AN UPDATE: CURRENT REVIEW OF FOUR SEWAGE DROP STRUCTURES

A.T. Margevicius (AECOM, USA), C. Wan (Jacobs, NZ)

ABSTRACT

There are numerous publications that discuss different types of sewage drop structures. This paper provides an update on the state-of-the-practice, as well as a comparison of four different types of sewage drop structures.

Dropping sewage from near-surface collection systems into deep tunnels involves several challenges, including air entrainment, energy dissipation, surge control, and maintenance access. The use of four specific types of drop structures to handle large flows is becoming more prevalent. Numerous types of drop structures have been used to convey sewage down to tunnels, with varying degrees of success. Several recent projects have demonstrated that not all drop structure types perform equally well. While numerous models (both mathematical and physical) have been used to analyse drop structures, there is relatively little data that compares the performance of each type. Much of the previous work has focused primarily on hydraulics, and comparatively little emphasis has been placed on the pneumatics of drop structures. Both full-scale prototypes and laboratory-scale models suggest that the flow regimes in drop structures can be complex and variable. Further, the true nature of two-phase flow, which occurs in many drop structures, is not well understood or modelled in many instances. Using both qualitative and quasi-quantitative criteria, this paper compares the relative performance of four types of sewage drop structures:

- The plunge drop,
- The helicoidal ramp,
- The vortex drop, and
- The cascade (baffle) drop.

In comparing the four types of drop structures, the paper draws on several case studies and lessons learned from others. This effort had several goals:

- To compare the relative performance of four different types of sewage drop structures.
- To describe the major factors influencing the air and water flow rates and pressures.
- To document the results of several case studies on the how certain drop structure features played a role in determining the selection of a drop structure.

KEYWORDS

Sewage drop structure, plunge drop, helicoidal ramp, vortex drop, cascade drop, baffle drop, tunnel, geyser

PRESENTER PROFILE

Recognised as an international expert in sewage drop structures, Tony Margevicius has successfully delivered dozens of operating sewage drop structures in New Zealand, Canada, China, and the USA. Tony maintains that knowing what works is desirable but knowing what fails (and why!) is vital.

Conny Wan is a Project Engineer on secondment to Watercare Services Ltd from Jacobs NZ Ltd for the Central Interceptor project. Conny has been involved in this project for five years through the design phase and is currently supervising the installation of FRP shaft liners on one of the project sites.

INTRODUCTION

Sewers have been used for centuries. In Mesopotamia in circa 3500 to 2500 BC, some homes included storm sewers. In terms of sewage drop structures, Babylonian latrines were connected to 450 mm diameter vertical drop structures lined with perforated clay pipes, which led to cesspools (Cooper, 2011).

Numerous advancements were made over the centuries in sewage drop structures, and some of these have been documented in various relatively recent publications (for example, see Ettema et al., 1982). In the "Modern Era" (i.e., from circa 1900 AD onwards), the sewage drop structure has undergone several changes, as evidenced by Figures 1 and 2 (Both figures are from Metcalf and Eddy, 1914).

Figure 1: Design for wellhole (an extremely deep drop structure), Cleveland, Ohio, (Metcalf and Eddy, 1914)

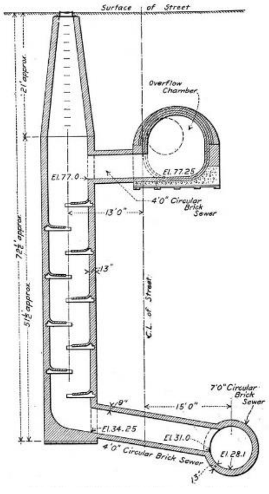
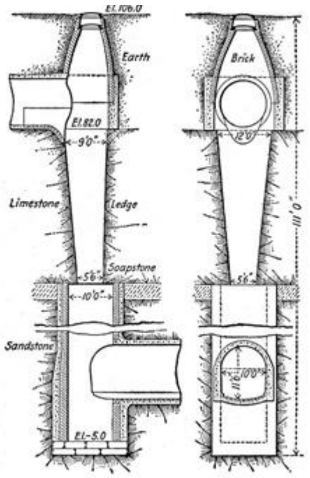


Figure 2: Design for wellhole (an extremely deep drop structure), Minneapolis, Minnesota, (Metcalf and Eddy, 1914)



In the past decade, there have been several innovations in drop structures. This paper highlights some of these innovations for four types of drop structures: the plunge drop, helicoidal ramp, vortex drop, and cascade (baffle) drop.

