APPENDIX G
HYDRAULIC GRADE LINE

1.0 Introduction

The hydraulic grade line is used to aid the designer in determining the acceptability of a proposed or evaluation of an existing storm drainage system by establishing the elevation to which water will rise when the system is operating under design conditions. Detail on this system performance analysis is presented in this appendix.

2.0 Definitions

Definitions of terms which will be important in a storm drainage analysis and design are provided in this section. These and other terms defined in the manual glossary will be used throughout the remainder of this appendix in dealing with different aspects of storm drainage analysis.

Energy grade line – Represents the total available energy in the system (potential energy plus kinetic energy).

Hydraulic grade line - The hydraulic grade line (HGL), a measure of flow energy, is a line coinciding with the level of flowing water at any point along an open channel. In closed conduits flowing under pressure, the hydraulic grade line is the level to which water would rise in a vertical tube (open to atmospheric pressure) at any point along the pipe. HGL is determined by subtracting the velocity head ($V^2/2g$) from the energy gradient (or energy grade line). Figure 1 illustrates the energy and hydraulic grade lines for open channel and pressure flow in pipes. As illustrated in Figure 1, if the HGL is above the inside top (crown) of the pipe, pressure flow conditions exist. Conversely, if the HGL is below the crown of the pipe, open channel flow conditions exist.

Critical depth – is defined as the depth for which the specific energy (sum of the flow depth and velocity head) of a given discharge is at a minimum. A slight change in specific energy can result in a significant rise or fall in the water depth when flow is at or near critical depth. Because of this, critical depth is an unstable condition and it rarely occurs for any distance along a water surface profile.

4.0 Tailwater

Evaluation of the hydraulic grade line for a storm drainage system begins at the system outfall with the tailwater elevation. For most design applications, the tailwater will either be above the crown of the outlet or can be considered to be between the crown and critical depth of the outlet. The tailwater may also occur between the critical depth and the invert of the outlet, however, the starting point for the hydraulic grade line determination should be either the design tailwater elevation or $(d_c + D)/2$, whichever is highest, where d_c is outlet critical depth and D is crown depth.

An exception to the above rule would be for a very large outfall with low tailwater where a water surface profile calculation would be appropriate to determine the location where the water surface will intersect the top of the barrel and full flow calculations can begin. In this case, the downstream water surface elevation would be based on critical depth or the design tailwater elevation, whichever was highest.

If the outfall channel is a river or stream, it may be necessary to consider the joint or coincidental probability of two hydrologic events occurring at the same time to adequately determine the elevation of the tailwater in the receiving stream. The relative independence of the discharge from the storm drainage system can be qualitatively evaluated by a comparison of the drainage area of the receiving stream to the area of the storm drainage system. For example, if the storm drainage system has a drainage area much smaller than that of the receiving stream, the peak discharge from the storm drainage system may be out of phase with the peak discharge from the receiving watershed. Table A provides a comparison of discharge frequencies for coincidental occurrence for a 10-year and 100-year design storm. This table can be used to establish an appropriate design tailwater elevation for a storm drainage system based on the expected coincident storm frequency on the outfall channel. For example, if the receiving stream has a drainage area of 200 acres and the storm drainage system has a drainage area of 2 acres, the ratio of receiving area to storm drainage area is 200 to 2 which equals 100 to 1. From Table A and considering a 10-year design storm occurring over both areas, the flow rate in the main stream will be equal to that of a five-year storm when the drainage system flow rate reaches its 10-year peak flow at the outfall. Conversely, when the flow rate in the main channel reaches its 10-year peak flow rate, the flow rate from the storm drainage system will have fallen to the 5-year peak flow rate discharge. This is because the drainage areas are different sizes, and the time to peak for each drainage area is different.

Table B - Correction For Benching

Bench Type	Correction Factors (C_B)	
	Submerged*	Unsubmerged**
Flat Floor	1.00	1.00
Half Bench	0.95	0.15
Full Bench	0.75	0.07
Improved	0.40	0.02
* pressure flow, $d_{aho}/D_o > 3.2$ ** free surface flow, $d_{aho}/D_o < 1.0$		

Table C ODOT Benching

Access Structure Type	Bench Type	Drawing
4 foot Standard Manhole	Full Bench	RD344
Standard Manhole	Half Bench	RD336
Shallow Manhole	Half Bench	RD342
Large Manhole	Half Bench	RD346
All inlet Boxes	Flat Floor	- - - - -

