TWO PHASE FLOW IN PRESSURE SEWERS
AND SMALL DIAMETER GRAVITY SEWERS

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Introduction

In pressure sewer systems a small diameter sewer main is used, similar to a water main installation, shallowly buried and following the contours of the ground. A small pump is located at each home or group of homes. A grinder pump (GP) may be used which grinds the solids to a slurry, or an effluent pump is used in conjunction with a septic tank. The septic tank effluent pump system is referred to as a STEP system.

Small diameter gravity sewers (SDG) are a technology similar to STEP systems in that a septic tank is used at the home to capture the troublesome matter in sewage; grit, grease, bulky and stringy material. As the name implies flow is by gravity, negating need for pumps. SDG systems take a variety of forms. One is for the main to be placed at a constant downgrade slope between cleanouts, similar to conventional sewer design practice, although the slope may be less steep due to the reduced velocity required for scouring since septic tank effluent is conveyed. Another form of SDG sewer is placed as a pressure sewer main; i.e. following the contours of the terrain. This form of sewer may flow in the direction of up pipe slope so long as the energy grade line slopes properly. This latter type of SDG sewer is called a variable grade sewer (VGS).

Technologies of pressure sewers (PS) and SDG systems may be combined into one collection system, especially STEP and VGS.

The hydraulic analyses of common domestic water supply systems apply somewhat to PS and SDG systems, as does gravity sewer technology. However, there are important differences.

The particular hydraulic consideration discussed in this paper is the matter of two phase flow (air and water).

Entrance of air

When air (or gas) pockets or bubbles are present in a hydraulic pipeline, flow problems occur. To expel the air, air release valves are typically placed at summits within the pipeline, however as explained later that practice is insufficient when used with some configurations of PS or VGS systems.

Air may enter a pipeline in a variety of ways. Lescovich pointed out that a typical water conveying pipeline, say one mile long, would contain enough dissolved air to completely fill over 100 feet of the pipe, allowing that water may contain about 2 percent dissolved air by volume (1). Air (or gas) volume present in sewage would differ by some unknown amount from that in water, but the concept is the same. The solubility of gases is a factor of pressure, so as the wastewater is conveyed through a pipeline over varying elevations, gas comes out of solution at higher points. Once out of solution, it will not readily return to solution.

In the case of a pressure sewer, air may also enter the main by vortexing at the pump, if pump submergence is shallow. For that reason, it is preferred to submerge the pump intake sufficiently, a factor of discharge rate.

When the pipeline configuration is such that the static hydraulic gradient of the main is at an elevation lower than the elevation of an adjacent pump intake another source of air entrance is presented. Suppose a time when flow in the system is zero or minimal. Then the hydraulic gradient for the main would be at or near static elevation. A siphoning condition can then develop, causing flow through the pump even though the pump is not running. This flow continues until the liquid level in the pump vault is lowered to the elevation of the pump intake, where the siphon is broken. Air then enters the service line connecting the main and the pump, and is forced into the main when that pump again operates. This is shown diagrammetrically in Figure 1.

An enormous amount of air may be introduced to a system at start-up, or following the repair of a ruptured main. Means of purging such large volumes of air should be provided by system design, and methods described in maintenance training.

Depending on configuration, a pressure sewer or VGS sewer main may flow "uphill" or "downhill", as shown in Figure 2. When some portion of the collection system is at an elevation higher than the point

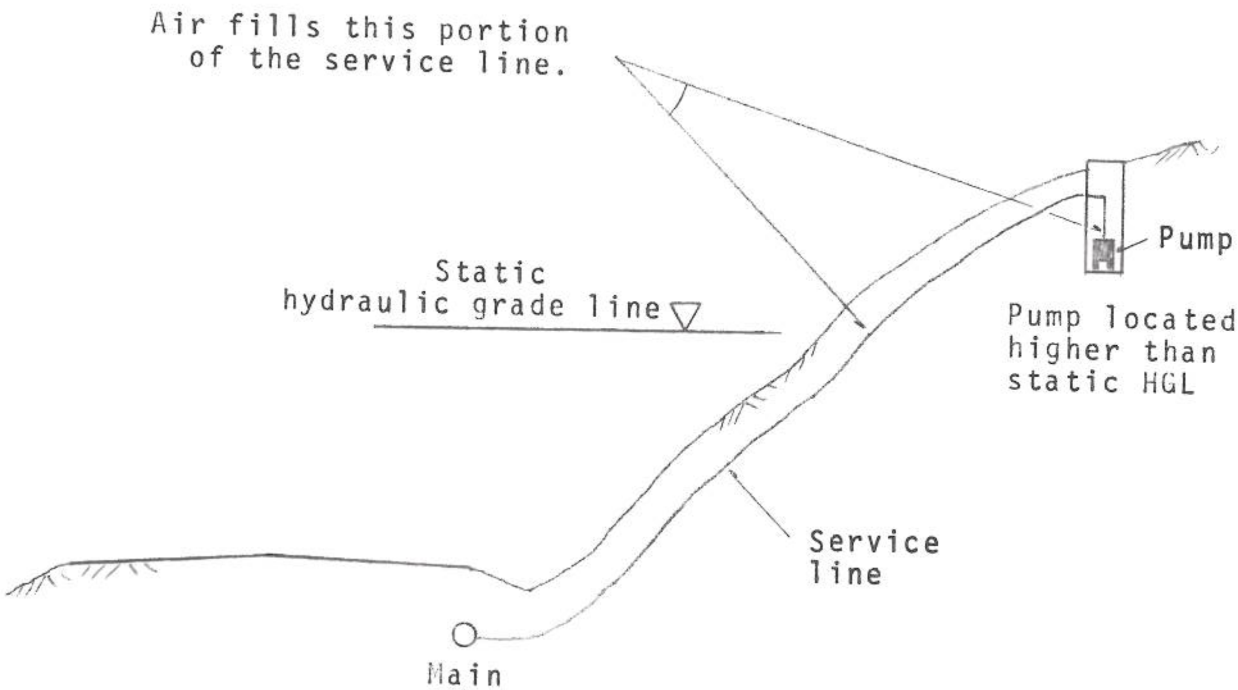
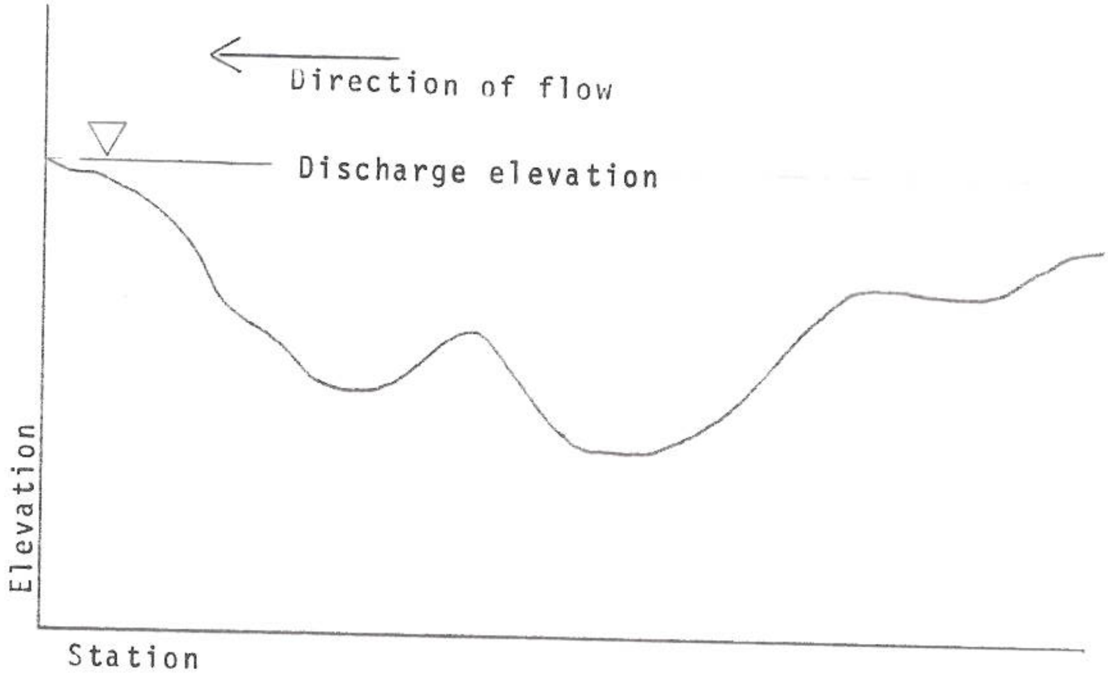
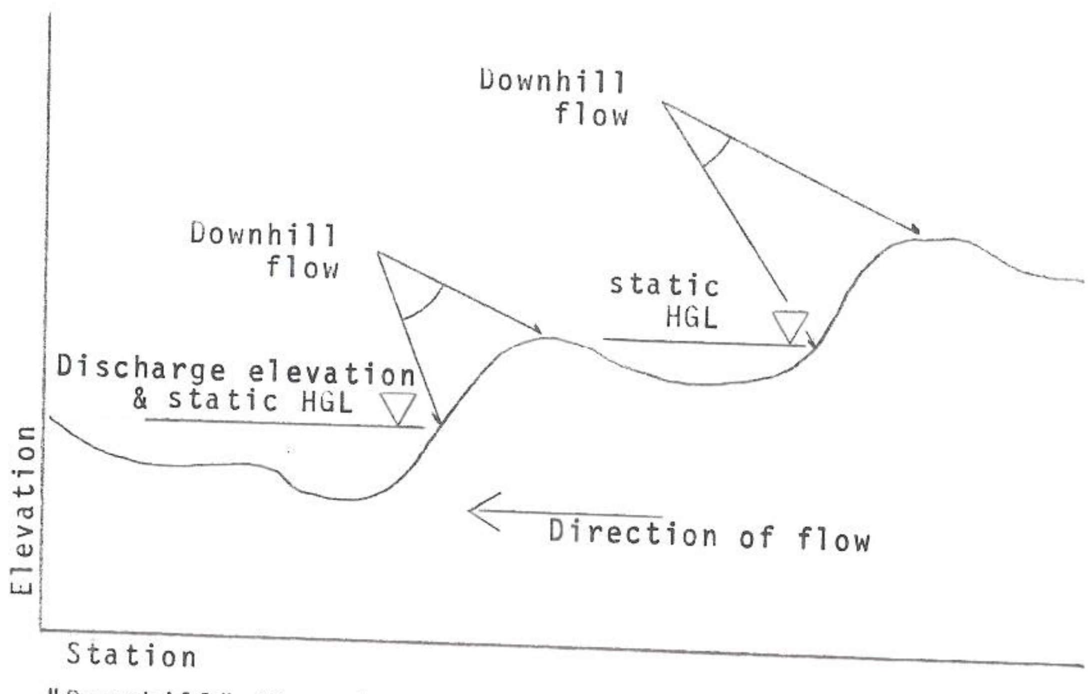