Since sewage consists of solids, water and gases, the sewage drop structures must accommodate all three phases. Throughout this paper, the word "air" and terms related to air (e.g., "pneumatic") will be used loosely, to include air and other gases commonly found in sewers and sewage drop structures.

The flow regime in sewage drop structures is inherently complex. The flow consists of at least two fluids: water (sewage) and air (including other sewer gases). In horizontally sloped sewers, these two fluids tend to remain distinct. In sewage drop structures, the extreme turbulence results in true two-phase flow. Further, air and sewage gases can be entrained or detrained from solution. The two fluids (liquid and gas) differ considerably from each other in density, viscosity, and compressibility. Even while the water rate remains constant, the air flow rate tends to vary tremendously in sewage drop structures, resulting in unsteady flow phenomena, such as blowbacks and geysers (see Figure 3 from Falvey, 1980).

Figure 3: Observed blowback in morning glory drop structure at the Ohywee Dam, Oregon (Falvey, 1980)

Whilst most sewage drop structures operate well, there have been some instances of problems or even catastrophic failures. These problems and failures are cited, but to protect the reputation of the people and organizations involved, the identities have been withheld.

1. BACKGROUND

1.1 SEWAGE DROP STRUCTURES: WHY AND WHEN?

As sewage drops in a freefall condition, the velocity increases due to gravity, with several deleterious effects, including increased potential for:

- Erosion from the water,
- Abrasion from the solids in the sewage,

- Air entrainment and air eduction,
- Noise,
- Cavitation,
- Vibration, and
- Impact loads, especially from debris in the sewage.

These deleterious effects increase with increasing velocity. Thus, the higher the drop height, the more likely that problems will occur.

Linear momentum is the product of mass and velocity. Momentum forces will increase with either an increase in velocity or an increase in mass. Thus, the greater the sewage flow rate, the more likely that problems will occur.

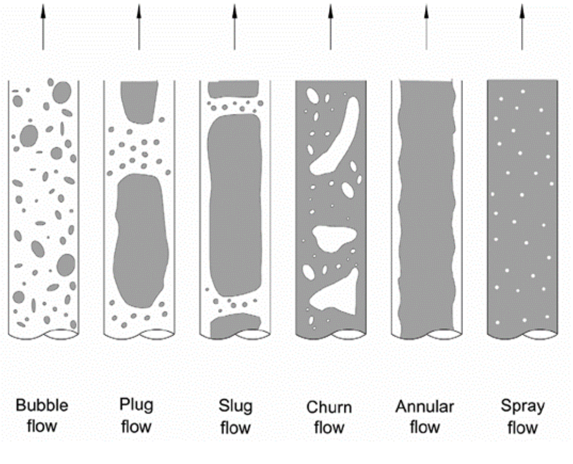
Whilst there is no universally accepted standard that mandates when to use sewage drop structures, many guidelines provide insight. For example, the Ontario, Canada "Design Guidelines for Sewage Works" states that drop pipes should be provided for a sewer entering a maintenance hole at an elevation of 610 mm or more above the maintenance hole invert. Likewise, this same guideline indicates that the velocities in sanitary sewer systems should not be more than 3 m/s, and velocities in storm sewers should not be greater than 6 m/s. Similarly, the Water Services Association of Australia's (WSAA) Gravity Sewerage Code sets a maximum velocity of 3 m/s in sewers (WSAA, 2014). In general, drop structures should be strongly considered whenever drop heights exceed about one metre.

Whilst the deleterious effects of the water and the solids in sewage is significant, the effects of air are often underappreciated.

1.2 AIR-WATER MIXTURES IN VERTICAL SHAFTS

Air flow in vertical shafts can take many forms (see Figure 4 (from Lauchlan et al., 2005)).

