning Equations.

CODES / REFERENCES / INPUTS

Design Standards for the Department of Wastewater Management, City and County of Honolulu, volume 1
Hydraulic Theory of partial flow in circular pipes: www.alansmith.com/theory-Pipe-Design.htm
ISCO Open Channel Flow Measurement Handbook.

CONCLUSIONS

Part 1. Introduction

The purpose of this calculation is to validate partial flow depths in circular pipes using the Manning's Equation. Data will be checked with ISCO Open Channel Flow Measurement Handbook. The full calculations will be completed through Excel Spreadsheets.

Part 2. Design Criteria

The Design Standards for the City and County of Honolulu. The County of Hawaii wastewater standards defaults to the City and County of Honolulu design standards.

Definition of Variables:

$$Q = \frac{M}{n} \mathrm{AreaRad}^{\frac{2}{3}} S^{\frac{1}{2}} \quad \text{Manning's Equation}$$

$$1 = \frac{Q^2 B}{g\mathrm{Area}^3} \quad \text{Critical Depth Energy Equation}$$

$$B = 2\left(Dd_c - d_c^2\right)^{0.5} \quad \text{Free surface width}$$

$$\mathrm{Area}_a = \frac{D^2}{8}\left(2\mathrm{acos}\left(1 - \frac{2d}{D}\right) - \sin\left(2\mathrm{acos}\left(1 - \frac{2d}{D}\right)\right)\right)$$

$$P_a = D\left(\mathrm{acos}\left(\frac{D - 2d}{D}\right)\right)$$

Q = Flow rate
M = 1.49 factor to convert metric to english
Area_a = Area
P_a = Wetted perimeter
Rad = Hydraulic radius $R = \frac{A}{P}$
S = Bed slope = energy grade line (assume to be the same)
D = Pipe Diameter
Q_r = Qpartial/Qfull
D_r = d/D
ϕ = Angle (see sketch from www.alansmith.com)
B = Free water surface width
d_c = critical depth = y_c
d_n = normal depth

Part 3. Calculations

Determine Q_r and D_r and export results to Excel Spreadsheet

$d := 8\text{in}$ Guess $\quad D := 10\text{in}$ $\quad \text{cfs} := \frac{\text{ft}^3}{\text{s}}$ $\quad \text{mgd} := 10^{-6}\,\frac{\text{gal}}{\text{d}}$

$$Q_r = \frac{\text{Qactual}}{\text{Qfull}}$$

Given

$$Q_r = \left[\frac{\frac{D^2}{8}\left(2\ \text{acos}\left(1-\frac{2\ d}{D}\right)-\sin\left(2\ \text{acos}\left(1-\frac{2\ d}{D}\right)\right)\right)}{\frac{\pi D^2}{4}}\ \frac{\left[\frac{\frac{D^2}{8}\left(2\ \text{acos}\left(1-\frac{2\ d}{D}\right)-\sin\left(2\ \text{acos}\left(1-\frac{2\ d}{D}\right)\right)\right)}{D\left(\text{acos}\left(\frac{D-2\ d}{D}\right)\right)}\right]^{\frac{2}{3}}}{\left(\frac{D}{4}\right)^{\frac{2}{3}}}\right]$$

$\text{Depth}\left(Q_r\right) := \text{Find}(d)$

$k := 1, 2 .. 1076$

$$Q_{r_k} := \frac{k}{1000}$$

$$y_k := \text{Depth}\left(Q_{r_k}\right)$$

$$D_{r_k} := \frac{y_k}{D}$$

$$\text{Area}_k := \frac{D^2}{8}\left(2\ \text{acos}\left(1-\frac{2\ y_k}{D}\right)-\sin\left(2\ \text{acos}\left(1-\frac{2\ y_k}{D}\right)\right)\right)$$

