# 24. Force Main Design.

## a. Alignment - Horizontal and Vertical

1) Locate the force main as if it is a water pipeline, see requirements under Part One (Water), with the following exceptions.

a) When adjacent or parallel to a water pipeline, design the force main in accordance with the requirements of the sewer pipelines, see Part Three, Section 3 (Pipeline Crossings and Clearances). Do not provide concrete encasement of the force main.

b) When the force main alignment is running parallel to a sewer pipeline, see the following requirements:

(1) Where the sewer is existing, design the force main in accordance with the requirements of relief sewers under Part Two, Section 23 (Relief Sewer Design) and Part Three, Section 3 (Pipeline Crossings and Clearances).

(2) Where the sewer is not existing, see Part Three, Section 3 (Pipeline Crossings and Clearances).

c) Provide minimum vertical slope on the pipeline in profile: provide one tenth (0.1) of a foot in fifty (50) feet of vertical alignment for pipelines 12" and smaller and one tenth (0.1) of a foot in one hundred (100) feet of vertical alignment for pipelines larger than 12".

2) For force mains in tunnels or casing pipes, see requirements under Part One, Section 18 (Tunnels or Casing Pipes).

## b. Profile Requirements.

1) See the requirements under Part One, Section 11 (Vertical Alignment - Profile).

2) Show the HGL on the profile for the design of the force main or provide a table on the plans, providing the HGL elevation every 50 feet along the length of the force main.

3) Design the top of the force main and its appurtenances, such as air release, and air and vacuum valves, lower than the HGL.

4) Ideally, the force main should be designed without intermediate high points, and with the top of the force main being below the hydraulic grade line at the minimum pumping rate so that air release valves will not be needed. If the elimination of high points is not feasible or if the design requires air and vacuum valves, for long, relatively flat vertical alignments, the design may require air release and air and vacuum valves, see requirements under Part Two, Section 26 (Air Valves).

## c. Allowable Pipe Material and Fittings.

1) <u>Allowable pipe material</u>.

a) <u>DIP</u>. For requirements using DIP, see Part One, Section 4 (Selection of Pipe Material).

b) AWWA C900 PVC. May be used for force mains in diameters 12-inch and smaller as an alternative to DIP if the PVC pipe meets the external load and internal pressure requirements, as stated in this section.

(1) Pipe dimension ratio for AWWA C900 PVC. The use of PVC for force mains is limited by the pipe diameter, operating pressure (including pump cyclic loading), and pipe dimension ratio (DR) as follows:

(a) AWWA C900 DR18, total allowable internal pressure, operating plus surge, not to exceed one hundred sixty (160) psi, except as noted in Pumping cyclic loading, in this section.

(b) AWWA C900 DR14, total allowable internal pressure, operating plus surge, not to exceed two hundred five (205) psi, except as noted in Pumping cyclic loading, in this section.

(c) Pumping cyclic loading.

[1] The on/off operation of pumps creates a cyclic loading, which may limit the total allowable pressure in the force main. Information on cyclic loading is available from the UniBell PVC Pipe Association.

[2] Confirm the number of pump "on" and "off's" during the life of the forcemain and submit calculations indicating whether total allowable pressure has to be reduced to account for cyclic loading. For purposes of this design criteria, use the following equations for finding the total allowable internal pressure:

DR18 pipe. The maximum total internal pressure $= 2768 \div C^{0.204}$.
Where C is the number of pump "on" and "off's" during the life of the forcemain.

Example: Assuming a pump operates twice per hour (4 "on" and "off's") 24 hours per day, 365 days per year for 75 years.
Then $C = 4 \times 24 \times 365 \times 75 = 2{,}628{,}000$.
The maximum total internal pressure $= 2768 \div 2{,}628{,}000^{0.204} = 135$ psi.

DR14 pipe. The maximum total internal pressure $= 3618 \div C^{0.204}$.
Where C is the number of pump "on" and "off's" during the life of the forcemain.