Figure 4: General patterns of air and water mixtures in vertical shafts under steady-state conditions (Lauchlan et. al., 2005)

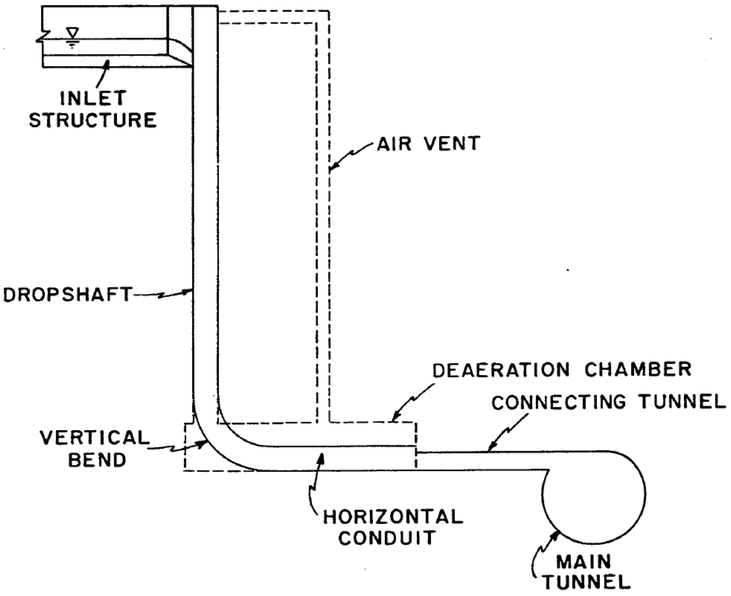


While Figure 4 presents some commonly cited flow patterns for air-water mixtures in vertical shafts, this list is not complete, nor is it universally agreed upon. For example, Rouhani and Sohal (1983) indicated that up to 84 different air-water flow pattern labels had been suggested in the literature. Air-water mixtures tend to be variable and complex. Due in part to the variability and complexity of air-water flow patterns, there are few universally accepted methods to analyse air and water in sewage drop structures.

1.3 GENERAL CONFIGURATION OF SEWAGE DROP STRUCTURES

Sewage drop structures vary in geometry. According to Jain and Kennedy (1983), most sewage drop structures include several common elements, as shown in Figure 5.

Figure 5: Main elements of a typical sewage drop structure (Jain and Kennedy 1983)



1.4 TYPES OF SEWAGE DROP STRUCTURES

Five types of sewage drop structures are commonly used:

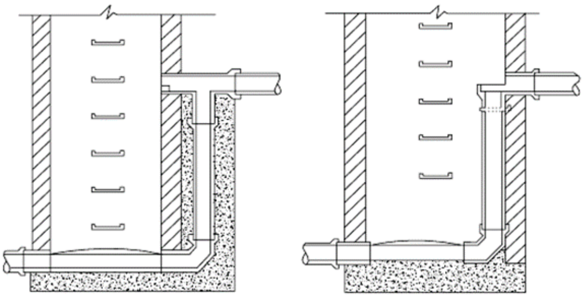
- The plunge drop (sometimes called the elbow drop),
- The helicoidal ramp,
- The vortex drop,
- The cascade drop (also known as the baffle drop), and
- Miscellaneous other types or combinations of the above.

This paper focuses on the first four types of drop structures listed above.

1.4.1 PLUNGE DROP

Compared to the other types of sewage drop structures, the plunge (or elbow) drop is one of the most common, simplest, least expensive, and oldest types of structures. It is often used for small flows (e.g., from a single residence or building) and for small drop heights (typically less than 3 m). The plunge drop consists of a pipe to drop the flow into the base of a maintenance hole. The drop is either internal or external to the maintenance hole (see Figure 6).

Figure 6: Typical drop (or elbow) maintenance hole with drop pipe located outside the maintenance hole (left) and inside the maintenance hole (right).

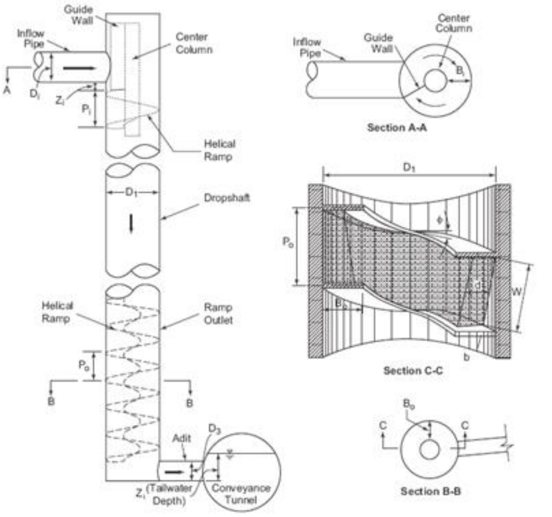


1.4.2 HELICOIDAL RAMP DROP STRUCTURE

Of the four types of sewage drop structures, the helicoidal ramp may be the least known or used. The helicoidal ramp structure consists of a ramp shaped in the form of a helix. The ramp is located inside the maintenance hole structure. Sewage is circulated along the periphery of the maintenance hole and then discharges near the base of the maintenance hole (see Figure 7, from Kennedy and Jain, 1987). Common variations on the helicoidal ramp include:

- Continuous or discontinuous ramps, and
- Single, double, or triple flights of ramps.

Figure 7: An example of a helicoidal ramp drop structure (Kennedy and Jain, 1987)



1.4.3 VORTEX DROP STRUCTURE

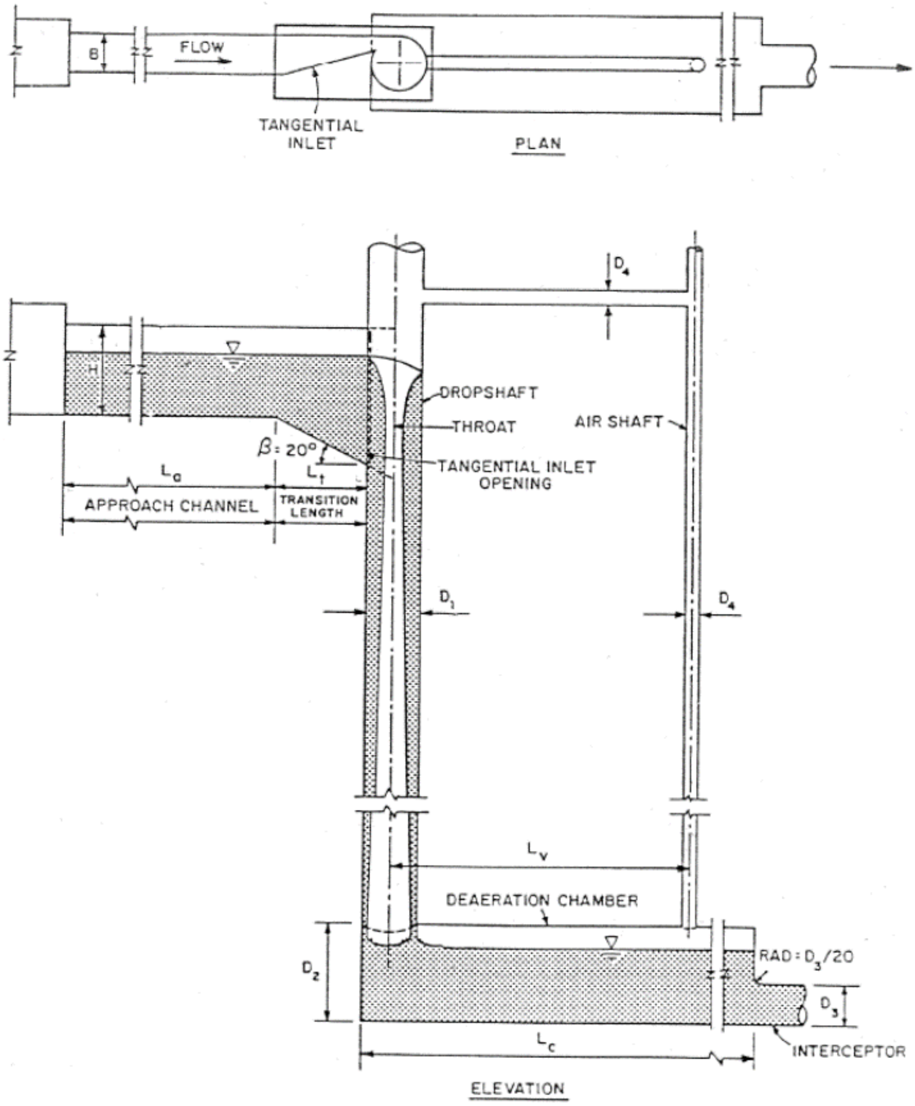
The vortex drop structure generally consists of three components:

- **The approach.** The purpose of the approach is to introduce the flow into the circular drop structure in such a way as to force the flow to the edges of the circular drop structure.
- **The drop structure.** The drop structure consists of a vertical cylinder. In vortex drop structures, the flow is intended to adhere to the sides of the vertical shaft, forming an air core at the centre.
- **The de-aeration chamber.** The drop structure terminates in the de-aeration chamber. The primary purpose of the de-aeration chamber is

to allow the air and water to separate. The air is often re-circulated to the drop structure or approach channel.