$$\text{Area}_{r_k} := \frac{\text{Area}_k}{D^2}$$

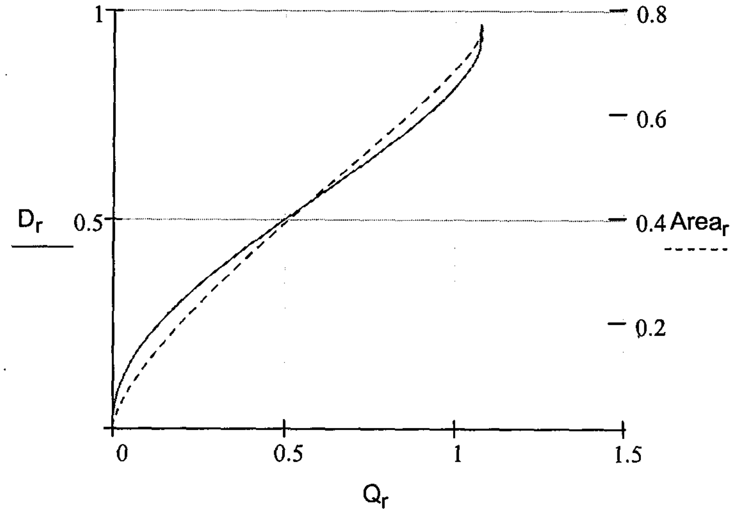
ExcelData :=

1.071	0.91248	0.751797		
1.072	0.958468	0.774255		
1.073	0.955679	0.773124		
1.074	0.952228	0.771677		
1.075	0.928561	0.760492		
1.076	0.938181	0.765289		

$$\left(Q_r \quad D_r \quad \text{Area}_r\right)$$

The exported data matches ISCO data.

Graph Results



Determine Critical Depth

$d_c := 1\,\mathrm{in}$ Guess

Given

$$\frac{Q_c^{2}\left[2\left(D\,d_c - d_c^{2}\right)^{0.5}\right]}{g\left[\frac{D^{2}}{8}\left(2\,\mathrm{acos}\left(1-\frac{2\,d_c}{D}\right)-\sin\left(2\,\mathrm{acos}\left(1-\frac{2\,d_c}{D}\right)\right)\right)\right]^{3}} = 1$$

$\mathrm{CriticalDepth}(Q_c, D) := \mathrm{Find}(d_c)$

$i := 1, 2 .. 1000$

$Q_{c_i} := \frac{i}{100}\mathrm{cfs}$

$y_{c6_i} := \mathrm{CriticalDepth}\left(Q_{c_i}, 6\mathrm{in}\right)$

$y_{c8_i} := \mathrm{CriticalDepth}\left(Q_{c_i}, 8\mathrm{in}\right)$

Export results to Excel

Excel2 :=

9.97	0.499997	0.666596				
9.98	0.499997	0.666596				
9.99	0.499997	0.666596				
10	0.499997	0.666596				

$$\left(Q_c \quad y_{c6} \quad y_{c8}\right)$$

Hydraulic Theory

Pipe Design

From the MIDUSS Version 2
Reference Manual - Chapter 8
(c) Copyright Alan A. Smith Inc.

This section summarizes the hydraulic principles which are used in MIDUSS for the analysis and design of pipes. Flow is assumed to be uniform within each reach of pipe, so that the depth and other cross-sectional properties are constant along the length of the pipe. It follows that the bed slope *S0*, the water surface and the slope of the energy line *Sf* are all parallel. The resistance is assumed to be represented by the Manning equation:

$$[8.1] \qquad Q = \frac{M}{n} A R^{2/3} S_0^{1/2}$$

where *Q* = normal discharge (c.m/s or c.ft/s)

M = 1.0 for metric units

1.49 for imperial or US customary units

n = Manning's roughness coefficient

A = cross-sectional area

R = hydraulic radius = Area/Wetted perimeter

S0 = bed slope (m/m or ft/ft)

No allowance is made for any apparent variation of 'n' with the relative depth of flow in the pipe.

Normal Depth in Pipes

Design makes the difference

Latest Update:
v2.07 Rev386
August 11, 2005

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View the results of our May 2004 User survey. No marketing fluff, just the facts. **Click here.**

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For a part-full circular section the cross-sectional properties are expressed in terms of the angle ϕ subtended at the centre by the free surface as shown in Figure 8.1.