Example: Assuming a pump operates twice per hour (4 "on" and "off's") 24 hours per day, 365 days per year for 75 years.
Then $C = 4 \times 24 \times 365 \times 75 = 2{,}628{,}000$.
The maximum total internal pressure $= 3618 \div 2{,}628{,}000^{0.204} = 177$ psi.

The above equations for the DR14 and DR18 for cyclic loading include a derating factor assuming a wastewater temperature of 80 degrees.

(2) Allowable cover for AWWA C900 PVC.

(a) AWWA C900 DR18, allowable cover is ten (10) feet. If DR 18 pipe is encased in granular material in accordance with the Specifications for PVC Gravity Sewer Pipe and Standard Detail M/8.1a, maximum allowable cover is twenty two (22) feet.

(b) AWWA C900 DR14, allowable cover is twenty five (25) feet. If the DR 14 pipe is encased in granular material in accordance with the Specifications for PVC Gravity

Sewer Pipe and Standard Detail M/8.1a, maximum allowable cover is forty (40) feet.

(c) The allowable cover with native bedding/backfill is based on a soil modulus of 0, deflection lag factor of 1.0, earth load calculated as prism load, and maximum allowable deflection 2.5%.

(3) Information required on the Drawings.

(a) Indicate the allowable type(s) of pipe; DIP and/or AWWA C900 PVC.

(b) If AWWA C900 PVC is allowed, the specifications require DR18 pipe, unless noted otherwise on the drawings. Calculate the maximum operating pressure and surge, and assure that the operating and surge pressure is less than one hundred sixty (160) psi and adjusted for cyclic loading. If greater than one hundred sixty (160) psi, but less than 205 psi and adjusted for cyclic loading, add a note to the drawings requiring DR14. In considering surge, note that the modulus of elasticity of PVC is much less than that for DIP and therefore, for a given change in velocity, the resulting surge is less for PVC than DIP. Consult the Unibell PVC Pipe Handbook for additional information.

(c) If granular material bedding is required due to the depth of cover, see "Allowable cover for AWWA C900 PVC" in this section, and include a note to provide bedding for the PVC according to Standard Detail M/8.1a.

2) Allowable fittings for AWWA C900 PVC.

a) Limit the type of fittings on the force main to only bends, see allowable fitting requirements under Part One, Section 7 (Allowable Fittings).

b) For DIP, see allowable fittings in accordance with Part One, Section 2 (Pipe Materials and Fittings).

c) For AWWA C900, the allowable fittings according to the Specifications can be PVC push-on or ductile iron or cast iron in accordance with Part One, Section 2 (Pipe Materials and Fittings). Restrained joints require ductile iron mechanical joint fittings.

3) Thrust restraint for AWWA C900 PVC.

a) For thrust restraint, concrete thrust blocks are the preferred method of restraint. If blocking is not possible, restrained joints may be used, see "Allowable fittings for AWWA C900 PVC", in this section.

b) Design the thrust restraint, in accordance with Part Three, Section 27 (Thrust Restraint Design for Buried Piping).

4) Design criteria for AWWA C900 PVC.

a) Design the PVC C900 pipeline without curves using fittings only. See Part One, Section 12 (Allowable Joint Deflections) and Part One, Section 14 (Joint Deflections at Fittings).

b) Field bending of PVC pipe is not permitted and the manufacturers' allowable PVC pipe joint deflection is limited. See Part One, Section 13 (Allowable Joint Deflections). Do not deflect PVC pipe in a restrained joint system. If deflection is required in a restrained joint, use ductile iron pipe.

**d. Appurtenances and Structures.**

1) Air release, and air and vacuum valves, see requirements under Part Two, Section 26 (Air Valves) and Profile Requirements, in this section.

2) Blowoffs.

a) Locate blowoffs near the wastewater pumping station. The wastewater pumping station by-pass piping may be used to blowoff the force main piping, see WSSC Design Guidelines for Wastewater Pumping Stations (DG-06).

b) Blowoffs along the force main normally are not required, however, where the force main contains a long depressed section between two high points or in case the force main needs a point to drain the system, WSSC may require a blowoff. The design of blowoff piping consists of a valve connection on the force main and piping to either a gravity sewer manhole or to a manhole so that a pump can be used to drain the force main to a gravity sewer manhole, tank truck, etc.

