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Understanding the Impact of Mesh on Tank Overflow System Capacity

Jonathan B. Burkhardt^{1,2,*}, James A. Goodrich², Jeff Szabo², John Hall², Jake Crosby³, Seth Tourney³, and Robert Clement³

¹. U.S. Environmental Protection Agency, National Risk Management Research Laboratory

². U.S. Environmental Protection Agency, National Homeland Security Research Center

³. U.S. Environmental Protection Agency, Region 8

Abstract

A 2016 incident that resulted in damage to a water storage tank's roof motivated pilot-scale experiments to be conducted to determine the impact of mesh on tank overflow capacity. A clean mesh installed near the outlet of an overflow system did not reduce the capacity during the weir dominated flow regime. The impact of a mesh was found to be a reduction in the area available to flow, which was found to lower the achievable capacity through the system. Considering only the head loss or pressure drop associated with the mesh and not area reduction resulted in an overestimation of achievable capacity, which could lead to an undersized overflow system. The results and formulas presented will help water utilities ensure overflow systems with mesh are appropriately sized.

INTRODUCTION

Water storage tanks are a vital component of water distribution networks. They help to ensure that a distribution network has sufficient pressure and capacity throughout the day. The proper sizing of an overflow system is crucial to the resilience and security of the tank, ensuring that if excess water were to be pumped into a tank it would be discharged from the tank and prevent damage. Although other components may also prevent a tank from overfilling, the overflow system is likely the last line of defense for a tank to prevent over-pressurization.

There are no federal regulations governing the design of overflow systems—only recommendations; however, the primacy agency responsible for overseeing a water utility may have specific requirements for storage tank design. General sets of recommendations are available from the American Water Works Association (AWWA D100 & D115

*Corresponding Author: burkhardt.jonathan@epa.gov.

DISCLAIMER

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Standards) and the “Ten State Standards” from the Great Lakes-Upper Mississippi River Board (2012). These standards are developed by committees as best practices that are used to support the drinking water industry, protect public health and support optimal operations.

The D100 Standard (AWWA 2011) states that “[t]he overflow shall have a capacity at least equal to the specified inlet rate, with a head above the lip of the overflow of not more than 12 in. (304 mm) for side-opening overflows and not more than 6 in. (152 mm) for other types of overflows.” Additionally, for ground discharges, it is stated that the discharge should be near grade, directed away from the tank, be located over a drainage inlet structure or splash block, and that the outlet of the pipe should be above possible debris or snow pack. The D100 Standard also states that “[t]he overflow should not be connected directly to a sewer or a storm drain without an air break.” The D115 Standard (AWWA 2006) sets the design goal to “pass the design inflow rate at a maximum head equal to 75 percent of the freeboard between the weir elevation and lowest roof structural element, i.e., bottom of beam or roof” and the system should “terminate with a flap gate”.

The Ten State Standards provides an additional requirement to include a #24 mesh on vents and overflows for ground storage tanks, which helps to prevent animal or insect intrusion. There has been concern that adding a #24 mesh screen to an overflow will reduce the overflow capacity of those tanks. Similar to the AWWA standards, there are requirements that the overflow outlet should be located on the outside of the tank, be visible, terminate between 12 and 24 inches above a splash plate and not be connected into “a sewer or storm drain”.

The standards provide guidelines around which to design the overflow system, but do not specify equations for those calculations. A designer may use rules-of-thumb such as “same size as inlet” or “1.5 times inlet pipe size”. Alternately, a designer could directly apply Bernoulli’s equation with the assumption that all head gain in the system (elevation change from maximum water level to outlet) contributes to the exit flow rate. Further, a factor (less than 1) can be multiplied by the Bernoulli’s solution, which will reduce the predicted capacity and approximate a reduction caused by the opening, orifice, or mesh. Capacities of some types of overflow systems can be predicted by realizing that below the ‘critical head’ the flow is dictated by weir-like behavior. The critical head represents the level at which the overflow pipe becomes full of water, and subsequently the flow is limited by backpressure rather than a weir. The predicted flow rates for each of these assumptions can vary considerably, and begin to diverge even at low levels of excess height. Which of these approaches to use will depend on the specific configuration of the system. This work presents data related to an overflow system which has an elbow oriented upwards (upturned elbow) that defines the overflow level (see Figure 1).