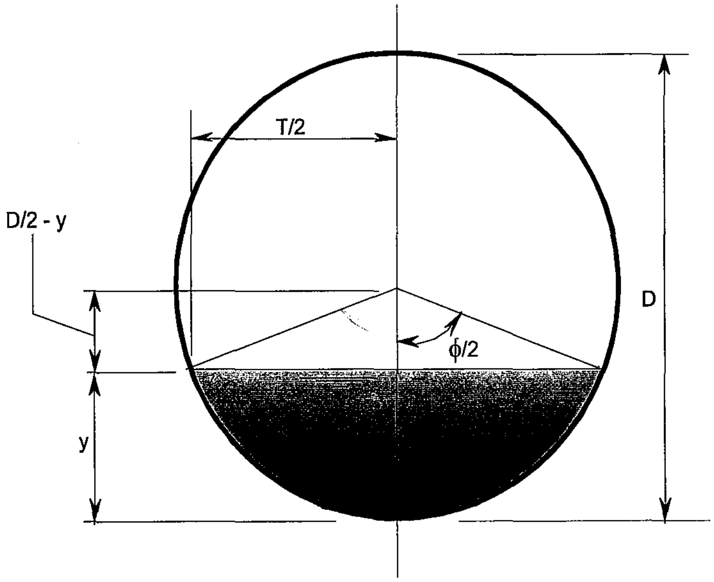

Figure 8.1 - Definition sketch of a part-full pipe.

The following equations can be obtained by considering the geometry of the triangle subtending the half-angle $\phi/2$ at the centre of the pipe.

$$y = \frac{D}{2}\left(1 - \cos\frac{\phi}{2}\right) \tag{8.2}$$

$$A = \frac{D^2}{8}(\phi - \sin\phi) \tag{8.3}$$

$$P = D\frac{\phi}{2} \tag{8.4}$$

The value of ϕ can be found in terms of the ratio of the discharge Q to the full-bore pipe capacity *Qfull* by an iterative solution of the implicit equation [8.5].

$$f(\phi) = \phi - \sin\phi - C_2 = 0 \tag{8.5}$$

where

$$C_2 = C_1\phi^{2/5} = \left(\frac{2\pi Q}{Q_{full}}\right)^{3/5}\phi^{2/5}$$

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Malaysia

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Equation [8.5] is solved by a Newton-Raphson procedure, thus:

$$[8.6] \qquad \phi_{k+1} = \phi_k - \Delta\phi_k = \phi_k - \frac{f(\phi_k)}{f'(\phi_k)}$$

where

$$f(\phi) = \phi - \sin(\phi) - C_2$$

and

$$f'(\phi) = 1 - \cos(\phi) - 0.4\frac{C_2}{\phi}$$

Equation [8.6] is applied until $\Delta\phi < 0.001$ radians; the depth is then determined from equation [8.7].

$$[8.7] \qquad y = \frac{D}{2}\left(1 - \cos\frac{\phi}{2}\right)$$

For a cross-section with a closed top it is usual to find that maximum normal discharge occurs at a depth slightly below full-bore flow. For a circular pipe this occurs at a relative depth of $y/D = 0.93818$. It follows that there must be a smaller depth which produces a discharge equal to the full-bore flow. In a part-full pipe this occurs when $y/D = 0.81963$.

The root finding procedure in MIDUSS will always find a solution within the relative depth range $0.0 < (y/D) < 0.81963$ as long as the discharge is less than the full-bore flow. If the discharge is greater than this then MIDUSS reports that the pipe will be surcharged and the slope of the hydraulic grade line is reported. (See Chapter 4 *Design Options Available,* Surcharged Pipe Design)

It is not possible, therefore, to take advantage of the slightly higher carrying capacity in the range $0.81963<(y/D)<1.0$. It is not normally good practice to design pipes for uniform flow in this range of depth because the slightest surface disturbance will cause the free surface to 'snap through' abruptly to a condition of pressurized flow.

Critical Depth in Pipes

When a pipe is designed it is often important to know if the normal flow depth $y0$ is less than or greater than the critical depth ycr. If $y0 < ycr$ then the flow is supercritical and there is a high probability that a hydraulic jump will occur at some point downstream. This is usually to be avoided.