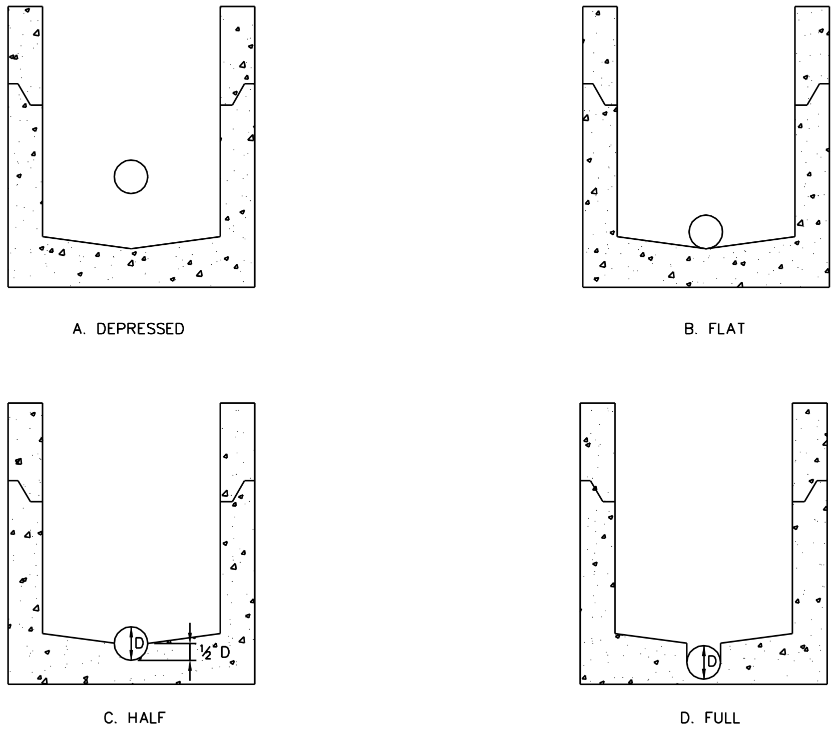


Figure 4 - Benching Type Schematic

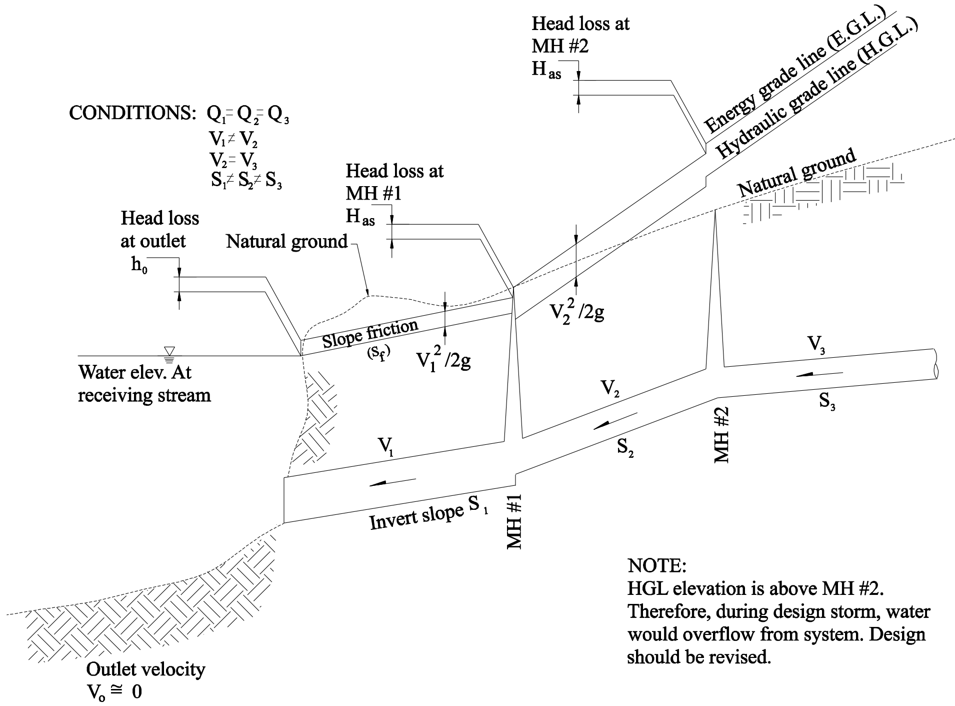
6.0 Surcharged-Full Flow (Pressure Flow Conditions)

Most storm drains discharge into natural receiving streams or drainages which do not submerge the outlet of the system; however, there are locations where a storm system must discharge into a stream or river where major floods in those streams will submerge the storm drain and back water into the system. During periods of little or no flow in the storm system, backwater from these streams usually is not a problem; however, when a peak flow of design magnitude occurs in the storm system simultaneously with a high flow in the receiving stream, the system becomes "surcharged" and operates under pressure flow conditions.

Under the "surcharged" condition, backwater from the receiving stream may raise the elevation of the water surface (Hydraulic Grade Line or HGL) in the system high enough that water could bubble out of manholes and inlets at low points in the highway grade.

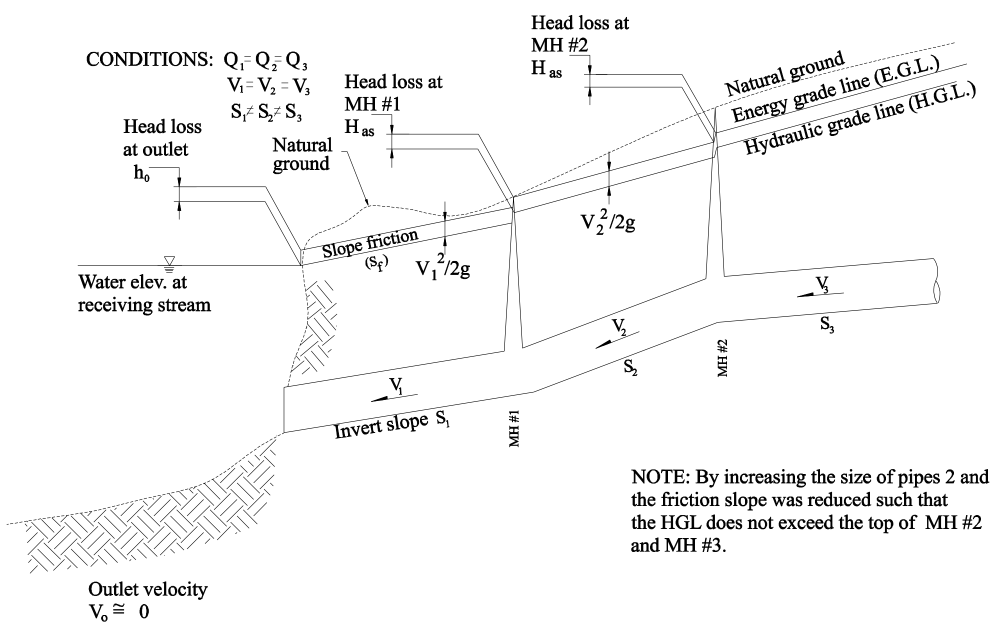
FIGURE 5
SURCHARGE FULL FLOW

IMPROPER DESIGN



NOTE:
HGL elevation is above MH #2.
Therefore, during design storm, water would overflow from system. Design should be revised.