The question of how water moves into and through systems is not new and has been extensively explored in the field of hydraulics. The amount of water that can be discharged through a system with an upturned elbow has been shown to behave as a weir for initial water levels above the opening (US Bureau of Reclamation, 1987). Horton (1907) provides a thorough treatment of weir behavior for a variety of weir configurations, including appropriate coefficients and equations. Binnie (1938) and Kalinske (1941) investigated

overflow pipe systems that utilize a straight vertical pipe. Kalinske reported that a partial vacuum was formed during experiments, which “caused the air above the water surface in the tank to push through and break up [the] jet flow.” Holley et al. (1992) and Smith & Holley (1995) reported drainage capacities for highway drain configurations, specifically how the location of elbows and orientation of pipe segments impacted discharge rates.

The range of excess heights that are relevant to overflow system design for storage tanks are likely to be less than a foot, as it is not desirable to design a storage tank with a significant amount of unusable space. Initial levels of excess height above an upturned elbow overflow inlet would be expected to contain a weir type flow and contain a vortex (Kalinske 1941, Binnie 1938, Jain et al. 1978). This vortex reduces the area that is available to flow and can result in possible air entrainment into the system. Simpson (1968) provides two formulas for determining the transition point to avoid air entrainment caused by air being sucked into the system. Jain et al. (1978) reported critical submergence levels for vertical pipe intakes. Piva et al. (2003) provide a theoretical approach for determining vortex formation. McDuffie (1977) provides a thorough treatment for vertical drains to quantify when a drain would achieve “vortex free downfall”. These previous investigations have shown that overflow systems will typically operate in a weir regime.

For systems with mesh, Padmanabhan and Vigander (1978) studied the impact of pressure drop through fine mesh screens with percent open areas ranging from forty to seventy percent. Their generalized findings indicate that the impact of mesh related to pressure drop effects was highest at low Reynolds numbers and reached a minimum after approximately a Reynolds number of 3,000. For flow rates that would be relevant to most utilities, the impact associated with pressure drop of a clean mesh would be expected to be minimal.

Data was collected using a pilot scale tank that was equipped with different sized overflow pipes to replicate larger systems. Figure 2 shows a theoretical relation between the flow capacity for a system with an upturned-elbow-inlet overflow system (shown as the solid black line). This article discusses formulas that can be used to determine the black line for an overflow system with a weir-type (e.g. upturned elbow) inlet, with specific discussions related to calculating the impact of the mesh. The green (solid) region in the lower left of Figure 2 reflects the weir dominated regime, and is calculated by the Francis formula. The red (cross-hatched) region relating to the line on the upper right is calculated by the backpressure limited formula presented herein. The green (striped) region reflects the transitional zone, which may not be properly predicted by either formula. If an inlet flow rate falls in the backpressure limited regime (red cross-hatched region) then the tank level may continue to rise because it exceeds the overflow system capacity. Initially the capacity is limited by what can enter the system (weir limited), but at some point the capacity is limited by what can get through the system (backpressure limited). By comparing the calculated plots developed for a specific system with the values of inlet flow rate and available or design excess height, designers or system owners can make decisions related to factors of safety when determining if an inlet flow rate is too high for an existing tank, or a specific overflow pipe size is appropriate for a given inlet flow rate for new or modified tanks.

METHODOLOGY

Experimental Setup

A pilot-scale tank system was constructed to test the capacity of overflow systems (see Figure 1). The 1,900-gallon elevated tank contains 3 outlets with 4-, 6-, and 8-inch diameter pipe systems. All pipes and fittings in the overflow system were standard schedule 80 PVC, and the actual overflow openings were 4.5, 6.625 and 8.625 inches for the elbows. Each outlet was designed such that the overflow height (lip of the upturned elbow) was eighteen inches from the top of the tank. All measurements presented herein treat the overflow height as zero (0) inches of excess height (or excess head). Water was pumped from a 6,000-gallon recirculation tank through one, or both, of the two system pumps (3 and 10 horsepower) into the bottom of the top tank—providing inlet flowrates of approximately 100–1,100 gallons per minute (gpm). The flow rate into the top tank was measured using magnetic mass meters on each pump's outlet. Under steady-state conditions the flow rate into the tank was equal to the flow rate out of the tank, so inlet flow rates are reported for steady state overflow capacities. The upper tank was equipped with a sight glass, with a ruler that was aligned with the overflow height of the system, and excess height measurements were recorded under steady-state conditions. The total height below the overflow elbow (z) of the 4, 6, and 8 in systems was 14.75, 15 and 15.6 feet, respectively, due to space limitations in the experimental system. A flapper valve was installed horizontally at the bottom of each vertical section to replicate a system with a flapper installed. The free surface of the water was below the outlet of the overflow system during experiments.