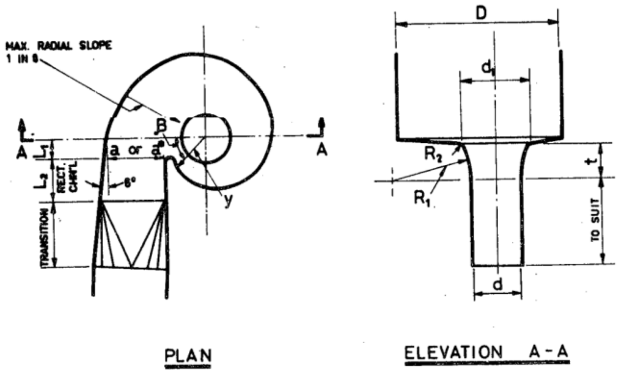
While there are numerous variations of the vortex drop structure, perhaps the most common type in North America is the H-4 tangential inlet vortex drop structure. This is shown in Figure 8 (from Jain, 1985).

Figure 8: An example of a tangential inlet vortex drop structure (Jain, 1985)



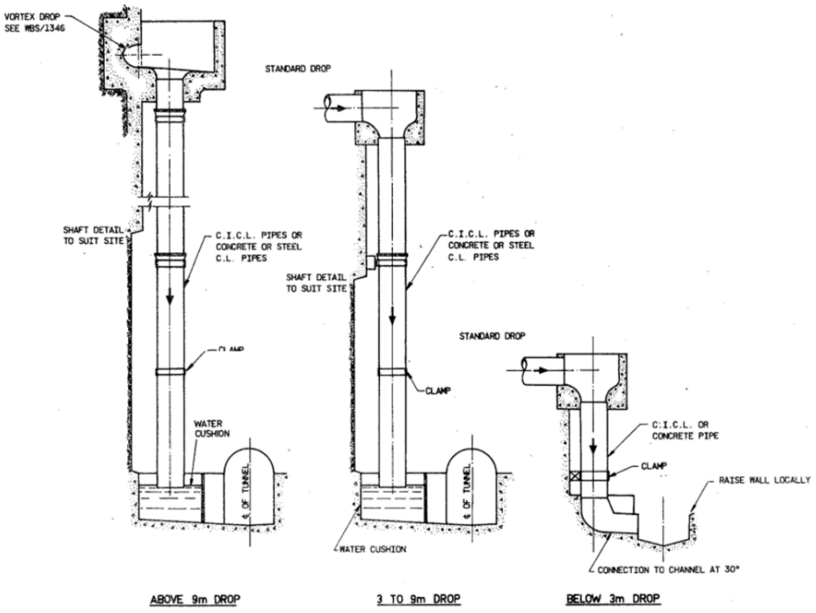
Outside North America, the vortex drop often takes alternative forms. For example, radial vortex generators have been used in Australia instead of tangential inlets, as shown in Figure 9.

Figure 9: Example of a radial vortex generator ("Internal Dimensions of Vortex Drop Chamber," 1983)



The bottom of the vortex drop uses a water cushion to dissipate the energy of the falling sewage and de-aeration occurs in over-sized vertical shafts (see Figure 10).

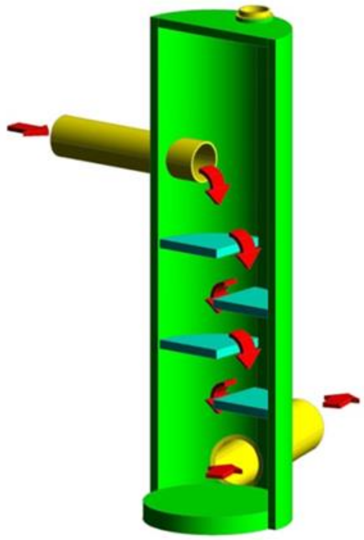
Figure 10: Example of an elevation sectional view of vortex drop ("Vertical Drops in Sewers: Provision of Inlets and Water Cushion," 1983)