The calculation of critical depth in a circular pipe is based on the critical flow condition of minimum specific energy which leads to the criterion of equation [8.8].

$$\text{[8.8]} \qquad \frac{Q^2T}{gA^3} = 1$$

This is solved by an interval halving procedure using a function of the form:-

$$\text{[8.9]} \qquad f(y) = \frac{A^3}{T} - \frac{Q^2}{g} = 0$$

in which *A* is obtained by combining equation [8.3] with equations [8.10] and [8.11] below.

$$\frac{ft^{2\cdot\cdot 6}}{ft}$$

$$ft^5 - \left(\frac{ft}{\cancel{s^2}}\right)^{\cancel{5}} \cdot \frac{\cancel{s}}{ft}$$

$$\text{[8.10]} \qquad T = 2\sqrt{\left(Dy - y^2\right)}$$

$$\text{[8.11]} \qquad \phi = 2\tan^{-1}\left(\frac{T/2}{\left(D/2 - y\right)}\right) = 2\tan^{-1}\left(\frac{T}{D-2y}\right)$$

Convergence is assumed when $\Delta y/y < 0.00001$.

Equation [8.9] cannot be solved if the free-surface width *T* is zero. A test is therefore made to ensure that the specified discharge is not greater than the critical discharge corresponding to a depth of $ycr = 0.999\,D$. If this condition is violated MIDUSS assumes the critical depth to be equal to the diameter. For further information on uniform or critical flow in pipes see a text on Open Channel Flow such as Henderson (References).

$$\frac{\left[\frac{D^2}{8}\left(2\tan^{-1}\left(\frac{2(D\cdot y - y^2)^{1/2}}{D-2y}\right) - \sin\left(2\tan^{-1}\left(\frac{\overset{2(Dy-y^2)^{1/2}}{\cancel{T}}}{D-2y}\right)\right)\right)\right]^3}{2(Dy - y^2)^{1/2}} - \frac{Q^2}{g} = 0$$

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Q

Find y

Section 2. Flow in Conduits

Open Channel Flow or Pressure Flow

When a conduit is not submerged, the principles of open channel flow apply. When the conduit is submerged, pressure flow exists because the water surface is not open to the atmosphere, and the principles of conduit flow apply. For circular pipes flowing full, Equation 6-3 becomes:

Equation 6-16:

$$Q = \frac{z}{n} D^{8/3} S^{1/2}$$

where:

Q = discharge (cfs or m^3/s)

z = 0.4644 for English measurement or 0.3116 for metric.

n = Manning 's roughness coefficient

D = pipe diameter, ft. or m

S = slope of the energy gradeline (ft./ft. or m/m) (For uniform, steady flow, S = channel

slope, ft./ft. or m/m).

Depth in Conduits

The equations for critical depth apply to conduits, too. Determine critical depth for a rectangular conduit using Equation 6-12 and the discharge per barrel. Calculate critical depth for circular and pipe-arch or irregular shapes by trial and error use of Equation 6-13. For a circular conduit, use Equation 6-17 and Equation 6-18 to determine the area, A, and top width, T, of flow, respectively. For other shapes, acquire or derive relationships from depth of flow, area, and top width.

Equation 6-17:

$$A = \frac{D^2}{8}\left[2\cos^{-1}\left(1 - \frac{2d}{D}\right) - \sin\left(2\cos^{-1}\left(1 - \frac{2d}{D}\right)\right)\right]$$

Equation 6-18:

$$T = D\sin\left(\cos^{-1}\left(\frac{2d - D}{D}\right)\right)$$

where:

A = section area of flow, sq. ft. or m^2

T = width of water surface, ft. or m

d = depth of flow, ft. or m

D = pipe diameter, ft. or m

the $\cos^{-1}(\theta)$ is the principal value in the range $0 \leq \theta \leq \pi$.

Use Equation 6-3 to determine uniform depth. For most shapes, a direct solution of Equation 6-3 for depth is not possible. The Slope Conveyance Procedure discussed in Chapter 7 is applicable. For rectangular shapes, area, A, and wetted perimeter, WP, are simple functions of flow depth. For circular pipe, compute area using Equation 6-17, and wetted perimeter is computed using Equation 6-19. For other shapes, acquire or derive the relationship from depth of flow, area, and wetted perimeter.

Refer to the table below for recommended Manning 's roughness coefficients for conduit.

Equation 6-19:

$$WP = D\cos^{-1}\left(1 - \frac{2d}{D}\right)$$

Roughness Coefficients

The following table provides roughness coefficients for conduits.