Figure 1. Cross section at pump installation. Pump is located higher than HGL of main.



"Uphill" flow. All parts of collection system are lower than the point of discharge to atmosphere.



"Downhill" flow in portions shown.

Figure 2. Profiles of two pipelines showing uphill and downhill flow.

of discharge to atmosphere, flow is "downhill" within some reaches of the piping. During static conditions with downhill flow, portions of the system will drain and fill with air, drawn into the main as previously described or from the main terminus, or through leaky pipe joints at zones of negative pressure.

While it is impossible to totally prevent the accumulation of air (or gases) within the piping system, the volume can be minimized by design, and negative aspects can be attentuated.

Effects of air in pipelines

It may be that engineers tend to adopt a conservative "C" or "n" flow coefficient to allow for unforeseen hydraulic conditions or demands, but that method is insufficient to allow for ventilation of pipelines. Some examples of air problems are offered.

Lescovich presented an explanation of classic air bound pipeline (1). Referring to Figure 3, suppose a situation exists where a pump is used to pump water from one reservoir to another. Water in the first reservoir is at elevation zero, and the pump has a shutoff head of 105 feet. Water in the receiving reservoir is at elevation 80. No portion of the interconnecting piping is at an elevation higher than 80 feet, the pump is running, but there is zero discharge.

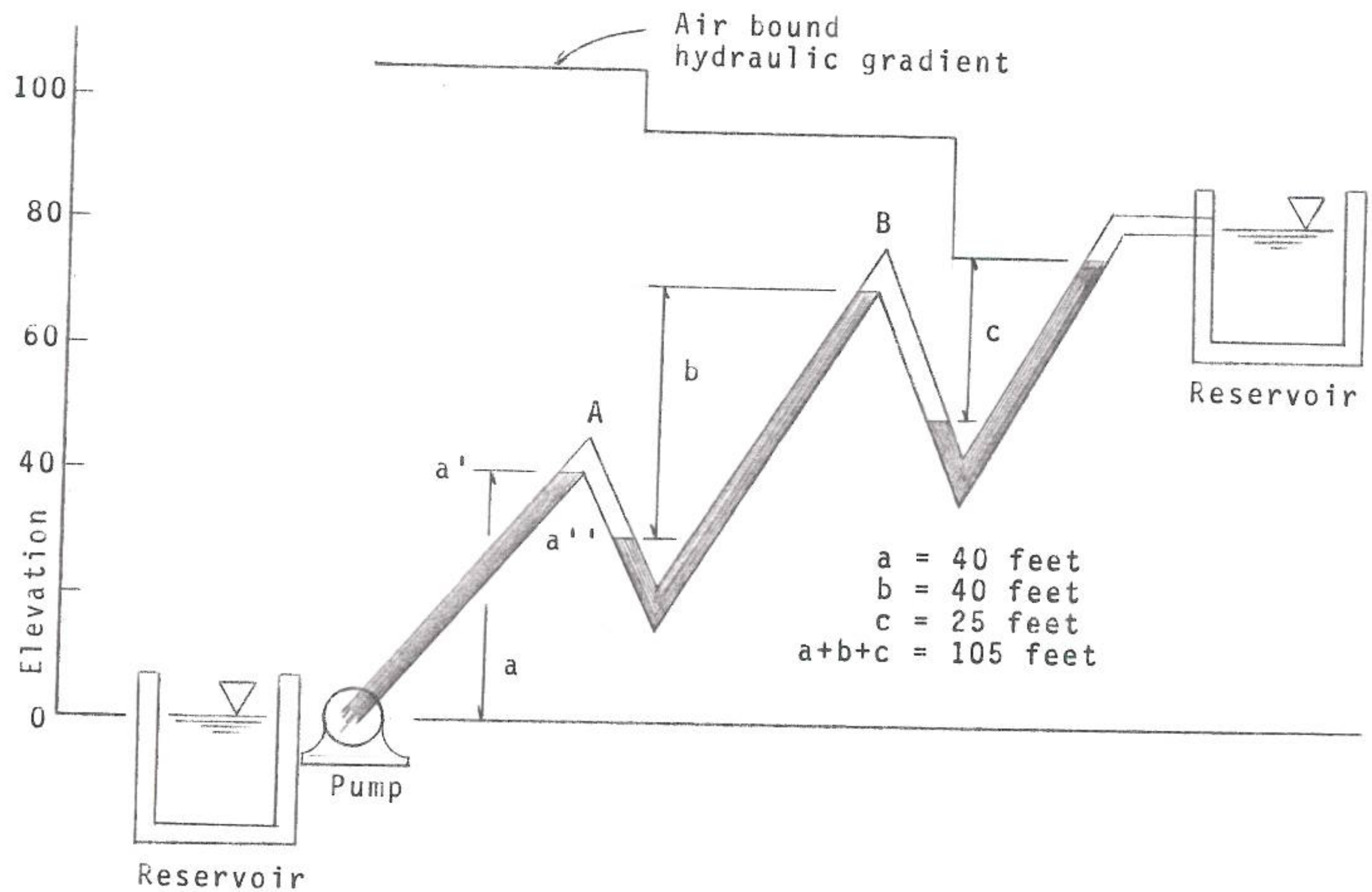


Figure 3. Air bound hydraulic gradient.

In this example, air is trapped at two summits, A and B. The air is displaced some in the direction of intended flow, as shown. At summit A the pressure at a' and a'' is the same (65 feet of head) even though the liquid level of a'' is ten feet lower in elevation that at a', due to displacement of the water. The same type of condition exists at summit B. Summing a+b+c=105 feet, the shutoff head of the pump. No flow is occurring, and the static hydraulic grade line is not at one elevation, but instead stepped as shown. One method which has been used to determine the presence and location of air in pipelines is to create a pressure on a static main, then determine the hydraulic gradient at particular stations. The example shows how countless pumps are no doubt operating at higher heads than necessary and points out a useful tool in hydraulic analysis.

In addition to air bound situations there are other concerns. When air is present in a hydraulic pipeline, flows are erratic, unpredictable, and have high head losses. Check valves are hammered and destroyed. Pumps fluctuate over a wide range of their curves. If the air pocket is stationary, acid may form on the pipe wall, creating a corrosive situation. Gravity flow or intermittent gravity flow may allow grease and other solids to air plate on the pipe walls. For the reason of grease and other solids plating, GP systems are not recommended for use in downhill flow situations.

When flow is downhill and siphoning through the pump occurs, the pump itself will often become airbound. When the liquid level in the pump vault again rises to "pump on" level, air is trapped in the volute. The pump will run, but will not pump water. This condition may continue until the motor burns out. Under the best circumstances a maintenance call is occasioned.

Pump and motor submergence cools that equipment, prolonging equipment life. Nonsubmergence of the motor violates explosion proof requirements (NEC 501-8(a)) (2).