Table 1 contains a list of the experimental conditions—specifically, the pipe size and mesh configurations used. A 24×24×0.014-inch mesh was used as part of these experiments, which was expected to have 44.2% open area. Epoxy was applied to block 25%, 50% or 60% of the mesh during some experiments. An additional set of experiments were conducted for the 8-inch system with a horizontal section to replicate additional piping used to drain water away from a tank. An elbow was added 13 feet below the overflow elbow, and a total of 30.25-feet of 8-inch horizontal pipe (with a slight pitch) was inserted, and returned to the recirculation tank through the same flange and flapper system used before. The pipe was routed back to the same flange and flapper system used before, resulting in 4 additional elbows and a maximum continuous length of horizontal pipe of approximately 16.5 feet. The overall height of the overflow system was the same for all conditions using 8-inch pipe.

Capacity Prediction Formulas

Data collected from the experiments was compared to the Francis formula (also referred to as the weir assumption, equation 1) and the formula reported by Kalinske (1941) (equation 2). The general form of the weir equation considered here, referred to as the Francis formula, is,

$$q = Clh^{3/2} \quad (1)$$

where q is the flow rate (ft^3/s), C is a multiplier factor (unitless), l is the weir length (ft) and h is the excess height above the weir (ft). The multiplier factor, C , was selected to be 3.33 for the systems described here, but can vary depending on other factors in the system—specifically the ratio of the height above a weir to the weir length (see Horton 1907 for a more information). The weir length for an upturned elbow is the circumference of the elbow, or $l = \pi \cdot d$, where d is the pipe diameter (ft).

Kalinske (1941) presented the equation for calculating flow through vertical overflow piping as,

$$q = C_k g^{1/2} d^{1/2} h^2 \quad (2)$$

where q is the flow rate (ft^3/s), C_k is multiplier factor (unitless), d is the pipe diameter (ft), g is the gravitational acceleration constant (32.147 ft/s^2), and h is the excess height (ft). For these results, the factor C_k was set to 3.4, which was the minimum value reported by Kalinske (1941). The rationale behind the selection of this value for C_k will be discussed along with the implication below. Kalinske found that this formula held until a critical head for pipe sizes up to approximately 6 inches.

The maximum flow rate through an overflow system with a mesh installed can be calculated from a modified Bernoulli's equation as:

$$Q_{max} = \pi \left(\frac{D}{2} \right)^2 \left(\%_{open} \right) \left(1 - \%_{blocked} \right) \sqrt{\frac{2g(z + EH)}{1 + (\%_{open})^2 (1 - \%_{blocked})^2 [K_{mesh} + f \frac{L}{D} + N_b K_b]}} \quad (3)$$

where, Q_{max} is the maximum flow rate (ft^3/s , multiply by 448.831 to get gpm), D is the pipe diameter (ft), $\%_{open}$ is the percent open area of a mesh, $\%_{blocked}$ is the percentage of mesh that is blocked by debris, g is the gravitational acceleration constant (32.147 ft/s^2), z is the vertical drop in the system (ft), EH is the excess height above the weir (ft), K_{mesh} is the pressure drop coefficient for the mesh (unitless), f is the Darcy-Weisbach friction factor (unitless), L is the total pipe length in the system (ft), N_b is the number of elbows (unitless), and K_b is the resistance coefficient for bends (unitless). The $\%_{open}$ term is a value that is reported for a given configuration of mesh—for the $24 \times 24 \times 0.014''$ used in this study the $\%_{open}$ equals 44.2%. K_{mesh} approaches 1.5 for higher flow rates (see Padmanabhan and Vigander, 1978), so this value was used for calculating Q_{max} . K_b for a regular 90-degree elbow is reported as $30 f_T$, where f_T is the fully developed turbulence friction factor (Crane, 1988). The $\%_{open}$ and $(1 - \%_{blocked})$ terms could be simplified to one variable, however, they are left separated to provide more control when applying them in this formula.