PROPER DESIGN



NOTE: By increasing the size of pipes 2 and 3 the friction slope was reduced such that the HGL does not exceed the top of MH #2 and MH #3.

The elevation of the HGL can be determined only after the Energy Grade Line (EGL) has been established. The EGL is a line showing the total available energy in the system (potential energy plus kinetic energy). If the sewer were of constant cross section with no manholes or angle points the EGL would have a constant and continuous slope equal to the FRICTION SLOPE, S_f . However, storm sewers are not constructed in this manner and each appurtance disrupts the flow pattern in the sewer, producing an energy loss which is indicated by a sudden drop in the elevation of the EGL.

Inundation of the highway can be prevented by increasing the size of the sewer pipes downstream from those areas where the elevation of the hydraulic grade line (HGL) exceeds the elevation of the low manholes and inlets. Increasing the size of the pipe reduces the friction loss in the line. Figure 5 shows a short section of a storm sewer. In the top drawing; Pipe 2 and Pipe 3 are small, thereby inducing large friction losses as indicated by the slope of the EGL. In the bottom drawing, the size of these two pipes has been increased to reduce the friction losses, thereby lowering the elevation of the EGL and HGL to a point below the top of each manhole.

6.1 Energy Grade Line and Hydraulic Grade Line

This section presents a step-by-step procedure for manual calculation of the energy grade line (EGL) and the hydraulic grade line (HGL) using the energy loss method. This has been included to aid the designer in understanding the analysis process, but the most efficient means of evaluating storm drain systems is with computer programs.

The following is the procedure to design sewers for surcharged-full flow conditions.

Step 1- Design the storm system with procedures outlined in Appendix F for FULL AND PARTIAL-FULL FLOW. Assume there is free outfall from the storm sewer.

Step 2- Draw a profile of the proposed sewer showing the highway grade and location of each manhole and its cover elevation. Note elevations of low gutters.

Step 3- Use tabular design sheet STORM SEWER DESIGN SHEET – SURCHARGED-FULL FLOW (Pressure Flow Conditions), Figure 6.

Step 4- Using Figure 6. Enter in Column 1 the station of the sewer outfall.

Step 5- Enter in Column 2 the design discharge, Q cfs for the outfall pipe.

Step 6- Enter in Column 3 the size of the outfall pipe, D in inches.

Step 7- Enter in Column 4 the length of the outfall pipe, L in feet

Step 8- Hydraulic structure losses and other minor pipe losses are determined and transferred to Figure 6 in columns 9 and 13. Refer to section 5.0 for Energy Losses.

Step 9- Enter in Column 5 the average flow velocity (V) in feet per second of the outfall pipe.

Step 10- Enter in Column 6 the velocity head for the outfall pipe.

Step 11- Enter in Column 7 the average flow velocity component in the outlet channel (which is parallel to the system) - in most cases this can be considered negligible.

Note: Column 7 is normally used only once to define conditions downstream from the storm drain system.

Step 12- Enter in Column 8 the velocity head for velocity in Column 7 - in most cases this can be considered negligible.

Note: The EGL and HGL at the outfall have now been determined. The next steps apply to the storm drain system.

Step 13- Hydraulic pipe characteristics, roughness coefficients, and equations are located in **Chapter 8** to aid in manual calculations. Also, nomographs for several types of pipes are located in **Chapter 8**. When the appropriate nomograph is available, use the DISCHARGE (Column 2) and PIPE DIAMETER (Column 3) and note the value on the SLOPE scale. This is the FRICTION SLOPE (S_f) of the EGL. Enter this value into Column 10.

Step 14- Multiply the value in Column 10 by the LENGTH in Column 4 to determine the FRICTION HEAD LOSS. Enter in Column 11.

Step 15- Enter in Column 12 the elevation of the energy grade line (Column 16, previous line, plus column 9) at the outlet of the drain.

Step 16- Enter in Column 16 the elevation of the hydraulic grade line at the outlet of the drain by subtracting from the value in Column 12 the value in Column 6.

Step 17- Enter in Column 1 the station identification of the upstream end of the outfall pipe.

Step 18- Enter in Column 12 the elevation of the energy grade line (EGL_o) at the upstream end of the outfall pipe by adding to the first value in Column 15 (on the previous line) (FRICTION HEAD LOSS) to the value in Column 11.

Step 19- Enter in Column 14 energy losses for structures, multiply Column 13 by Column 6.

Step 20- Enter in Column 15 the elevation of the energy grade line, EGL_i , Column 14 is added to Column 12 (previous line).

Step 21- Enter in Column 16 the elevation of the hydraulic grade line at the upstream end of the outlet pipe. Note: the EGL and HGL should be parallel and separated by the amount of the velocity head in the storm drain pipe (HGL = EGL – $V^2/2g$).

Step 22- Repeat procedure starting with Step 13 for the next upstream run of pipe.

Step 23- Plot the HGL and EGL on the storm sewer profile to determine if the HGL elevation exceeds the gutter grade elevation of the highway.

Step 24- If the HGL elevation is above the highway grade, the *size* of the pipes downstream from the point of inundation should be enlarged to reduce the elevation of the HGL. The pipes should be enlarged sufficiently to assure the hydraulic grade line is 0.5 feet or more below the rim elevation of any drainage structure which may be affected. The EGL must also be at or below the rim elevation of any drainage structure which may be affected.

6.2 Storm Drain Design (Surcharge-full Flow) Example

The following example demonstrates the design process and calculation for a double branch surcharged storm drain that is surcharged-full flow. The drain system will be designed to convey stormwater from the drainage basins displayed on Figure 7 (drainage map) to G. K. Elliot Bay which is located at Tillamook, Oregon. The double branch surcharged-full storm sewer will remove the storm water runoff from the two hatched basins shown on the Drainage Map (Figure 7).