Previous research

Problems of air in pipelines, requiring special design considerations have been the subject of intensive design efforts on some larger systems. Typically these pipelines convey water from mountain regions to distant population centers, and are on overall descending grades. The large size of the systems make them dissimilar from PS or SDG projects. The problems are similar though of smaller magnitude when small diameter pipes and comparitively low velocities are used. The large size of the aqueduct projects has justified large engineering investments.

Burton and Nelson describe the use of upstream control on a closed conduit in Texas 320 miles in length and ranging in diameter from 54 inches to 96 inches (3). Pipe stand and pipe check and vent structures were used, among other reasons to maintain a full pipeline upstream from the control structure to reduce or eliminate surge and air entrainment problems. A pipe check and vent is shown in Figure 4. Whitsett (4) drew on 30 years of experience with 415 miles of mains in Southern California to describe problems with air entrainment on large pipelines of overall descending grade (downhill flow). Pipelines as large as 18 feet in diameter were mentioned, with flow rates as high as 750 cubic feet per second. Pipe stand control structures were used to eliminate air entrainment problems.

In his doctoral thesis, Kent investigated the entrainment of air in downhill flow (5). A 4 inch diameter clear plastic pipe was used, which allowed observation and scientific evaluation.

Air pockets form in the pipeline, as shown in Figure 5. When the initial depth of flow is not below critical, a hydraulic jump cannot be formed. Nevertheless, the action below an air pocket closely resembles a jump. The jump is violent, with associated high head losses, and bubbles are ripped from the pocket. The bubbles move downstream, with smaller bubbles traveling faster that larger ones. The bubbles tend to join, and form another pocket from which bubbles are again torn, and the process continues. The pocket may be stationary, moving upslope, or moving downstream, depending on the diameter and slope of the pipe. Kent developed equation 1 to describe the velocity required for the pocket to remain stationary,

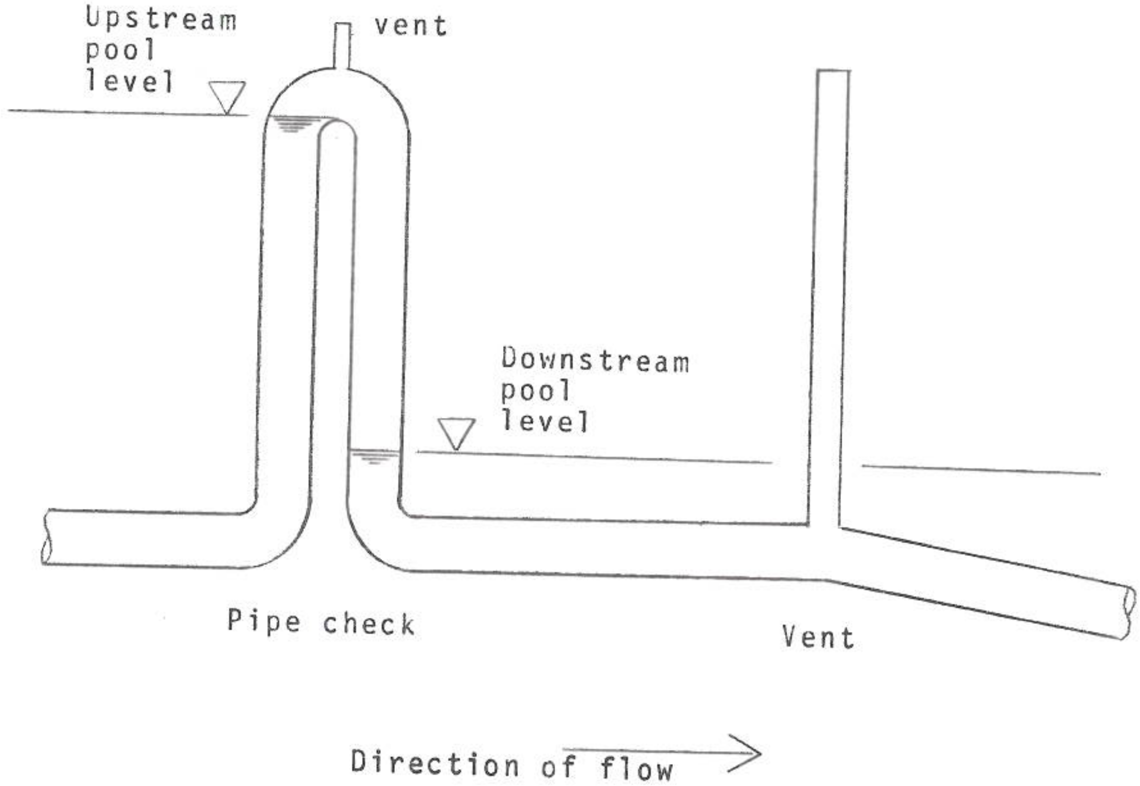


Figure 4. Pipe check and vent.

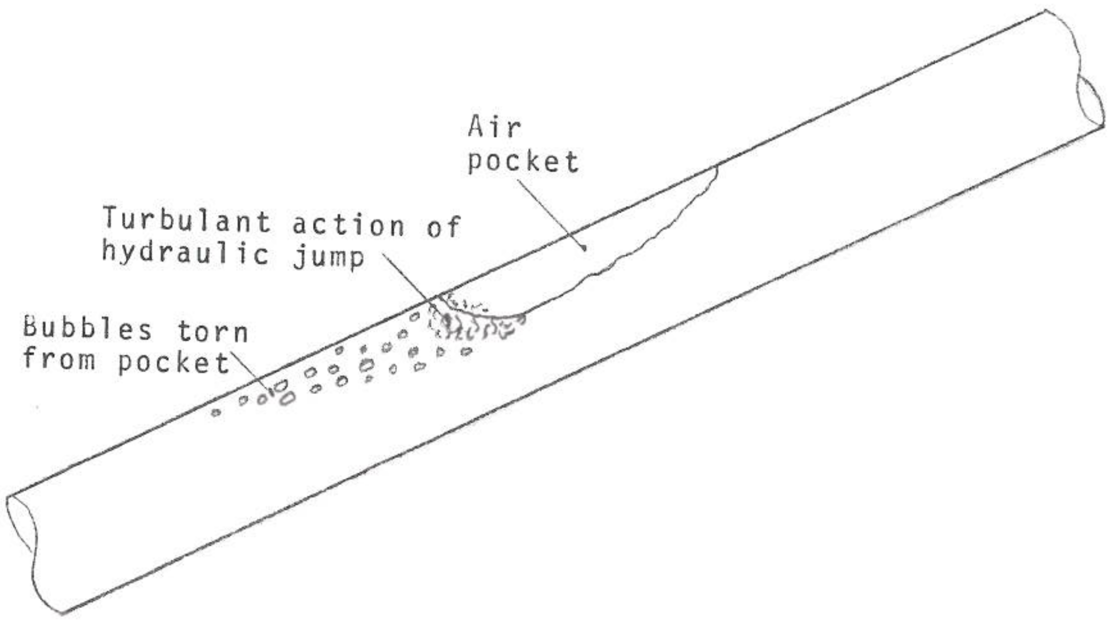


Figure 5. Sketch of air pocket and bubbles encountered in downhill flow.

which is the point where drag and buoyant forces are equal.

$$V_{min} = C_o^{1/2} (gD \sin \theta)^{1/2} \qquad \text{(Eqn. 1)}$$

where V_{min} = the minimum velocity to keep an air pocket stationary, ft/sec.

$C_o^{1/2}$ = a constant when the air pocket length is $\geq$ 1.5 pipe diameters, dimensionless.

g = acceleration due to gravity, 32.2 ft/sec^2

D = pipe diameter, ft.

θ = angle of pipe from horizontal

For 4 inch pipe, $C_o^{1/2}$ = 1.23. By calculation using typical values for pipe slope, V_{min} in PS or VGS applications will typically range from about 1/2 to 2 feet per second, the higher values related to larger diameter pipes and steeper slopes. In most PS and VGS systems, the air will not become purged in time by movement of air to the terminus of the pipeline, as flows of sufficient velocity are not of long enough duration. The air will be moved downstream only a limited distance, to return upslope when the peak flow condition has passed.

The head loss due to the presence of air developed by Kent is given in equation 2.

$$h_L = \frac{\lambda \sin \theta}{100} \qquad \text{(Eqn. 2)}$$

where h_L = head loss per foot due to air, ft. of water.

λ = percentage of air by volume

θ = angle of pipe from horizontal

From equation 2, head loss increases with quantity of air and as pipe slope increases. By a few sample calculations, it is seen that the head losses due to air can be large and of substantial importance to PS or VGS design. For example, a 1 percent volume of air, with a 10 percent (5.7 degree) pipe slope would correspond with a headloss of 0.001 ft/ft. At 10 percent air, a headloss of 0.01 ft/ft would be calculated. Recognizing that these head losses would be additive to losses determined by hydraulic equations, we see that they are easily excessive.