3) Provide flushing connections on the force main if required by WSSC. Design the flushing connection to allow WSSC to clean the force main. WSSC will determine the size and spacing, if required.

4) Transition manhole.

a) Design the connection between the force main and gravity sewer with a transition manhole so that wastewater will be flowing full at all times in the force main. Typically, the invert of the gravity sewer will be one (1) inch above the crown or top of the force main.

b) For force mains smaller than 12-inch in diameter, see the WSSC Standard Detail S/6.6.

c) When the force main is 12-inch and larger, provide a design for the transition manhole with a connection to the manhole that will allow the force main to remain full at all times. The design must also protect maintenance personnel or others from falling in the pipeline because of the steep slope required for the channel when larger force mains are used.

d) Hydrogen Sulfide ($H_2S$) corrosion mitigation. See the Specifications for interior coatings and specify on the drawings the limits of interior coating for the transition manhole, at least one-hundred (100) feet of the force main before the transition manhole and distance from the transition manhole along the gravity sewer pipeline if it is other than PVC pipe. The minimum distance along the gravity sewer pipeline is to the next manhole for the interior coating, but the design may require several downstream manholes and pipeline sections to have interior coatings, see Specifications for transition manholes.

**e. Hydraulic Design of Force Mains.**

1) Guidelines for hydraulic design of force main are as follows:

a) The design of a sewage force main must be coordinated with the design of the wastewater pumping station. Provide a design criteria report, which discusses the range of design flow for the planning period, the proposed design of the pumping station, and the force main as a unified system.

b) Develop the proposed alignment in plan and depict the changes in force main elevations in profile.

c) The number of air valve installations should be minimized. This can be achieved by reducing the number of high points and slope breaks, and by using a profile that rises continuously from the pumping station toward the transition manhole. This allows the use of air injection as a method for the control of hydrogen sulfide ($H_2S$) corrosion and odor problems, if necessary.

d) Develop the system curve for the force main, which shows the total energy losses associated with the range of possible pumping rates. Using the system curve, develop the HGL profiles.

(1) Use Hazen-Williams (HW) equation for estimating friction losses; HW friction factors applicable for the type of pipe material and age of the force main. Since the friction factor cannot be exactly defined for a new design, two values of HW friction factors may be selected to cover a range of possible pump operating points. Incorporate minor losses at transitions and bends. Darcy-Weisbach equation may be used as an alternative.

(2) Develop HGL profiles for the range of pumping rates (minimum, average and maximum rates) planned for the pumping station.

(3) For calculating friction losses in an existing force main, existing flow and pressure data, if available for the force main and pumping station system can be used to determine the HW friction factor.

(4) Base the static head on the difference in vertical elevations between the wet well low operating level and the point of force main discharge to the gravity sewer.

e) It is desirable to minimize the length of the force main so as to minimize the cost of construction and operation.

f) Vertical alignment.

(1) <u>Uphill pumping</u> is preferred in a force main, where the force main discharge point to the gravity sewer is at a higher elevation than the rest of the system, so as to keep the force main under pressure.

(2) If an intermediate high point in the force main lies above the downstream point of the gravity discharge, a partial vacuum condition can be created at the high point, when the force main drains after pumps shut off and when the HGL profile drops below the high point.

(3) <u>Downhill pumping</u>, vertical profiles which are conducive to siphoning at high points and gravity drain/air locking in downhill pumping conditions will require special analysis to ensure proper hydraulic performance. These types of force main profiles are also conducive

to potential severe waterhammer pressures caused by rapid velocity change in the force main resulting from pump start up or shut down. It is therefore recommended that force main profiles which can generate downhill flow be avoided. If downward pumping condition cannot be avoided, then proper hydraulic performance of the force main should be ensured based on sound engineering and design principles. Consider the following, when downhill pumping is required.