Recommended Culvert Conduit Roughness Coefficients

Type of Conduit	n-Value
Concrete Box	0.012
Concrete Pipe	0.012
Smooth-lined metal pipe	0.012
Smooth lined plastic pipe	0.012
Corrugated metal pipe	0.015-0.027
Structural plate pipe	0.027-0.036
Long span structural plate	0.031
Corrugated metal (paved interior)	0.012
Plastic	0.012-0.024

Energy

The energy equation, Equation 6-6, applies to conduit flow, too. Additionally, the following concepts apply to conduit flow.

- For pressure flow, the depth, d, represents the distance from the flowline to the hydraulic grade line.
- For pressure flow, the slope of the energy grade line and hydraulic grade line through the

Existing Honokaa Collection System Gravity Sewer

Pipe Material	PVC	
"n" coefficient	0.015	Design Standards for the Department of WW Management, vol 1
Upstream	Honokaa Hospital	
Downstream	Honokaa WWTP	
Start of SMH	Upstream	

SL-"A"

Manhole	Invert, ft	Station, ft	Pipe size, inch	Direction, deg	Length, ft	EGL Slope, ft/ft	Qa, mgd	Va, fps	Qf, mgd	Vf, fps
SMH-A1	1186.07	0+00.00								
			6	205.00	91.47	13.70%	0.168	6.537	1.163	9.17
SMH-A2	1173.54	0+91.47								
			6	205.00	115.90	13.70%	0.168	6.537	1.163	9.17
SMH-A3	1157.66	2+07.37								
			6	205.00	215.34	6.36%	0.168	4.958	0.792	6.24
SMH-A4	1143.97	4+22.71								
			6	191.80	272.83	8.32%	0.168	5.466	0.907	7.14
SMH-A5*	1121.27	6+95.54								
			8	194.76	363.30	8.32%	0.168	5.299	1.952	8.65
SMH-A6	1091.05	10+58.84								
			8	189.44	214.75	8.73%	0.168	5.388	1.999	8.86
SMH-A7*	1072.31	12+73.59								
			8	189.22	188.30	8.73%	0.168	5.388	1.999	8.86
SMH-LCC	1055.88	14+61.90								
Subtotal										

SL-"B"

Manhole	Invert, ft	Station, ft	Pipe size, inch	Direction, deg	Length, ft	EGL Slope, ft/ft	Qa, mgd	Va, fps	Qf, mgd	Vf, fps
SMH-LCC	1055.88	0+00.00								
			8	196.57	5.00	57.60%	[redacted]	[redacted]	5.137	22.77
SMH-B1	1053.00	0+05.00								
			8	196.57	195.00	11.79%	0.168	6.007	2.325	10.30
SMH-B2	1030.00	2+00.00								
			8	196.57	350.00	14.29%	0.168	6.455	2.558	11.34
SMH-B3	980.00	5+50.00								
			8	196.57	200.00	13.00%	0.168	6.253	2.440	10.82
SMH-B4	954.00	7+50.00								
			8	196.57	120.00	10.00%	0.168	5.677	2.140	9.49
SMH-B5	942.00	8+70.00								
			8	196.57	50.00	16.00%	0.168	6.674	2.707	12.00
SMH-B6	934.00	9+20.00								
	930.00		8	196.57	190.00	19.47%	0.168	7.169	2.987	13.24
SMH-B7	893.00	11+10.00								
			8	196.57	340.00	17.06%	0.168	6.830	2.796	12.39
SMH-B8	835.00	14+50.00								
			8	191.95	333.00	15.62%	0.168	6.674	2.675	11.86
SMH-B9	783.00	17+83.00								
			8	187.22	135.00	15.56%	0.168	6.674	2.670	11.83
SMH-B10	762.00	19+18.00								
			8	187.22	300.00	14.33%	0.168	6.455	2.563	11.36
SMH-B11	719.00	22+18.00								
			8	191.82	350.00	11.43%	0.168	5.948	2.288	10.14
SMH-B12	679.00	25+68.00								
	677.00		8	191.82	350.00	9.14%	0.168	5.480	2.047	9.07