Experiments performed

To better understand the phenomena of two phase flow, the author performed several experiments.

A 1-inch diameter transparent plastic tube, about 30 feet long was fastened to wall-mounted pegboard, by hooks which could easily be adjusted to alter the pipeline profile. Tees were placed in the tubing periodically, and fitted with vertically rising 1/2 inch clear tubing to serve as piezometers or as air release points, depending on their location. A pressurized water supply was connected and a venturi aspirator used to inject dye to make the flowing water (and air pockets and bubbles) more visible, or to introduce air to the pipeline.

The experiment was operated for several hours daily over a period of about two weeks. When flow was uphill, the system ran quietly and predictably. When air was introduced to the system, it was effectively expelled by the air release vents. At high flow velocities, some air bubbles would pass the vents, but the volume was small, and no particular difficulties were noted.

It was a different matter when flow was downhill. The larger volume of air created by the draining of portions of the tubing changed the hydraulics completely. Pockets and bubbles formed as described by Kent. The violence of the hydraulic jumps was impressive. Flow was highly erratic, unpredictable, and accompanied by high head losses. Water would suddenly spurt out of the piezometers and tubing used as air release vents, and the hydraulic grade line was much steeper than when flow was uphill. Under uphill flow conditions, water would never spurt from the vertical tubing, nor would the hydraulic gradient rise to near the top of the tubing, even at much higher flow rates.

This was a worthwhile experiment, and easy to construct and operate. It is a recommended experience for engineers contemplating two-phase flow design.

Considering that the experiment may not represent PS or VGS sewer application by virtue of the small diameter of the experimental tubing, another test was conducted. In this we used 6-inch diameter transparent plastic piping, about 100 feet long, sloped at 2.5 percent, and flowing at 185 gpm, or about 2 feet per second velocity. Discharge was to a receiving vessel with liquid level at an elevation such that the static hydraulic grade line intersected the sloping pipes as shown in Figure 6. During static conditions, the length of the ellipse formed by the water surface in the pipe at the static HGL was about 20 feet long. When flow began, the jump would develop about 3 to 4 feet upstream from the toe, or most downstream point of the ellipse.

Test results were fairly similar to that obtained in the previous test and as described by Kent, excepting for a few parameters. Bubbles traveling downstream would often pass pockets rather than joining them. Very small bubbles (approximately 2 millimeters diameter) seemed to move downstream at an effective rate slower than larger bubbles, in that they took a more erratic path, darting about as they traveled.

Air bubbles and pockets were effectively removed by a 1/4 inch

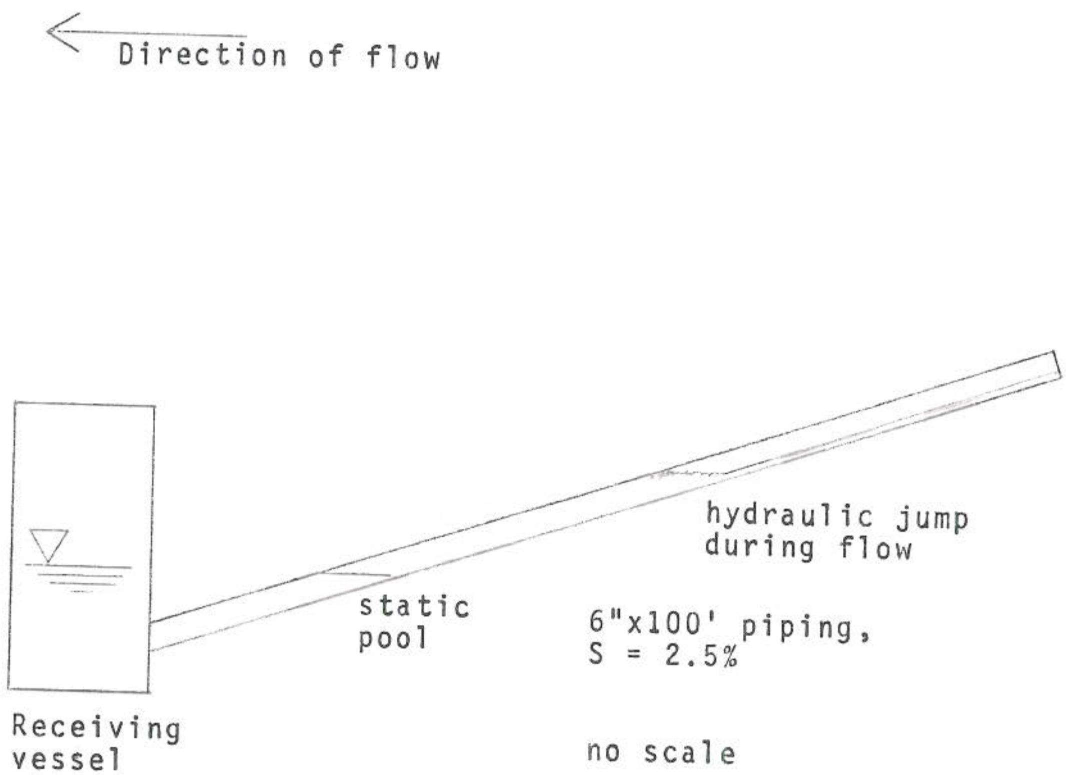


Figure 6. Test apparatus using transparent piping.

diameter hole drilled in the crown of the pipe. When the hole was placed 14 diameters below the jump, the vent was an estimated 95 percent effective in removing air. A greater distance would not have been any more effective.

This work was being done to advance the knowledge of PS and VGS hydraulics generally, but in specific design of the Glide, Oregon pressure sewer system. Glide is the world's largest STEP system, and combines a few VGS connections (6). Downhill pumping was mandated in some instances by topographic conditions and yet it was necessary to provide the most reliable hydraulics possible. Twenty-five miles of main are involved. The system is sized to serve 7,300 people, and initially would serve 2,000. Peak flows were expected to be 1,050 and 350 gpm respectively.

Much of the collection system had been installed at the time these experiments were being conducted, yet design refinements were continuing. It was decided to investigate the hydraulics of two-phase flow in a two-mile portion of the main.

The test section involved 2,350 lineal feet of 12-inch diameter main, and 8,270 feet of 10-inch. The maximum elevation difference of the pipeline profile was 58 feet. Two automatic air release valves (AARV) were a part of the original installation, but by the time testing was completed, one more had been added, and one relocated, for a total of 3. The AARV's were sewage type air release valves, not vacuum or combination valves, with 5/16 inch orifice.

Flows of from 200 gpm to 700 gpm were produced by pumping river water using a diesel fuel powered pump. Flows were measured using an impact tube type meter (Metraflex model 23) and check with reasonable agreement using the XY coordinate method calculation of water drop, also checked against the pump curve. Pressure recording stations were located at four points along the main. Laboratory test gauges were used, the accuracy checked daily with a mercury manometer.

The main was slowly filled with water over a period of two days, and air purged. A plot of the profile of the main is shown in Figure 7. Drawn on that plot are the static hydraulic grade lines, as well as the theoretical dynamic hydraulic grade line based on the Hazen Williams equation using an assumed C value of 140 and a flow rate of 600 gpm. The assumption was temporarily made that flow would break to gravity flow in the steeply sloped pipe reach between approximate stations 70 and 80. In developing the dynamic gradient, no allowance was made for headlosses due to air. The dynamic HGL was drawn to allow a quick visual comparison between actual conditions and theoretical conditions without allowances for air.

The system was then slowly started up, with constant checks being made that the air release valves were working properly. The system