(a) The downward sloping force main section following the high point may not flow full during initial line start up because the flow carrying capacity exceeds the line filling rate. The elevation of the high point, in this case, will give the highest static head that the pump must overcome during initial start up.

(b) The downward sloping force main section may not flow under pressure at some pumping rates during normal operation of the pumping station and when pumps shut down. Consider whether and how the pressurized pipe flow should be achieved and maintained.

(c) The extent and effects of partial vacuum condition/siphon action on force main hydraulic performance. Consider allowing the partial vacuum condition during normal conditions and how is it maintained.

(d) The trapping of air/sewer gases at the high point and the downward sloping section, and the effects on pumping head and removal of the air/gas from the force main.

(e) Potential waterhammer pressure due to pump shutdown or power failure.

g) In general, a minimum velocity of two (2) feet per second (fps) is required to maintain solids in suspension. Velocities ranging from three (3) to three and one half (3.5) fps would be required to re-suspend solids that have settled in the force main. This higher velocity is required for force main profiles which exhibit multiple high points and low points. Relatively small stations with intermittent pumping of one or two pumps generally should be designed for higher minimum velocities in the force main, compared to larger stations having more than three pumps. The minimum velocity required must be based on engineering as well as operation and maintenance considerations.

h) The maximum velocity in a force main is about six (6) fps. High velocities generating high headlosses and potential severe waterhammer pressures are not desirable. Flow velocity can vary in a force main, depending on the number of pumps operating in a pumping station. Base the maximum force main velocity on the peak pumping rate that would be delivered during the peak wastewater influent condition.

i) The minimum size for a force main size is 4-inch diameter.

j) Evaluate the severity of waterhammer pressures in the force main under the worse case scenario assuming power failure at the pumping station coincident with firm pumping capacity. Upon power failure at the pumping station, severe down surge (low pressure) can propagate throughout the entire force main, followed by upsurge (high pressure). Examine potential for water column separation in the force main. Methods of waterhammer pressure control and relief should be incorporated, if necessary.

k) Consider the operating pressure and the surge pressure in designing thrust restraint for the force main, see Part Three, Section 27 (Thrust Restraint Design for Buried Piping).

l) Submit drawings, details and final hydraulic calculations to support the force main design.

**f. Hydraulic Transients.**

Hydraulic transients are the time-varying phenomena that follow when the equilibrium of steady flow in a system is disturbed by a change of flow that occurs over a relatively short time period.

1) Surge Control for Raw Sewage Force main: The strategies for controlling surge in raw sewage force main/ sewage pumping stations are limited as compared to the pumping of clean water, because some of the valves (globe and butterfly, for example are unsuitable, the reliability of other valves (such as vacuum and air release) depends on frequent and vigilant maintenance, and air chambers are far more maintenance-dependent for sewage than for water. However; adequate control strategies remain and any proposed solution should be checked thoroughly.

2) Transients are important in hydraulic systems because they can cause rapture of pipe and pump casings, pipe collapse, vibration, excessive pipe displacements, pipe fitting and support deformation /failure, vapor cavity formation, cavitations and column separation. There is no simple, easy way to perform reliable transient analyses. Computer modeling is the most effective means available, but there are practical constraints on time and cost. .Every pump and pipeline system is subject to transient pressures, but it is impractical to spend the time and expense necessary to analyze all of them. The following guidelines can be used to decide whether a complete transient analysis is required or not:

a) Do Not Analyze:

(1) Pumping station with flow rate less than 100 gal/min. Discharge piping is usually such that velocity is low and transient pressures are low.

(2) Pipelines in which the velocity is less than 2ft/sec.

(3) Pumping systems with a static differential pressure between suction and discharge of less than 30 ft. Warning: it is possible that a very low static head coupled with a relatively high dynamic head could result in a column separation problem.

b) Do Analyze:

(1) Pumping systems with a total dynamic head greater than 50ft if the flow rate is greater than 500 gal/min.

(2) High lift pumping systems with a check valve, because high surge pressures may result if the check valve slams shut upon flow reversal.