PART A.

The following design steps outline the proposed storm drain system's characteristics (i.e., preparing a drainage basin map, delineation of drainage basins, horizontal computations, collection alignments, hydrologic computations, and collection structure selection) which are necessary prior to pipe sizing design.

Step A.1- Locate and sketch the storm sewer system as shown on Figure 8, 9 and 10. Add stations from the most distant points on the basins to the outfall at G. K. Elliott Bay. An equation at the manhole was included to separate the left branch from the right branch.

Step A.2- Enter in Column 1 of "STORM SEWER DESIGN SHEET - FULL AND PARTIAL-FULL FLOW", Figure 11, the stations which had been sketched and located on Figure 8. A Type III non-reinforced concrete pipe will be used with a required minimum cover of 1.5 feet. A Manning's "n" value of 0.013 will be assumed. The outfall pipe from the manhole will be sized to convey the 50-year peak design discharge.

Step A.3- Enter in Columns 2, 3, 4, 5 and 6 of Figure 11 the drainage areas Basin 1 (ΣCA = 5.4 acres) and Basin 2 (ΣCA = 9.45 acres) which are shown on Figure 7.

Step A.4- The times of concentration of 6.3 minutes (Basin 1) and 29.5 minutes (Basin 2) were used for the design of the storm sewer. These times of concentration were calculated as explained in **Chapter 7**. Enter these times of concentration in Columns 7 and 8 of Figure 11.

Step A.5- Obtain the 10-year rainfall intensity corresponding to durations of 6.3 minutes and 29.5 minutes in **Chapter 7**. Enter 2.5 inches per hour and 1.25 inches per hour in Column 9, Figure 11.

Step A.6.- Multiply Column 9 times Column 6 and enter 11.8 cubic feet per second and 13.5 cubic feet per second in Column 10 of Figure 11.

Step A.7- Two profiles which show the controlling elevation, the manhole location and the G. K. Elliott Bay receiving channel, were drawn on Figures 9 and 10. From these figures enter in Column 18 of Figure 11 the controlling ground elevations of 117.0, 110.0 and 109.5 feet. These are the elevations which must not be exceeded by the hydraulic grade line. If these elevations are exceeded, localized flooding will occur.

Step A.8- Enter in Column 15 of Figure 11 the pipe lengths of 570, 370, and 170 feet.

Step A.9- Estimate the invert slope as follows:

Right Branch Invert Slope = (117.0 – 109.5)(100) / 570 = 1.316 percent
Left Branch Invert Slope = (110 – 109.5)(100) / 170 = 0.294 percent

Step A.10- The previously estimated design discharges and invert slopes were used to tabulate the pipe size, capacity flowing full and velocity flowing full for each branch. This data was determined using Figure 12 (circular concrete pipe nomograph). Enter in Columns 11, 12, 13 and 14 of Figure 11 the following table:

Note: Additional hydraulic pipe characteristics, roughness coefficients, and nomographs are located in Chapter 8.

	Design Discharge, Cubic feet per Second	Invert Slope, Percent	Pipe Size, Inches	Capacity Flowing Full, Cubic Feet per Second	Velocity Flowing Full, Feet per Second
RIGHT Branch	11.8	1.316	18	12.2	7.0
LEFT Branch	13.5	0.294	27	16.5	4.2

Step A.18- Add the flow times calculated above to the previous total time of concentration and enter the following results in Column 8.

29.5 minutes + 1.4 minutes
= 30.9 minutes (total time of concentration for right branch)

6.3 minutes + 0.7 minutes
= 7.0 minutes (total time of concentration for left branch)

Step A.19- Obtain the 50-year rainfall intensity corresponding to durations of 30.9 and 7.0 minutes using the Zone 2 Intensity-Duration-Frequency curve (**Chapter 7**). Enter 1.65 inches per hour and 3.20 inches per hour in Column 9, Figure 11.

Step A.20- Multiply Column 9 times Column 6 and enter 24.5 cubic feet per second and 19.5 cubic feet per second in Column 10 of Figure 11. The outfall pipe will be sized to convey 24.5 cubic feet per second, the greater peak discharge.

Step A.21- For Station 3+ 70, enter in Column 17 the Invert Elevation of 99.6 feet. The elevation places the outlet of the outfall pipe at the bottom of the channel. An outlet velocity of approximately 3.0 feet per second would minimize erosion at the end of the outfall pipe.

Step A.22- Given a design discharge of 24.5 cubic feet per second, determine slope, pipe size, and velocity for the outfall, Station 3+ 70. Using Figure 12, enter in Columns 11, 12, 13 and 14 of Figure 11 for the outfall pipe 0.145 percent, 36-inch, 24.5 cubic feet per second and 3.6 feet per second. The 36-inch diameter pipe is the smallest standard size pipe which can carry the design flow (24.5 cubic feet per second) and also satisfy the minimum velocity criterion (3 feet per second).

Step A.23- For the outfall pipe, Station 0+ 00 Ah to Station 3+ 70, determine fall and enter in Column 16 as shown below:

Fall = (0.145) (370) / 100 = 0.67 feet

Step A.24- Calculate and enter in Column 17 the Invert Elevation as shown below:

99.6 + 0.67 = 100.27 feet
This will be the invert elevation at Station 0+ 00 Ah.

PART B.

Check the storm sewer design as a surcharged full flow (pressure flow) system by determining the energy and hydraulic grade lines. The 50-year storm is the design storm for the surcharged condition.

Step B.13- Subtract 0.20 (Column 6) from 107.74 (Column 12) and enter in Column 16 the HGL elevation 107.54 feet for the right and left branches.

Step B.14- Enter in Column 18 the top of manhole elevation 109.5 feet (see Figure 7).

Step B.15- The elevation of the EGL inside the manhole is calculated by adding the manhole loss to the EGL of the outfall pipe.