RESULTS AND DISCUSSION

Figures 3–5 contain the results from experiments with each of the three overflow pipe sizes. Results from the Francis and Kalinske formulas for each pipe size are plotted as black

continuous and dashed lines, respectively. Work of Kalinske, Binnie, McDuffie, Simpson, and Jain et al. suggested that a transition out of the weir-limited flow regime would occur for excess height levels near one-pipe diameter above the overflow open (shown as a vertical dotted line in each figure, for reference).

Figure 3 shows the results from the experiment with a 4-inch overflow pipe when no mesh (grey line) or a clean mesh (blue line) was installed. The flow capacity during experiments with and without clean #24 mesh exceeded (i.e., was conservatively predicted by) the capacity calculated by the Francis formula up to one-pipe-diameter. Although the Kalinske formula predicted capacities for low values of excess height, it generally over predicted the overflow capacity. With clean mesh installed, increasing flow from 450 gpm to 465 gpm resulted in a 4 inch increase in level, indicating the system had reached the backpressure limited regime (which can be calculated using equation 3). Above 465 gpm, the water level in the tank continued to increase and the experiment was terminated. Negligible differences in achieved overflow capacities were observed between tests with or without a clean mesh for excess heights up to one pipe diameter for the 4-inch system. The rapid transition to backpressure limited flow for clean mesh (blue line) and blocked mesh (red line) is discussed below.

Figure 4 shows the results from the experiments with a 6-inch overflow pipe. The blue line indicates the experiment with the mesh installed, and the gray indicates where the mesh was not installed. Similar to the 4-inch system, results for experiments with a clean mesh or no mesh are essentially identical, with differences being attributed to measurement error or flow variability that occurred during the experiments. The overflow capacity is over predicted by the Kalinske formula and under predicted by the Francis formula. The red line shows experimental results from the 60% blocked mesh experiment.

Figure 5 shows the results from the experiments with an 8-inch overflow pipe. The gray lines indicate experiments without a mesh installed for a single vertical overflow pipe, blue lines indicate experiments with mesh for the single vertical case, and red lines indicate experiments in which there was an additional 30.25-feet of horizontal of pipe installed in the system. For systems without the horizontal section of pipe near the bottom of the system, the Francis formula under predicted the capacity for systems without a mesh and with up to 25% blocked mesh. The 50% blocked system without a horizontal section was within 5% of the prediction of the Francis formula (see Table 2).

The horizontal section of pipe was installed at the bottom of the overflow system (shown as red lines in Figure 5) to mimic a system that might have a section of pipe at or below ground level intended to manage where water flows during an overflow event. Unlike the system without a horizontal section, the Francis formula generally overestimated the capacity by about 10% when compared to the experimental data (see Table 2) for systems with or without mesh. Similar to all other experiments, the difference in overflow capacity between a clean mesh and no mesh was negligible. A more thorough discussion related to the impact of mesh is presented below.

Table 2 contains a summary of relative overflow capacity for all experiments—reported as actual measured flow divided by predicted flow for a given excess height condition. Values above 1.0 indicate that more flow was achieved than was predicted by the Francis formula. Both 4-inch and 6-inch experiments showed a 19% and 23% improvement, respectively, relative to the weir assumption prediction with and without a mesh installed. The Francis formula provided a good estimate of flow capacity for the 6-inch system with a 60% blocked mesh until the transition point (see Figure 4). Experiments with the 8-inch vertical only system resulted in a slight improvement (4–8%) relative to predicted capacities up to 25% blocked mesh, with the 50% blocked case averaging only 98% of the expected flow. The addition of the horizontal pipe section resulted in a reduction in flow capacity to approximately 90% of that predicted by the weir assumption for the no mesh, clean mesh and 25% blocked mesh cases. The 50% blocked case for a system with a horizontal section near the bottom will be discussed below.