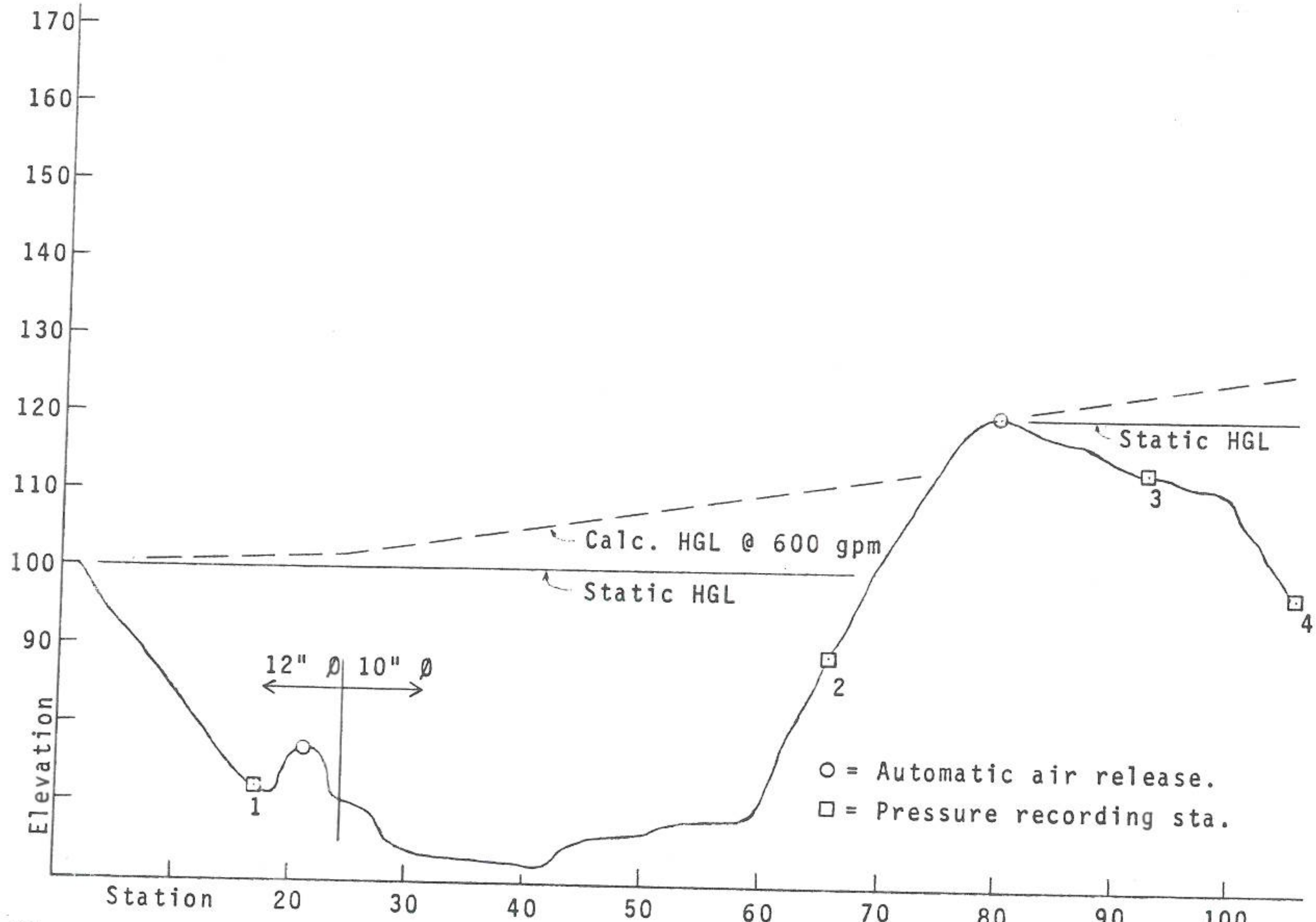


Figure 7. Profile of two mile test section of Glide pressure sewer system showing static HGL and theoretical HGL @ 600 gpm, ignoring air considerations.

was operated for a full day at flows ranging from 200 to 600 gpm. As expected, headlosses were high. From pressure readings at the observation stations, the elevation of the hydraulic grade line was determined. A typical HGL for that day, at a flow rate of 600 gpm is shown in Figure 8. This has been drawn as a straight line between pressure stations for ease in viewing, but in actuality the headlosses would vary in each reach, and the true HGL would take on other shapes. Notice how much higher the headlosses are in actuality at 600 gpm than hydraulic calculations would predict without accounting for air. Realize that this was a two mile test section typical of the 25 miles of main comprising the system. Such a system that ignored special air considerations in the design would not seem to operate suitably at all.

The shutoff valve at station 0 was then slowly closed while the pump was still running, and pressure readings taken at the stations at one minute intervals. The close time intervals were necessary as the static pressures were constantly changing due to air. A typical plot is shown in Figure 9. Note that the pressurized static HGL does not attain a single elevation, thereby revealing trapped air, much as shown in the example, Figure 3. Clearly, air was trapped in the reach between approximate stations 70 and 80. No doubt much air was contained between pressure station #1 and #2, but is not revealed by the pressure readings due to the fairly flat shape of the pipeline profile between these points.

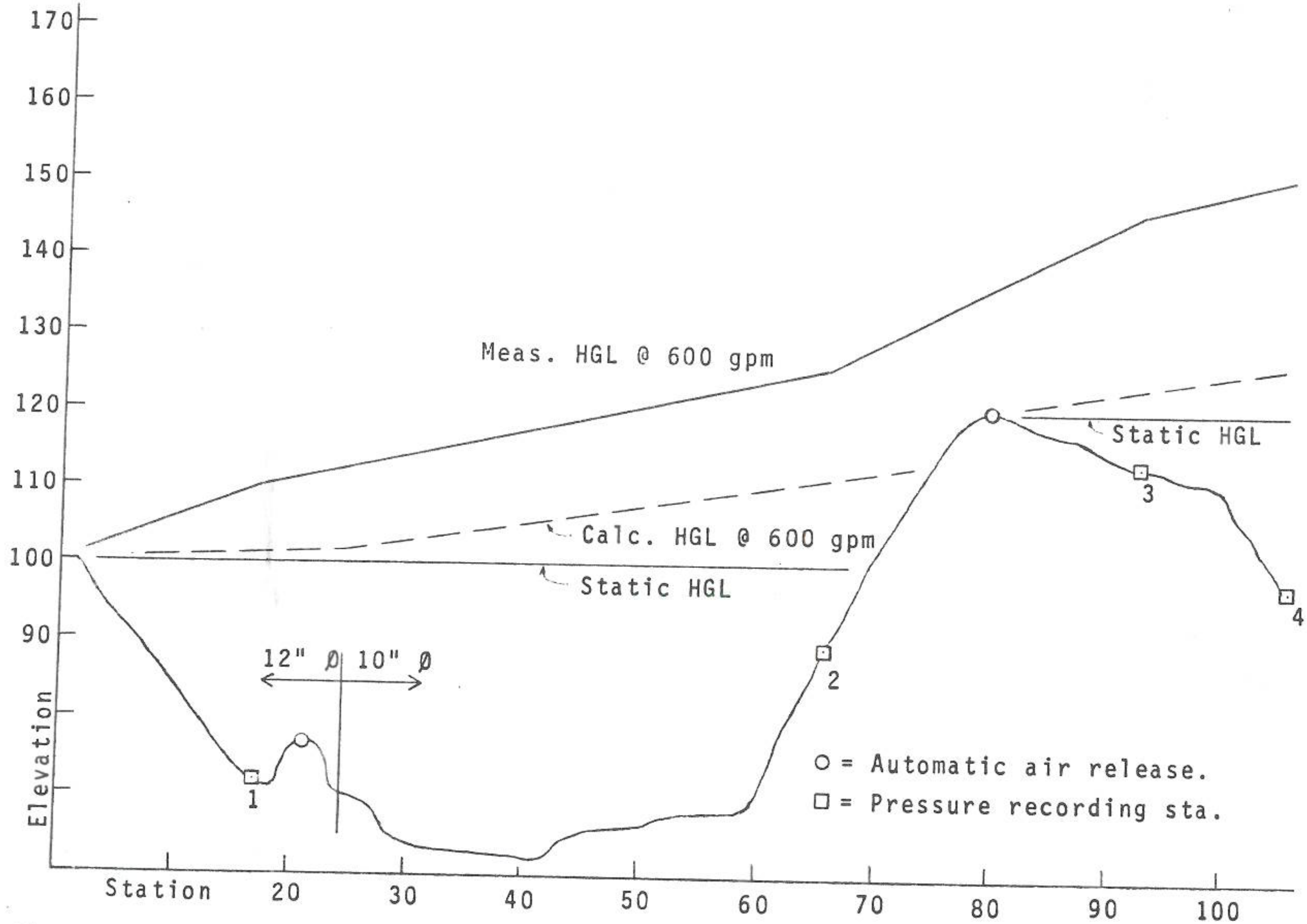


Figure 8. Measured HGL at 600 gpm.