Manhole	Invert, ft	Station, ft	Pipe size, inch	Direction, deg	Length, ft	EGL Slope, ft/ft	Qa, mgd	Va, fps	Qf, mgd	Vf, fps
SMH-B13	645.00	29+18.00								
			8	191.82	228.02	7.02%	0.168	5.014	1.793	7.95
SMH-B14	629.00	31+46.02								
			8	180.23	221.98	5.86%	0.168	4.697	1.638	7.26
SMH-B15	616.00	33+68.00								
			8	180.23	250.00	9.60%	0.168	5.576	2.097	9.30
SMH-B16	592.00	36+18.00								
	589.00		8	175.00	200.00	8.75%	0.168	5.433	2.002	8.87
SMH-B17	571.50	38+18.00								
			8	226.00	195.00	13.08%	0.168	6.253	2.448	10.85
SMH-B18	546.00	40+13.00								
			8	224.00	172.00	2.91%	0.168	3.659	1.154	5.12
SMH-B19	541.00	41+85.00								
			8	228.00	298.00	13.09%	0.168	6.253	2.449	10.85
SMH-B20	502.00	44+83.00								
	500.00		8	228.00	35.00	34.29%	0.168	8.774	3.963	17.57
SMH-B21	488.00	45+18.00								
	484.00		8	219.00	100.00	24.00%	0.168	7.763	3.316	14.70
SMH-B22	460.00	46+18.00								
			8	219.00	80.00	10.50%	0.168	5.782	2.193	9.72
SMH-B23	451.60	46+98.00								
			8	164.93	200.00	6.30%	0.168	4.831	1.699	7.53
SMH-B24	439.00	48+98.00								
	434.00		8	181.00	30.00	63.33%	[redacted]	[redacted]	5.387	23.88
SMH-B25	415.00	49+28.00								
			8	181.00	105.00	2.86%	0.168	3.641	1.144	5.07
SMH-B26	412.00	50+33.00								
	410.00		8	181.00	35.00	34.29%	0.168	8.774	3.963	17.57
SMH-B27	398.00	50+68.00								
			8	181.00	100.00	7.00%	0.168	5.014	1.791	7.94
SMH-B28	391.00	51+68.00								
			8	181.00	141.00	1.42%	0.168	2.827	[redacted]	3.57
SMH-B29	389.00	53+09.00								
			8	106.00	165.00	2.50%	0.168	3.457	1.070	4.74
SMH-B30	384.88	54+74.00								
			8	155.00	54.00	31.26%	0.168	8.493	3.784	16.77
SMH-B31	368.00	55+28.00								
			8	246.00	146.00	11.64%	0.291	7.037	2.310	10.24
SMH-B32	351.00	56+74.00								
	348.00		8	195.00	230.00	12.17%	0.291	7.118	2.362	10.47
SMH-B33	320.00	59+04.00								
	318.00		8	207.00	178.00	10.67%	0.291	6.807	2.211	9.80
SMH-B34	299.00	60+82.00								
			8	179.50	96.00	10.42%	0.291	6.734	2.185	9.68
SMH-B35	289.00	61+78.00								
			8	172.25	150.00	17.33%	0.291	8.073	2.818	12.49
SMH-B36	263.00	63+28.00								
			8	153.75	112.00	9.82%	0.291	6.593	2.121	9.40
SMH-B37	252.00	64+40.00								
			8	112.75	110.00	7.27%	0.291	5.930	1.825	8.09
SMH-B38	244.00	65+50.00								
			8	157.75	61.20	13.07%	0.291	7.331	2.447	10.85
SMH-B39	236.00	66+11.20								
			8	180.00	263.95	15.87%	0.291	7.858	2.696	11.95

Manhole	Invert, ft	Station, ft	Pipe size, inch	Direction, deg	Length, ft	EGL Slope, ft/ft	Qa, mgd	Va, fps	Qf, mgd	Vf, fps
Headworks	194.11	68+75.15								
Average					171.88	15%			2.4751	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Maximum					350.00	63%			5.3866	

SL-"C" Haina Town

Manhole	Invert, ft	Station, ft	Pipe size, inch	Direction, deg	Length, ft	EGL Slope, ft/ft	Qa, mgd	Va, fps	Qf, mgd	Vf, fps
SMH-Haina	384.82	0+00.00								
			6	368.00	30.00	19.40%	0.291	8.639	1.384	10.91
SMH-C1	379.00	0+30.00								
			6	246.00	87.74	12.54%	0.291	7.387	1.113	8.77
SMH-B31	368.00	1+17.74								
Average									1.249	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
Maximum									1.384	