1.4.4 CASACADE (BAFFLE) DROP STRUCTURE

The cascade drop (or baffle drop) structure consists of a vertical shaft that is bifurcated into a "dry side" and a "wet side." On the "wet side" of the cascade drop, sewage cascades through a series of horizontal shelves in a stepwise manner before discharging at the base of the shaft. The "dry side" and "wet side" are separated by a vertical wall. The wall includes small openings located below each shelf, to allow equalization of air pressures between the two sides of the shaft, as well as to allow inspection of the shelves. Despite cascade drops being used for over a century (Figure 1), the cascade drop structure is not generally well known or widely used. Figure 11 below shows a typical cascade drop structure.

Figure 11: Longitudinal section of a baffle-type drop structure showing the "wet side" of the structure



2 COMPARISON OF SEWAGE DROP STRUCTURES

2.1 NUMBER OF INSTALLATIONS AND USE

Plunge drops are the most common type of sewage drop structure and are suitable for low drop heights and low flow amounts. However, due to numerous reasons explained later in this paper, plunge drops are not recommended for large drop heights or for large flow rates, and thus rarely used for tunnel systems. For large drop heights and large flow rates, the various forms of the vortex drop structure are probably most common. Cascade (baffle) drops are gaining in popularity and have been installed in many countries (e.g., France, U.K., China, New Zealand, USA, etc.) Due to the concern over clogging, complexity of construction, and construction costs, helicoidal ramp drop structures are the least commonly used drop structure of the four options considered in this paper.

2.2 ENERGY DISSIPATION

Looking at the drop structure holistically, each of the four drop structures dissipates the energy of the fall. However, plunge drop structures and vortex drop structures result in relatively high vertical velocities within the drop, whereas the cascade and helicoidal ramp are better at limiting vertical velocities in the drop structures. By limiting vertical velocities, helicoidal and cascade drops also limit other undesirable effects (e.g., erosion, abrasion, air entrainment, noise, cavitation, vibration, impact loading, etc.)

2.3 HYDRAULIC EFFICIENCY AND DIAPHRAGMING

Hydraulic efficiency refers to the amount of cross-sectional area needed to convey a given amount of flow. Of the four options, the vortex drop structure and plunge drop structure provide the best hydraulic efficiency, followed closely behind by the helicoidal ramp. The cascade (baffle) drop is the least hydraulically efficient.

The vortex drop structure and the plunge drop structure convey both sewage and air. For the plunge drop, the fall of sewage is not managed, so the amount of air being conveyed is exceptionally high (see the discussion on "Air Entrainment and Air Eduction" below). For the vortex drop, the flow generally adheres to the walls of the drop pipe due to the vortex, forming an air core down the centre of the pipe. If the flow separates from the wall of the pipe, then the sewage can "leap" across the air core, in a process known as diaphragming. On inception of diaphragming, air pressures become erratic. Blowbacks, hydraulic instabilities, and other undesirable outcomes are possible. Below the point of diaphragming, the flow regime in the drop structure resembles that of a plunge drop.

Minor shaft imperfections, such as shaft being out-of-plumb, being out-of-round, or having horizontal joints in the pipe, can result in diaphragming in a vortex drop structure. In one case study, the vortex broke down because the shaft was out-of-plumb. Whilst there have been no formal investigations as to what an acceptable tolerance on verticality and plumbness are, the authors recommend that a tolerance of 1 H: 480 V be used for vortex shafts, and an overall plumbness tolerance of less than 50 mm be used. In another case study, the contractor elected to use precast concrete pipe as the drop structure for vortex drop. The joints for the precast concrete pipe were within standards for pipe, but these were too rough for a vortex drop. The vortex flow separated from the wall at the first joint and every joint thereafter. The solution was to grind down each joint in the pipe and fill them with non-shrink grout, so that the joints were smooth.

Excessively high (or low) flow rates in the vortex drop structure results in nonideal hydraulic performance. When the thickness of the sewage flow exceeds about 30% of the cross-sectional area of the shaft, then diaphragming is possible. If flows are small, then too little momentum is available to create a strong vortex and minor shaft imperfections can result in the flow separating from the wall.