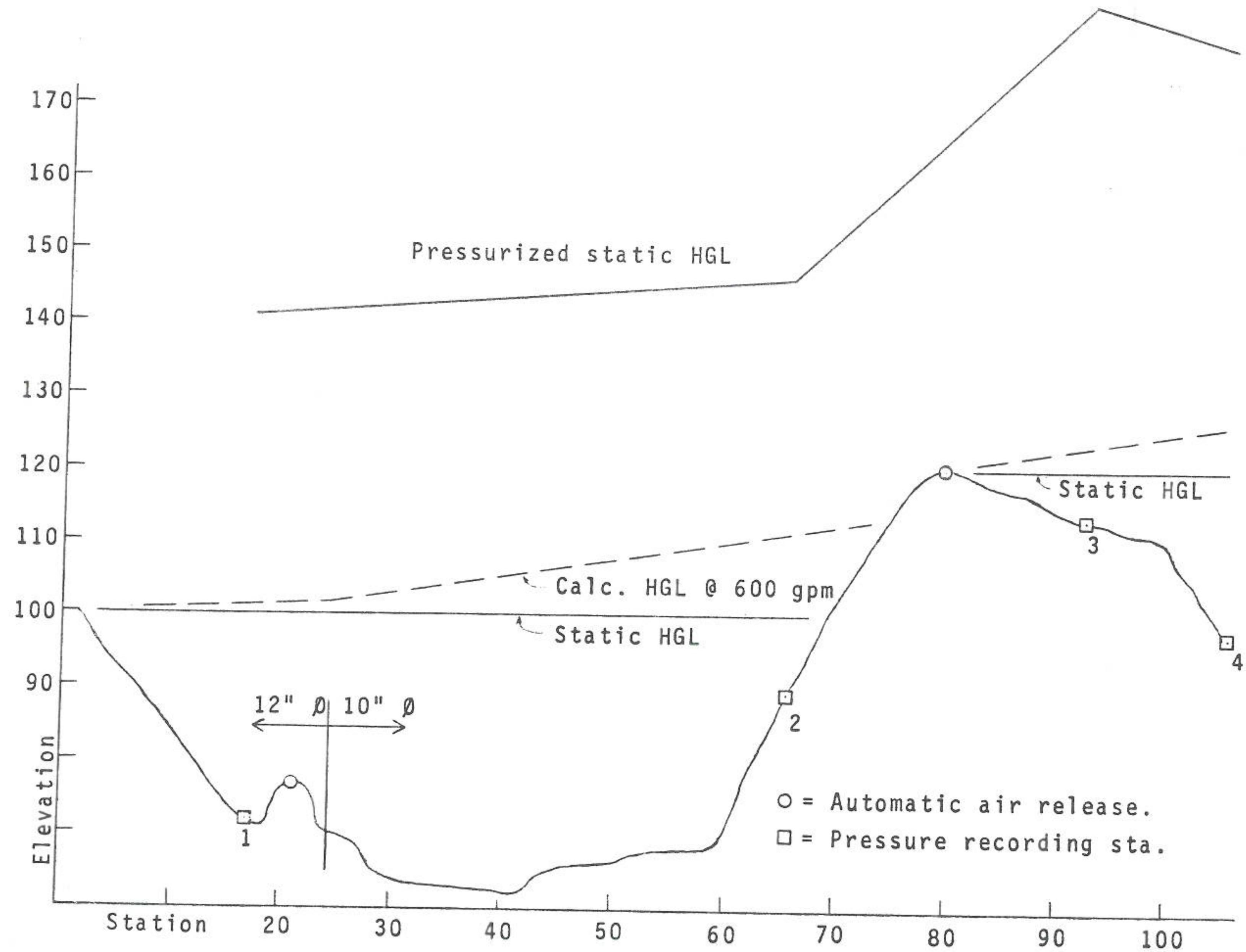


Figure 9. Pressurized static HGL.

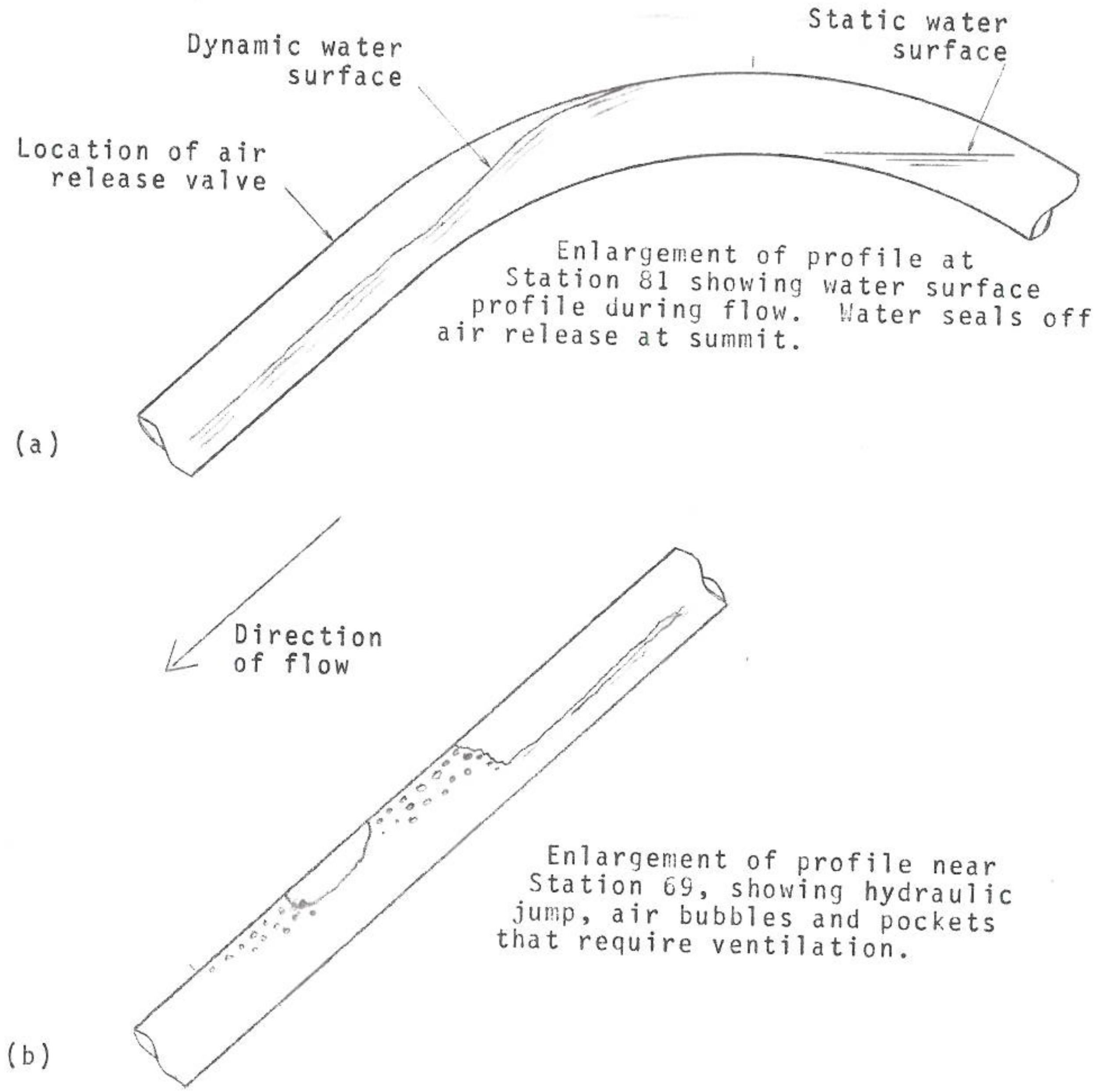


Figure 10. Enlargement of pipeline profiles at Stations 69 and 81.

Then, some modifications were made to the piping system. The air release valve at about station 81 had been placed on the exact summit of the pipeline. This was relocated to a point several hundred feet downstream. An automatic air release valve was also added at station 69.

These changes had been anticipated from experience in operating the model studies. The reason for the change at station 81 is that under static conditions, water would stand to the right of the invert summit as shown in Figure 10a. As flow begins, the profile of water surface would soon seal off the entrance to the air release at the summit. Yet, as flows increase and the hydraulic grade line rises in the reach between stations 70 and 80, over 4,000 gallons of water (septic tank effluent) fill that reach. The displaced air must be expelled.

The situation at station 69 is shown in Figure 10b. Under flow, a hydraulic jump is formed where the dynamic hydraulic grade line intersects the main. The jump is violent and pumps air bubbles into downstream reaches . To capture and ventilate that air, the connection of the air release assembly to the main must be made below the jump.

Once installations of the air release valves had been made in the revised locations, flow at various rates was again introduced to the system. Time was required to work the air out of the pipeline.

During this period, gauge readings were taken at the pressure stations. Typical results are shown in Figure 11. Note that the HGL is much lower than in Figure 8, and as time progressed with flow occurring, the HGL continued to lower and become of flatter slope, approaching theoretical.

Design of the Glide, Oregon system

A portion of the Glide piping system was designed and now operates as previously described, and as shown in Figure 11. Another portion of the collection system had a different profile, characterized by downhill runs that were not so steep nor distinct, and multiple locations of hydraulic jumps. Treatment of the situation by installation of air release valves as used at station 69 and station 81 was not practical.