The Francis formula consistently under predicted the capacity of the system for systems with no horizontal section near the bottom of the system. During the weir limited flow regime, clean mesh did not result in noticeable reduction in capacity relative to the same system without a mesh. Kalinske's formula consistently over predicted capacity for all tested configurations.

Flow through an overflow system can be limited by either (1) how much water can get into the overflow system (i.e., the weir behavior) or (2) how much water can move through the overflow system (i.e., any backpressure limitations). For low levels of excess height, typically less than the 6- to 12-inch design standard for pipes larger than 6 inches, the discharge capacity of the overflow system would be expected to be predicted by the Francis formula. The system removes as much water as can be supplied into the overflow elbow, and any further head gain below the overflow level served to overcome downstream pressure or other losses but not increase total capacity. During the weir limited regime, the flow rate achieved by the system does not correspond to the flow rate that would be calculated for the maximum velocity exiting using the Bernoulli's equation. Once the maximum velocity in the system is achieved, the system has reached a backpressure limited regime. During the weir limited flow regime for the tested configurations, a clean mesh was not observed to reduce the overflow capacity relative to a system without the mesh installed. However, if that maximum velocity is reached as water passes through the mesh, then mesh becomes a limiting factor. In this way, it can be seen that the direct impact of a mesh is the reduction in flow area—where flow capacity is equal to area multiplied by velocity—and the reduction in effective area will reduce actual flow capacity. A similar transition to backpressure limited flow occurs for systems without mesh, at the maximum velocity calculated for a system, but the corresponding flow rate would be calculated across the full pipe area, not a reduced area accessible through the mesh. In general, for low levels of excess height weir flow controls capacity since the maximum system capacity calculated for backpressure limited flow is higher than the weir can supply. A reduction in maximum achievable flow rate can occur if (1) there is little or no vertical drop in the system or (2) as the mesh becomes significantly blocked. Equation 3 can be used to calculate the achievable flow rate with mesh and provides a method of assessing when the mesh will result in reduced flow capacity, and is not intended to calculate the flow rate for all values of excess height.

Five scenarios were performed that demonstrate the effect of area reduction and test equation 3. During the experiment with clean mesh in the 4-inch system, the system reached the backpressure limited regime for an inlet flow rate of 452 gpm at which point the height of the tank continued to increase and did not stabilize. The intersection of equations 1 and 3 for this system was found at a discharge capacity of 412 gpm, which corresponds to the predicted transition capacity. The transition between the two flow regimes for this system was abrupt (see Figure 3). A 50% blocked mesh on the 4-inch system expected to limit the flow to 251 gpm, and the system was unable to reach a stable level above 250 gpm (see red line in Figure 3). A third test was conducted with 60% blocked mesh on the 6-inch system, which was predicted to stop following the Francis formula and to continue filling when inlet flow was above 480 gpm, and a stable level could not be achieved above 496 gpm (see red line in Figure 4). When the mesh was blocked by 50% for the 8-inch system with a horizontal section, the predicted maximum flow rate was approximately 977 gpm, and our maximum measured flow was 924 gpm under stable flow conditions—above which the level continued to rise within the tank (see Figure 5). In general, the additional long horizontal section had a 10–15% lower capacity compared to the system without the horizontal section, which is consistent with this difference between the predicted and measured flows. For comparison, for the clean mesh case for the 8-inch overflow and the horizontal piping having approximately 15-feet of system head the calculated maximum flow rate was 1,510 gpm. During a test where the mesh continued to clog with debris from the installation of the horizontal section for the 8-inch system (see Figure 5), the system was not able to sustain a stable overflow level when inlet flow exceeded 660 gpm. Based on equation 3, a $\%_{\text{blocked}}$ value of approximately 65–70% would account for the reduction in flow, which was consistent with the visual inspection of the mesh following the experiment. In both tests involving 50+% blockages for the 8-inch system, the transition to maximum flow was much more gradual (i.e., the height above the overflow was providing less and less capacity relative to the weir prediction). Equation 3 was consistent with observations from systems that lacked the horizontal section near the bottom of the system and slightly overestimated the capacities for the cases with a horizontal section.