As the flow drops down a vortex drop structure, the flow accelerates, forming an expanded helix. At the base of deep vortex drops, there is an annular jet that attains a terminal velocity. The have been reports that the vortex flow pattern breaks down in the pipe after a distance, even when the pipe is built to proper tolerances. Jain (1985) suggests that the annular jet in a vortex drop achieves ninety percent of its terminal velocity withing a vertical distance of about 14 shaft diameters. After that point, there is some question as to whether the vortex remains intact beyond about 14 shaft diameters. If not, then the flow regime likely breaks down to be equivalent to a plunge drop. Jain (1985) hints at this, when he states, "… the relative amounts of air entrainment for a vortex flow may approach that for a plunge flow if the vortex flow is weak."

2.4 ACCESS FOR OPERATIONS AND MAINTENANCE

At times in their life cycles, drop structures need to be inspected and maintained. Only the cascade (baffle) drop has built-in access for personnel, via the "dry side" of the shaft. As inspection technologies improve, the need for personnel access is likely to be replaced by newer technologies, such as robotics or unmanned inspection vehicles (i.e., drones).

2.5 ACCOMMODATING MULTIPLE INCOMING SEWERS IN ONE SHAFT

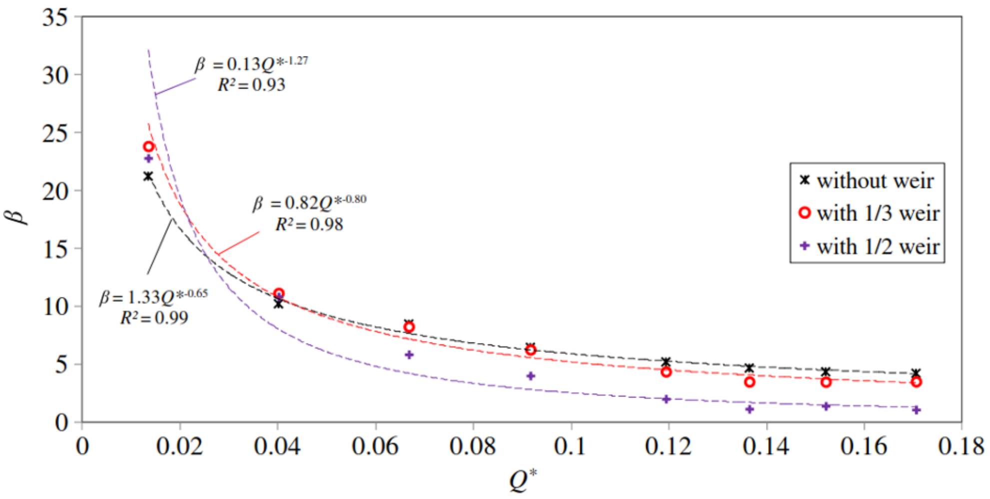
Two or more sewers in a given location may need to be brought to a tunnel. Often, these local sewers are at different elevations. For both the vortex drop and the helicoidal drop structures, the local sewers must either be combined into a single pipe upstream of the drop structure, or multiple separate drop structures need to be constructed. Either way, this incurs more construction cost.

For both the plunge drop and the cascade (baffle) drop, multiple sewers can be accommodated by a single drop structure.

2.6 AIR ENTRAINMENT AND AIR EDUCTION

As sewage flows, the viscous drag force between the surface of the water and the air will tend to drag air with it. The amount of air being conveyed has been studied by several investigators (e.g., Pescod and Price, 1992); Edwini-Bonsu and Steffler, 2006a, b). Whilst air in drop structures has been modelled both mathematically (e.g., CFD) and physically in the hydraulics lab, the amount of air being conveyed in prototype drop structures is not well understood and investigated. Ma et al. (2016) found that the measured ratio of air to water flow rates for a plunge drop can exceed 20:1 at low sewage flow rates; that is, for every cubic metre of water that falls in a plunge drop, more than 20 cubic metres of air may be entrained. At high sewage flow rates, the air-to-water ratio drops to about 5:1. See Figure 12.