EGL = 0.20 + 107.74 = 107.94 feet

Step B.16- The EGL and HGL calculations for the right (18-inch pipe) and left branch (27-inch pipe) upstream runs of pipe are shown in the following table.

FOR 18-INCH PIPE ON RIGHT SIDE				
STA.	VELOCITY HEAD	HEAD LOSS, Feet	EGL ELEV RIGHT, Feet	HGL ELEV RIGHT, Feet
0+00 Rt	0.20		107.74	107.54
M.H.		0.20	107.94	
15+70 Rt	1.21		107.94	106.73
10+00 Rt	1.21	13.11	121.05	119.84
9+99 Rt	0.00	0.24	121.29	121.29
FOR 27-INCH PIPE ON LEFT SIDE				
0+00 Lt	0.20		107.74	107.54
M.H.		0.20	107.94	
8+70 Lt	0.08		107.96	107.88
7+00 Lt	0.08	0.15	108.11	108.03
6+99 Lt	0.00	0.02	108.13	108.13

Step B.17- Second design attempt with 24-inch pipe for the Right Branch. Need to determine the EGL and HGL. As shown in the table above, the proposed upstream run of 18-inch pipe for the right branch would result in an improper design as shown on Figure 1. The calculated EGL and HGL elevation of 121.29 feet exceeds the natural ground elevation of 117.0 feet shown on Figure 10. For a proper design the EGL and HGL elevation must be below elevation 117.0 feet. A 24-inch will be investigated with its design information tabulated below. The information below will be used in Figure 13.

	Design Discharge	Invert Slope	Pipe Size	Capacity Flowing Full	Velocity Flowing Full
RIGHT Branch	11.8 cfs	0.27 %	24-inch	11.8 cfs	3.7 fps

Step B.18- Calculate as shown below the velocity and velocity head for a 24-inch pipe which would convey a discharge of 15.6 cfs (see step 5 above). Enter the values in Columns 5 and 6.