(3) Any system in which column separation can occur:

(a) Systems with “knees” (high points).

(b) A force main that needs automatic air venting or air-vacuum valves.

(c) A pipeline with a long (more than 300ft.), steep gradient followed by a long, relatively flat gradient.

3) A serious surge may occur if any one of the following conditions exists and if two or more conditions exist, a surge will probably occur with a severity proportional to the number of conditions met:

a) High spots in pipe profile.

b) Steep gradient: Length of force main less than 20 TDH.

c) Flow velocity in excess of 4 ft/sec.

d) Factor of safety (based on ultimate strength) of pipe(and valve and pump casing) less than 3.5 for normal operating pressure.

e) Slowdown and reversal of flow in less than $t_{c.}$ (Critical Period, sec.).

The critical period ($t_c$) is the roundtrip time of travel of the pressure wave from and back to the point of flow change and is given by the following equation:

$t_c = 2L/a$, where

L = length of force main between point of flow change and point of reflection, (ft) and
*a* = velocity of pressure wave, (ft/sec.). The velocity of a water hammer pressure wave depends on the physical properties of the fluid and the force main pipe, and the acceleration due to gravity. It can be calculated with the following equation:

$$a = \frac{4720}{\sqrt{1 + C1(kd/Ee)}} \quad \text{(U.S. customary units)}$$

C1 = 1, for pipe with expansion joints throughout
= 1 - $\mu^2$ for pipes anchored against axial movement (buried force mains, for example)
= 5/4 - μ, for pipes without expansion joints and anchored at the up-stream end
μ = Poisson's ratio
k = bulk modulus of water, taken as 300,000 $Ib/in^2$
d = pipe diameter, in
E = modulus of elasticity of pipe material, $Ib/in^2$
e = thickness of pipe wall, in

f) Check valve closure in less than $t_{c.}$

g) Any valve closure ( or opening) in less than 10 sec.

h) Damage to pump and motor if allowed to run back ward at full speed.

i) Pump stopped or speed reduced to the point where shut-off head is less than static head before the discharge valve is fully closed.

j) Pump started with discharge valve opened.

k) Booster stations that depend on operation of main pumping station.

l) Presence of quick-closing automatic valves that become inoperative if power fails or pumping system pressure fails.

4) References

Fluid Transients in Systems (Wylie & Streeter),
Collection and Pumping of wastewater (Metcalf & Eddy, INC)
Pumping station design (Robert L. Sanks).

**g. Field Testing Requirements for Force Mains.**

1) According to the Specifications, a contractor is required to field test newly constructed sewage force mains to pressures indicated on the drawings or in the special provisions. Develop the required test pressures based on operating and surge pressures and indicate them in the contract documents. This may require the calculation of these numbers based upon force main configuration and pump characteristics. Some of the information required to develop these numbers may be obtained from the pumping station design or found in the contract documents for the pumping station. Submit documentation or calculations for test pressures.

**h. Required Analysis for Hydrogen Sulfide ($H_2S$) Generation and Release.**

1) Generation.

a) Perform the analysis for the proposed design indicated in Part Two, Section 28 (Hydrogen Sulfide ($H_2S$) Control) to determine the potential for hydrogen sulfide generation.

b) Design the system piping layout to minimize the total piping lengths and pipe sizes within the constraints of the hydraulic design criteria, so as to minimize sewage detention time in the system. Downhill pumping conditions with a high point above the transition manholes will potentially cause the release and accumulation of hydrogen sulfide gas at the high points. Avoid high points in the design, if possible.

2) The discharge of sewage from a force main into a gravity sewer can potentially generate odor and the release of hydrogen sulfide at the transition manhole and in the downstream gravity sewer. Turbulence in the transition manhole should be minimized. Consider in the design and selection of gravity sewer pipe material downstream of transition manholes, corrosive effects of hydrogen sulfide, see the requirements in Transition Manhole, in this section and Part Two, Section 28 (Hydrogen Sulfide ($H_2S$) Control) and Part Two, Section 3 (Selection of Pipe Material-Gravity Sewer).