The type of profile referred to is shown in Figure 12. To obviate the problems of downhill flow, upstream reaches were kept full by the use of standpipes. The standpipe design is shown in Figure 13, and its application shown in Figure 14. The standpipe was PVC piping, located in an area of relatively steep side slope topography so that the standpipe could be buried at the usual depth and run a short distance to attain the desired elevation at the crest to keep the upstream reaches submerged. A hydraulic jump occurs in the downleg of the standpipe. This downleg is steeply sloped, and of larger diameter to reduce flow velocity and prevent the conveyance

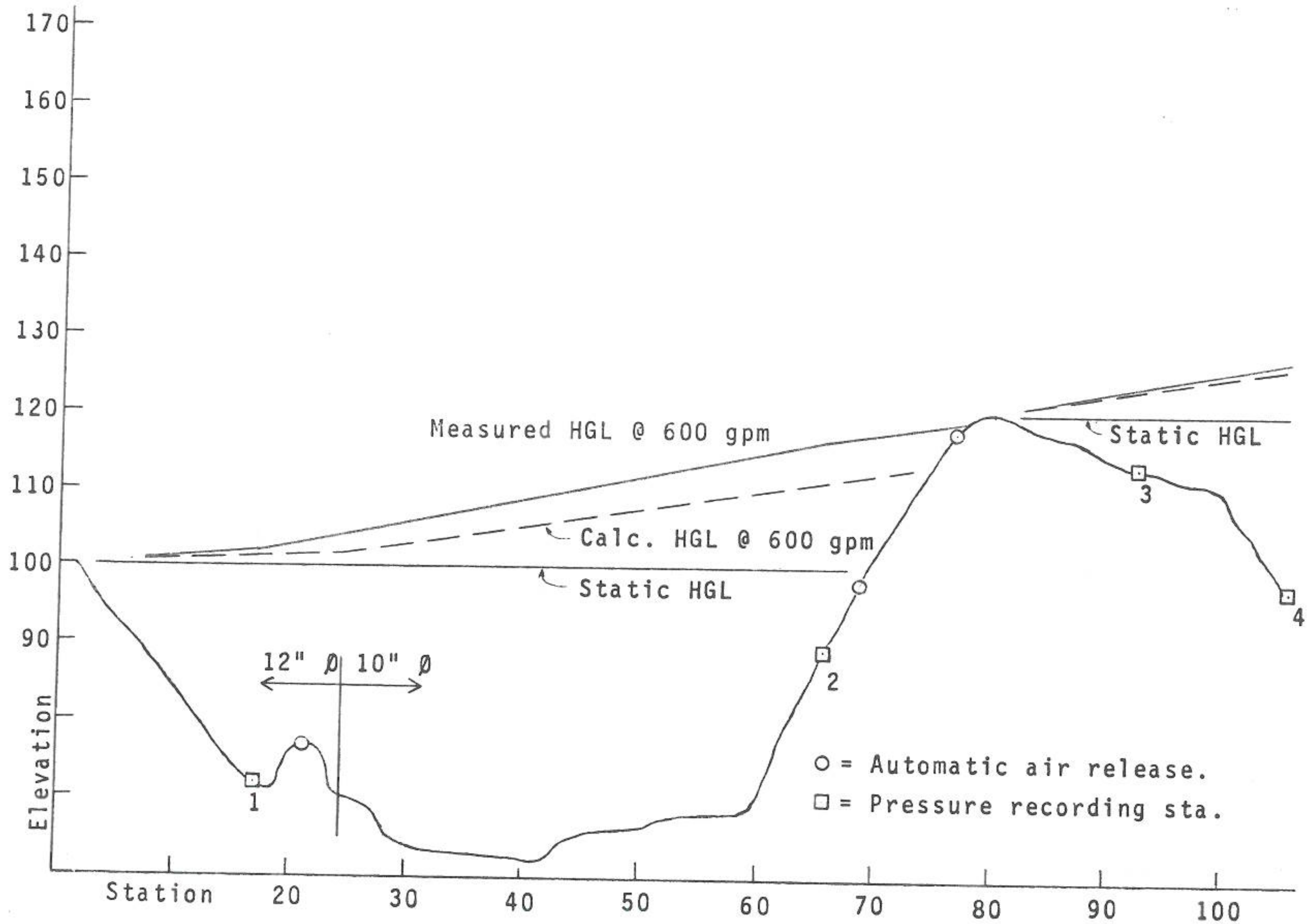


Figure 11. Measured HGL @ 600 gpm after alterations of pipe ventilation.

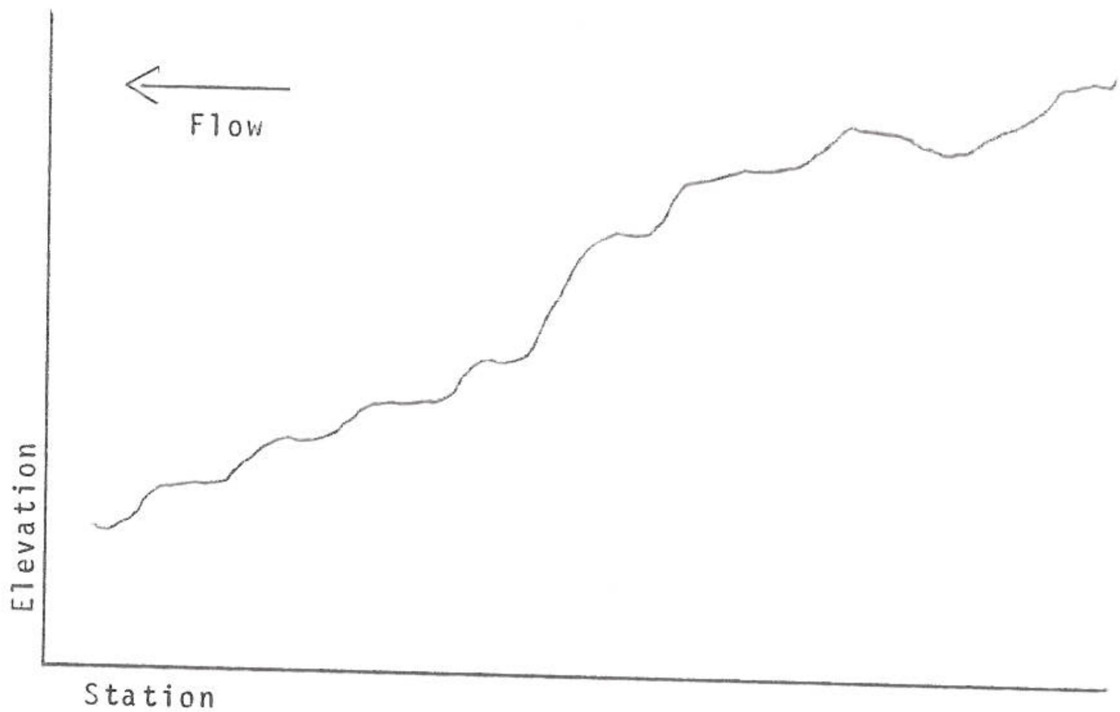
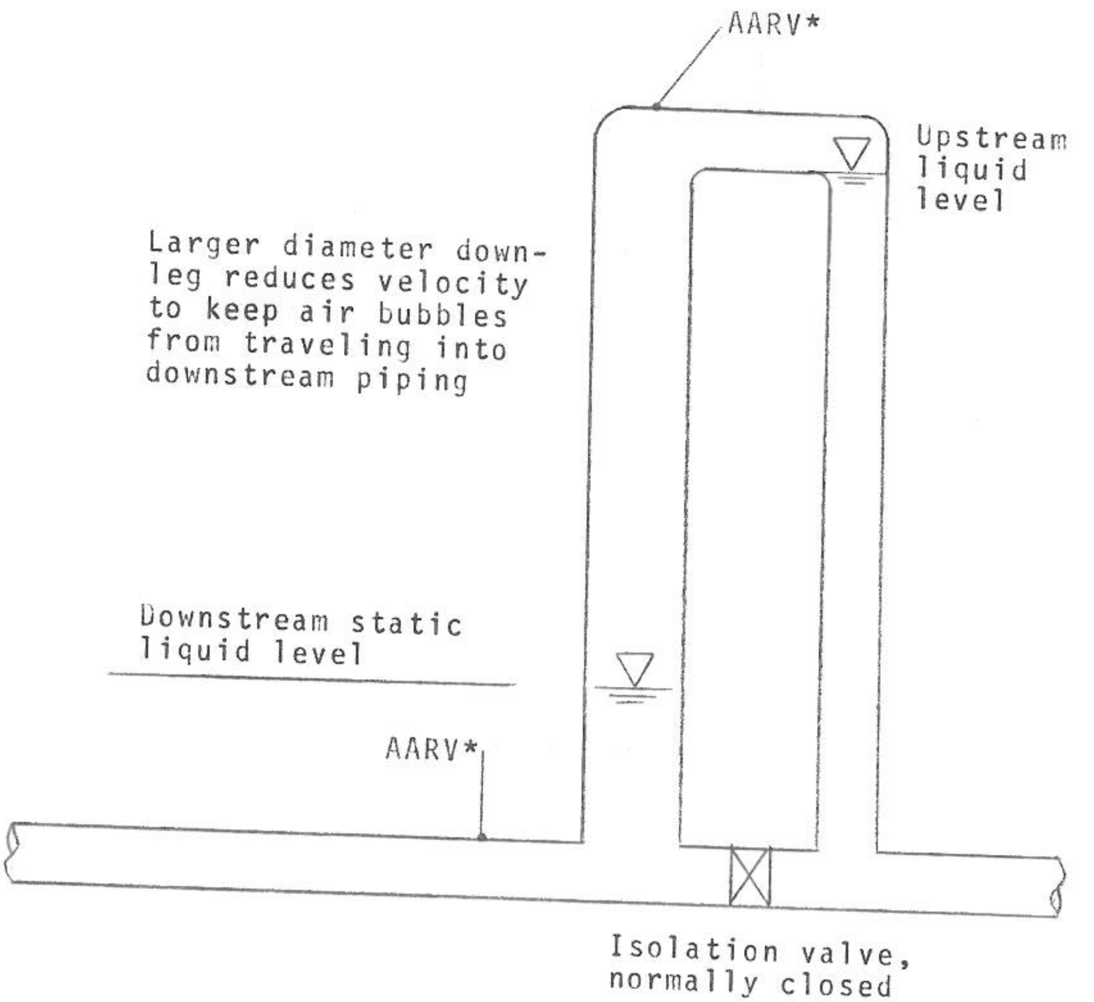


Figure 12. Pipeline profile showing numerous downhill flow situations.