FIGURE 7

DRAINAGE MAP

All elevations are assumed Datum

Impervious area to be drained into Storm Sewer

Basin 1 =Σ CA = 5.4 Acres

Basin 2 =Σ CA = 9.45 Acres

Total Impervious Drainage Area = 5.4 + 9.45 = 14.85 Acres

Tillamook, Oregon
No Scale

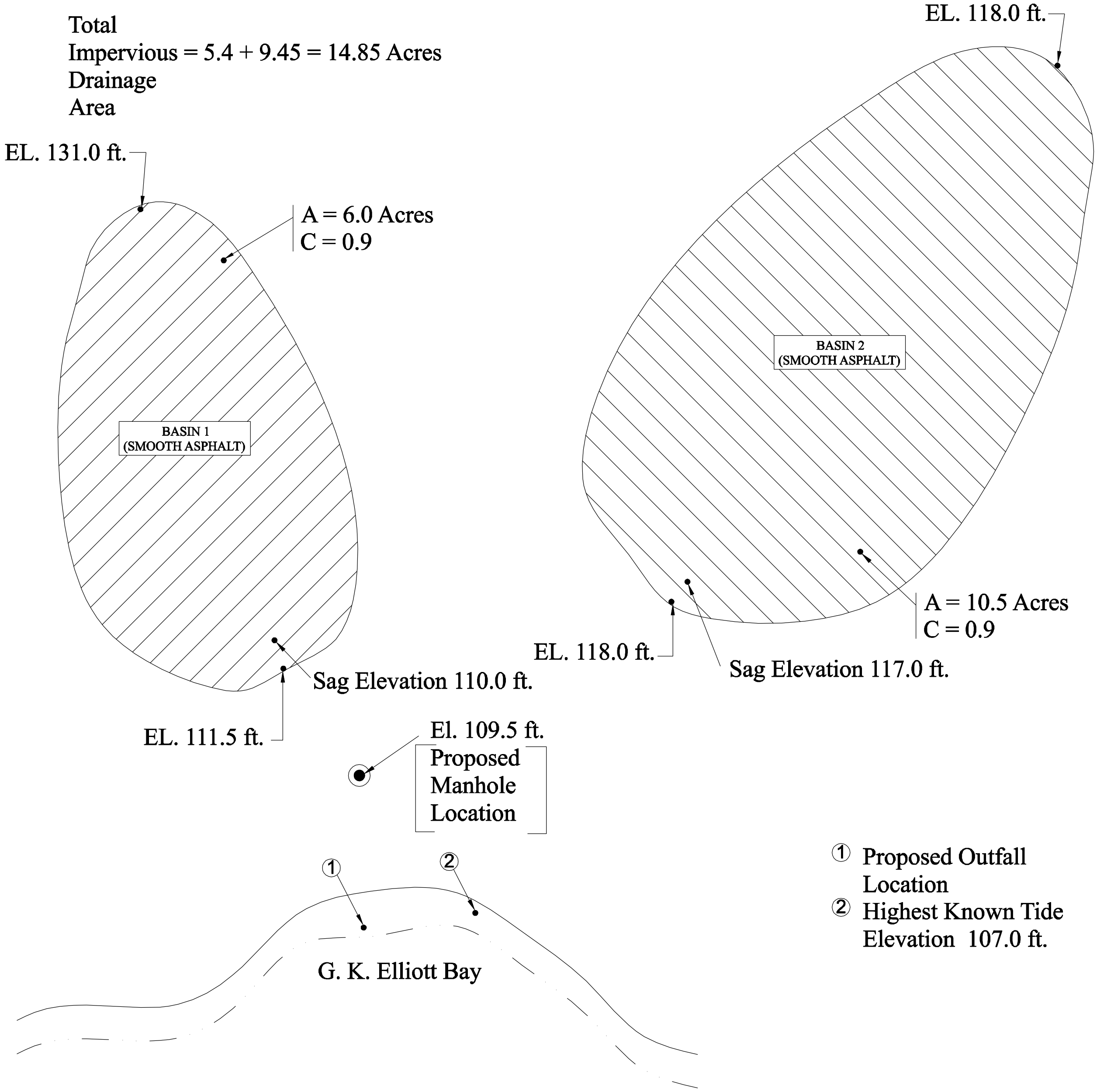


FIGURE 8
SYSTEM LAYOUT

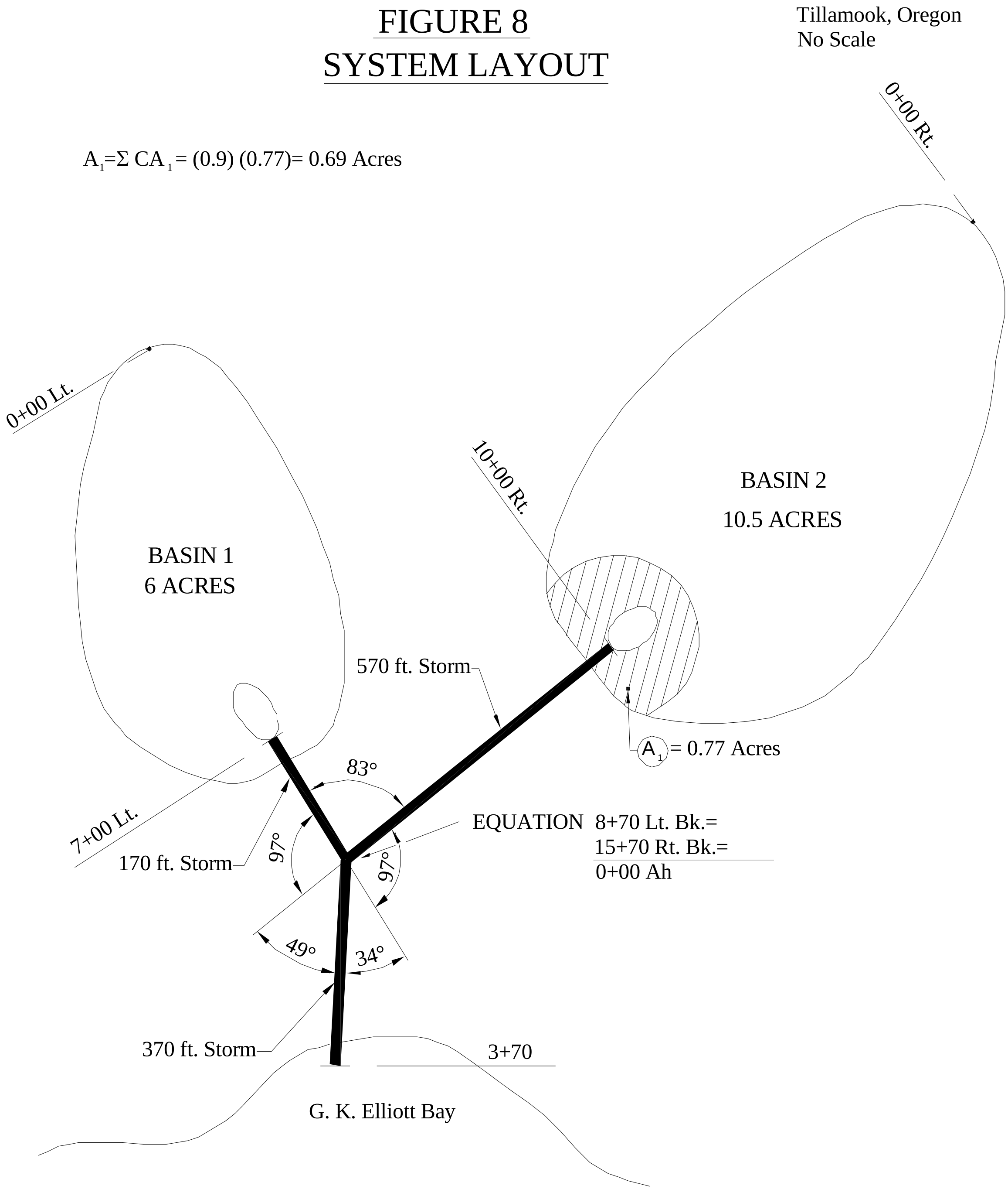


FIGURE 11
STORM DRAIN DESIGN SHEET
FULL AND PARTIAL-FULL FLOW

PROJECT: Example Problem DESIGN FREQUENCY: 10- Year * 50- Year DESIGNED BY: JOE SMITH DATE: 2005