Since overflow systems do not contain active components (e.g. pumps), their sizing and configuration will dictate achievable discharge capacities. The initial flow restriction is the amount of water that can actually get into the system at a given excess height (weir limited regime). Per Bernoulli's equation, the maximum achievable flow of the system will be related to the maximum velocity which corresponds to the total head of the system minus head losses. However, initially the water will coat the inner surface, but leave an air channel in the middle, which results in a lower total overflow capacity for water compared to Bernoulli's equation, since the effective area experiencing flow in the pipe is reduced. Once the pipe fills, the flow rate will be controlled by all the components in the system, or rather be limited by the system's backpressure. Per Holley's work (Holley et al., 1992, Smith & Holley 1995), the relative location of a source of backpressure can impact the flow capacity. An elbow nearer to the overflow was found to result in an earlier transition from weir limited to backpressure limited flow, when compared to an elbow further from the opening. This generalized view of an overflow system is consistent with the data presented by Kalinske, who demonstrated that longer sections of overflow piping resulted in higher levels of critical

head, or the point at which backpressure begins to determine the overflow capacity. Understanding when the transition from weir limited to backpressure limited flow regimes occurs (excess height or flow rate) is important for proper overflow system design.

The consistent reduction in capacity observed for a system with a long horizontal section of pipe near the bottom could not be explained by this conceptual model of the overflow. The system had not reached the backpressure limited regime in most of the experiments, and generally followed the Francis formula's prediction only at a slightly reduced capacity for low levels of excess height. It is suspected that this could be related to the presence of two-phase flow. Numerous discussions of induced suction, air-entrainment or two-phase flow have been presented previously (Kalinske, 1941, Simpson, 1968, Binnie, 1938). A "gulping" sound was observed during experiments at higher flow rates along with a vortex at the overflow elbow. Two-phase flow (i.e., air-water) would be expected to result in difficult to predict transient behavior.

CONCLUSIONS

This work set out to study the overflow capacity of an upturned elbow style overflow system and understand the impact of mesh on discharge capacity. For a system with a single vertical pipe outside the tank and a very short horizontal segment at the bottom, with a clean #24 mesh and a flapper valve, the Francis formula was found to be a conservative estimate of overflow capacity for excess height conditions approaching six inches (the target height listed as part of the AWWA D100 Standard). A clean mesh was observed to result in negligible reduction in flow capacity compared to systems that lacked mesh during the weir limited regime. Tests conducted with a long horizontal section of pipe at the bottom of the system resulted in a reduction in actual overflow capacity to below the values calculated by the Francis formula even without a mesh installed. These results can help tank designers implement recommendations found in both the AWWA D100 and D115 Standards and the Ten State Standards.

This research demonstrated that the impact of the mesh was related to a decrease in flow area in addition to the head loss or pressure drop of the mesh. Equation 3 was found to provide a good estimate for the discharge rate related to both clean and partially blocked mesh cases. Calculating the intersection between the Francis formula (equation 1) and equation 3 provides a method for determining the transition point to the backpressure limited regime for systems with clean or partially blocked mesh. An accurate prediction of this transition point aids in the proper sizing of overflow systems. This research has provided experimental data and associated equations to support a utility when installing, or assessing the impact of, #24 or other mesh on their tanks' overflow systems.

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Figure 1:
Diagram of experimental system (not to scale)

Figure 2:
General Idealized Overflow Capacity Diagram

Figure 3:
Experimental results for 4-inch overflow

Figure 4:
Experimental results for 6-inch overflow

Figure 5:
Experimental results for 8-inch overflow

Table 1

Experimental configurations

	4"	6"	8"	8" with horizontal section
No Mesh	x	x	x	x
Clean Mesh	x	x	x	x
25% Blocked			x	x
50% Blocked	x	60%	x	x

Table 2

Overflow capacity relative to Francis formula (actual flow rate/predicted flow rate)

Percent blocked	4"	6"	8" vertical only	8" with horizontal section
No Mesh	1.19 ± 0.12	1.23 ± 0.05	1.08 ± 0.04	0.90 ± 0.05
Clean Mesh	1.19 ± 0.12	1.23 ± 0.06	1.06 ± 0.05	0.91 ± 0.04
25% Blocked	-	-	1.04 ± 0.03	0.91 ± 0.04
50% Blocked	1.10 ± 0.08	1.01 ± 0.03 (60% blocked)	0.98 ± 0.06	0.87 ± 0.07