AARV* = Automatic air release valve vented to soil bed for odor absorption

Figure 13. Standpipe.

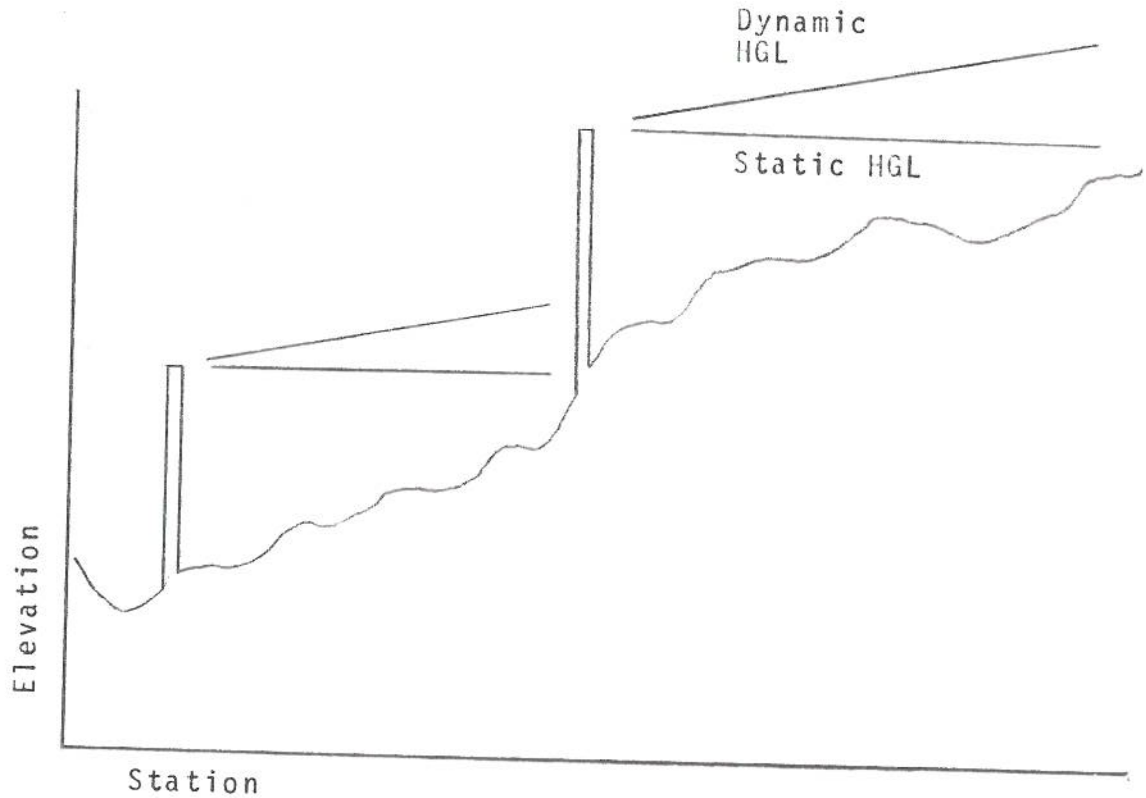


Figure 14. Pipeline profile using standpipes, showing static and dynamic hydraulic grade lines.

of air bubbles into the downstream reaches. Air release valves were used at the exact summits of the pipeline upstream from the standpipes.

An investment of several months engineering time was made to investigate the use of special backpressure sustaining valves in lieu of standpipes. Despite special attention given to the design and selection of the valves by valve company engineers, none worked properly. A variety of problems developed. In some cases, the valve opening and closing pressures differed too much for them to be used. Some designs would not close completely enough, especially if even small solids were caught on the valve seat. Some valves would constantly hunt for position, and others were so complicated and expensive as to preclude their use. Valve failure modes were undesirable. Neither failing open nor failing closed were suitable options. The standpipes were passive and accomplished the goal of maintaining full upstream reaches simply, realiably, and economically.

As air release valves are normally used on a force main, only small volumes of air (gas) are expelled. Large volumes are expelled at installations such as at station 69, 81, and the standpipes. Expecting odor problems from hydrogen sulfide gas, the air release valves were vented to soil beds for odor absorption (7,8).

When a septic tank was located at an elevation higher than the dynamic HGL, a VGS installation was used. The tank was fitted with a 1¼-inch diameter outlet tee, located at an elevation lower than it would be in septic tank practice. The purpose of the lowered level was to provide reserve volume within the tank. In the event valves on the pressure sewer main were closed to allow for repairs on the main, flow from the home could continue for at least one day before tank overflow.

The VGS service line was 1¼-inch PVC, placed without regard to grade, the same as used on the STEP installations. A check valve was used on the service line at the main in those cases where a STEP pump could pump to a VGS tank if an isolation valve on the main were closed.

Operating experience with the Glide system

Over three years have passed since the Glide, Oregon system became fully operational. During this time, performance has been carefully monitored. Air release stations are inspected frequently. Pressure readings are taken at designated stations throughout the system, and compared with previous charts.

The automatic air release valves have proven reliable. Rarely does one malfunction, and never to cause any difficulty, contrary to the general reputation of sewage type air release valves. This performance is attributed to the low grease and solids content characteristic of septic tank effluent (9).

No odor has ever been detected at air release stations vented to soil beds. It is not known if odor problems would exist if the valves were vented in the usual way, but it is logical to expect.

Peak flows are on the order of 350 gpm, while the system is sized for 1,050 gpm, so it operates far below its ultimate capacity. However, on two occasions flooding of the area occurred, with standing water on the ground surface, which entered the pressure sewer pump vaults. Peak flows to an estimated 1,200 gpm occurred at those times. Some of the pressure sewer pumps were dominated by others to shutoff head during these periods as would be expected since flow exceeded design. The very fact that design flows could occur, and in fact be exceeded, testifies that the system was performing properly.

There has been no evidence of any problem wiht air plating, or any other problem with the collection system piping for that matter. Some treatment occurs in the pipeline, but it is unknown how much can be attributed to air entrainment at the hydraulic jumps. (9,10).

There are a few installations where pumps are located at an elevation above the static hydraulic gradient. These pumps occasionally become air bound. In one case, a pump was located at an elevation substantially higher than the static HGL, and higher than the dynamic gradient.

About weekly, the service line at this installation would become air bound similar to as shown in Figure 3, and the pump would be driven to shutoff head. This was converted to a VGS connection, and no problems have occurred since. The trickle gravity flow from the septic tank to the service line allows air to escape from the service line back through the tank outlet tee rather than becoming trapped by the sudden and larger flow produced by the pump.

There never has been a problem with the VGS installations. Concerns that zooglea or other matter might form in the service lines have so far proven unfounded. From evidence of the effluent level in the VGS interceptor tanks it is apparent that the level has risen perhaps a foot at times. Overtopping of the tanks has not occurred, so apparently this small rise in liquid level has developed enough head to overcome whatever restriction developed in the service line.

Summary and conclusions

When flow is "downhill" in a closed conduit, such as a pressure sewer or variable grade gravity sewer, a hydraulic jump is formed at the intersection of the pipe and the dynamic hydraulic gradient. Bubbles are ripped from air pockets and conveyed further into the piping system. The presence of air (or gas) causes flow to occur in ways that would not be predicted by standard hydraulic equations such as Mannings or Hazen Williams. Head losses are high, and flows and pressures are erratic.

By proper design, systems can be engineered to flow downhill and avoid air problems. The techniques are not in common knowledge. An air release station is placed a short distance downstream from the jump, and at the upper reach to vent the air displaced. Standpipes may be used to locate the jump in a steeply sloped pipe section that may be of larger diameter to produce a low flow velocity.

Septic tank effluent pump pressure sewers (STEP) and septic tank effluent variable grade gravity sewers (VGS) have been effectively combined on the Glide, Oregon project using hydraulic techniques herein described.

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