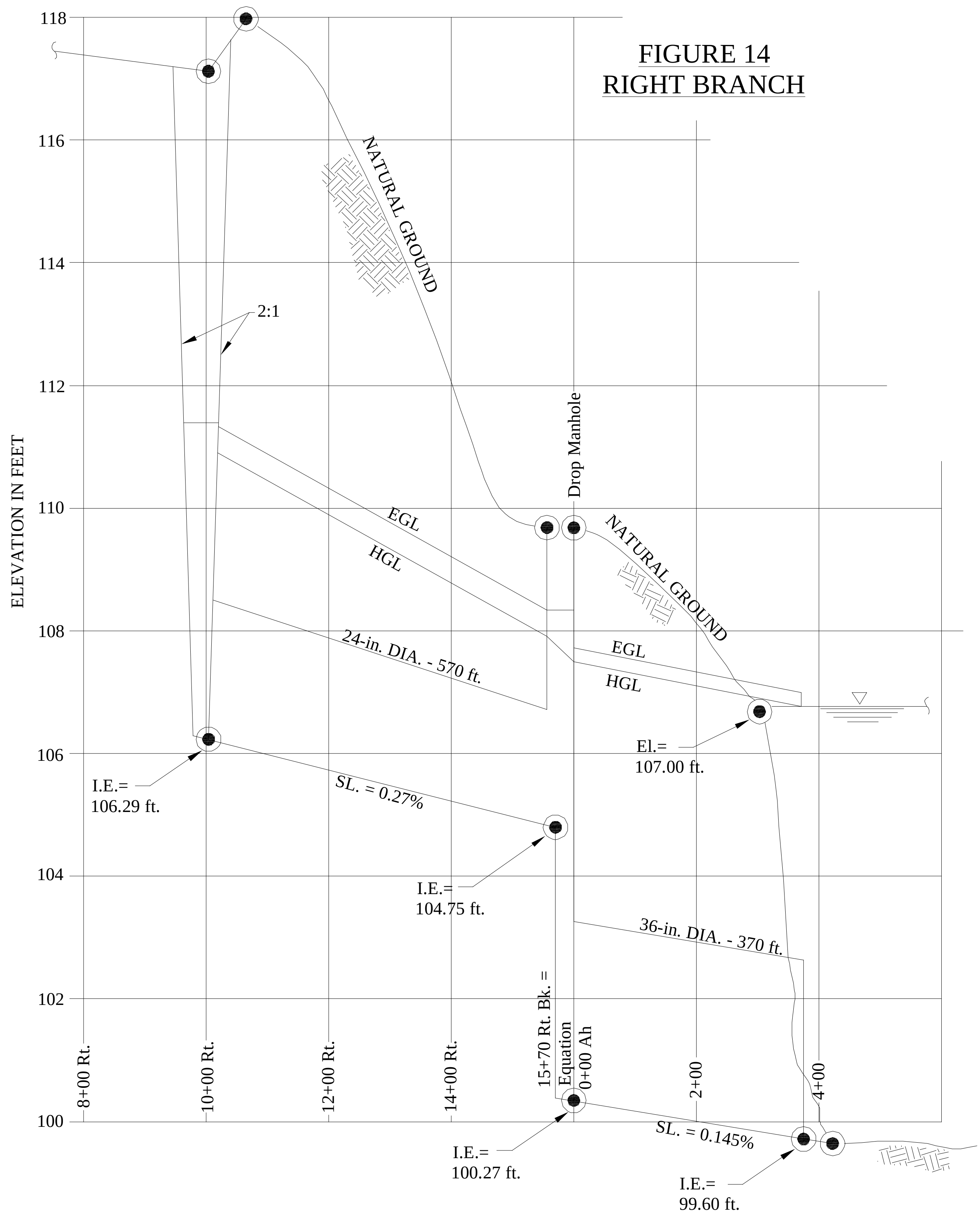
Station	Node I.D.	Drainge Area Index No.	Drainge Area Area A	Runoff Coeff. C	Equiv. Area for 100% Runoff CA (3) x (4) Acres	Total Impervious Drainage Area ΣCA Acres	Time of Concent. or Flow Time, T_c Minutes	Total Time of Concent. T_c Minutes	Average Rainfall Intensity I in/hr	Design Discharge Q (6) x (9) cfs	Invert Slope S %	Pipe Size D Inches	Capacity Flowing Full Q_f cfs	Velocity Flowing Full V_f fps	Length L feet	Fall feet	Invert Elevation feet	Top of Manhole Elevation feet	Remarks
1a	1b	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
10+00 Rt																			
		②	10.5	.9	9.45	9.45													
							29.5	29.5	1.25										
7+00 Lt										11.8							106.29 112.79	117.0	
		①	6.0	.9	5.40	14.85					0.27 1.316	24 18	11.8 12.2	3.7 7.0	570				
15+70 Rt Bk							1.4	30.9	*1.65							1.54 7.50	104.75 105.29		(in)
0+00 Ah										24.5							100.27	109.5	(out)
											0.145	36	24.5	3.6	370				
																0.67			
3+70																	99.6		(outfall)
0+00 Lt																			
		①	6.0	.9	5.40	5.40													
							6.3	6.3	2.50										
7+00 Lt										13.5							104.92	110.0	
		Ⓐ1	0.77	.9	0.69	6.09					0.294	27	16.5	4.2	170				
8+70 Lt Bk							0.7	7.0	*3.20							0.50	104.42		(in)
0+00 Ah										19.5							100.27	109.5	(out)
											0.145	36	24.5	3.6	370				
																0.67			
3+70																	99.6		(outfall)

FIGURE 13
STORM DRAIN DESIGN SHEET
SURCHARGED FLOW (Pressure Flow Conditions)

PROJECT: Example Problem DESIGN FREQUENCY: 50-Year DESIGNED BY: JOE SMITH DATE: 2005

PIPE DATA					HEAD LOSSES														
Station I.D.	Node I.D.	Discharge cfs	Pipe Size D inches	Pipe Length L feet	V_1 fps	$\frac{V_1^2}{2g}$ feet	V_2 fps	$\frac{V_2^2}{2g}$ feet	Minor Pipe Losses feet	Friction Slope S_f %	Friction Head Loss (4) x (10) feet	Energy Grade Line EGL_0 feet	K	$K\frac{V^2}{2g}$ feet	EGL_i feet	Piezometric or water Surface (HGL) feet	Crown of Pipe feet	Low Gutter/ Surface Elevation feet	Remarks
1a	1b	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Outfall												107.00				107.00			Outfall
3+70		24.5	36		3.6	0.20	0.0	0.0	0.20						107.20	107.0	102.60		Just inside pipe at outfall pipe
0+00 Ah		24.5	36	370	3.6	0.20			0.0	0.145	0.54	107.74				107.54	103.27		Just inside inlet end of outfall pipe
													0.97	0.20	107.94			109.50	Inside manhole
15+70 Rt		15.6	18	570	8.8	1.21						107.94				106.73			Just inside pipe as it enters manhole
10+00 Rt		15.6	18	570	8.8	1.21				2.30	13.11	121.05				119.84			Just inside outlet of pipe
9+99 Rt									0.24						121.29	121.29		117.00	Exceeds ground level, try next size pipe
15+70 Rt		15.6	24	570	5.0	.39						107.94				107.55	106.75		2nd Try
10+00 Rt		15.6	24	570	5.0	.39				0.47	2.68	110.62				110.23	108.29		
9+99 Rt									0.08						110.70	110.70		117.00	Does not exceed ground elevations
																			Design is okay
Outfall												107.00				107.00			Outfall
3+70 Lt		24.5	36		3.6	.20	0.0	0.0							107.20	107.00	102.6		Just inside pipe at outfall
0+00 Ah										0.145	0.54	107.74				107.54	103.27		Just inside inlet end of outfall pipe
													0.97	0.20	107.94			109.50	Inside manhole
8+70 Lt		8.9	27	170	2.2	.08			0.02			107.96				107.88	106.67		Just inside pipe as it enters manhole
7+00 Lt		8.9	27	170	2.2	.08				0.090	0.15	108.11				108.03			Just inside outlet pipe
6+99 Lt									0.02						108.13	108.13	107.17	110.00	Just outside inlet end of pipe
																			HGL & EGL do not exceed ground
																			elevations. Design is OK

FIGURE 14
RIGHT BRANCH



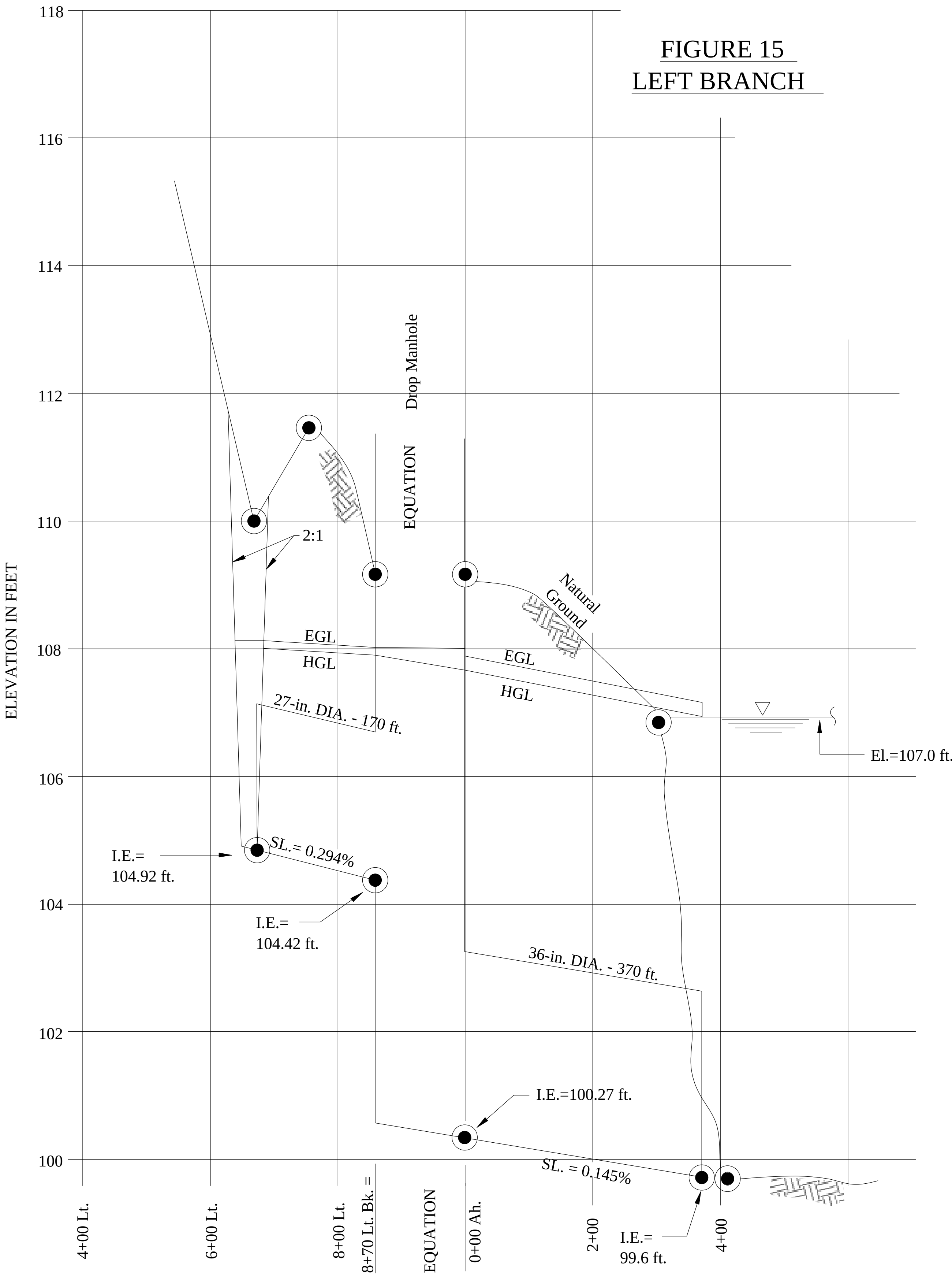


FIGURE 15
LEFT BRANCH
ELEVATION IN FEET
118
116
114
112
110
108
106
104
102
100
Drop Manhole
EQUATION
2:1
Natural Ground
EGL
HGL
EGL
HGL
27-in. DIA. - 170 ft.
El.=107.0 ft.
I.E.= 104.92 ft.
SL.= 0.294%
I.E.= 104.42 ft.
36-in. DIA. - 370 ft.
I.E.=100.27 ft.
SL. = 0.145%
I.E.= 99.6 ft.
4+00 Lt.
6+00 Lt.
8+00 Lt.
8+70 Lt. Bk. =
EQUATION
0+00 Ah.
2+00
4+00