Figure 12: Dimensionless Sewage Flow Rate vs. Air Ratio. Q is Dimensionless Sewage Flow Rate and β is the Ratio of Air Flow to Sewage Flow (From Ma et al., Figure 6b, (2016).*



Air entrainment can cause numerous deleterious effects in the trunk sewer or tunnel downstream, such as air binding of the pipe, geysers, surges, damage to structures, etc. At the base of the drop structure, data suggests that the plunge drop entrains the most air, followed by the vortex drop, then by the helicoidal ramp, and then by the cascade drop structure. Cascade drops seem exceptionally good a limiting air entrainment. According to Lyons et al. (2007), "Air entrainment was too small to be measured in the model study…" Similar work at a different lab yielded "Negligible air entrainment" in the cascade (baffle) drop (Swann & Melville, 2015). Importantly, Froude-scale models underpredict prototype air flow rates. Peterka (1956) suggests that the underprediction may be a factor of four.

If installed with a separate de-aeration chamber, all the drop structures will reduce the amount of air being transferred to the tunnel. Constructing a separate de-aeration chamber at tunnel depth is often risk-laden and expensive. Without a separate de-aeration chamber, the cascade drop is the best alternative in terms of limiting air to the tunnel. In fact, most cascade drop structures are built without a de-aeration chamber. Often, helicoidal ramps are built without de-aeration chambers, but transfer more air to the tunnel than cascade drop structures.

2.7 SURGE AND GEYSER MITIGATION

When a sewage tunnel fills to the point where the downstream end of the tunnel fills the tunnel to soffit, a surge wave results. Theoretically, this surge wave travels upstream at the acoustic wave velocity (i.e., celerity) of the sewage. The height of the surge wave depends on numerous factors. The authors have created models that show surge wave heights of ten metres. As the surge wave passes a shaft, the hydraulic grade line in the shaft rises. The shaft tends to dissipate some of the energy from the surge wave. Plunge, vortex, and helicoidal ramp drop structures theoretically do less to alleviate surge in tunnels than cascade drop structures. The "dry side" of the cascade drop structure is believed to provide limited relief from surge, and the other drop structures lack a similar feature.

Whilst rare, geysers have been documented on sewage tunnel systems (see Figure 13). For this paper, a geyser is defined as a hydropneumatic phenomenon that is caused, in part, by air pockets trapped in the tunnel under pressure, which results in eruptions at ground level. Wright et al. (2011) differentiates surges and geysers and, in the instance shown in Figure 13, "geyser formation in this tunnel system is not directly connected with surging in the tunnel system." Geysers erupting at ground surface have been known to produce plumes up to 40 m high. The fluid accompanying the eruption is sewage, representing an obvious concern for the environment and people around the eruption. Whilst all the factors that create geysers are still being investigated, geysers have been recreated in the hydraulics laboratory on shafts and, in one instance, a tangential inlet vortex drop structure. The authors have witnessed a geyser on the vent shaft of a vortex drop structure in the field. The authors are not aware of geysers forming on any other type of drop structure. Further research on geyser formation in drop structures is warranted.

Figure 13: Observed expulsion of air and water (i.e., geyser) from a stormwater tunnel in Minneapolis, Minnesota on July 13, 1997. Image from a video recorded by St. Anthony Falls Hydraulics Laboratory, University of Minnesota.

2.8 ODOURS AND CORROSION

Virtually all drop structures produce turbulence. Regardless of the drop structure type, odours are likely to be released from sewage, if the sewage contains sufficient odorous compounds (i.e., storm water and dilute combined sewage often lack sufficient concentrations of odorous compounds to be of concern). Little field data are available about which types of drop structures result in more odours than others. The author is aware of one community that has hundreds of drop structures, including 32 vortex drop structures, over 200 plunge drop structures, and 18 baffle drop structures. This community has five air treatment facilities (i.e., odour management facilities) installed adjacent some of the drop structures. Four of these facilities treat air from vortex drop structures, one facility treats air from a plunge drop, and there are no air treatment facilities installed on any of the cascade (baffle) drop facilities. The author knows of no other "side-by-side" comparison between drop structures, and this represents one data point. Based on this one case, cascade (baffle) drops may be better at reducing odours than either plunge drops or vortex drops. Further research in this area is warranted.

Hydrogen sulphide is often a primary reason for odours in sewers. Hydrogen sulphide may be released in areas of hydraulic turbulence. For the plunge and vortex drop structures, the most hydraulic turbulence occurs at the base of the drop structure. Biological activity within the sewers can transform hydrogen sulphide gas into sulfuric acid, which is corrosive to most cementitious materials. The author is aware of one installation where considerable deterioration has occurred at the base of the drop structure. However, insufficient forensic evidence is available to determine if biologically induced corrosion was the primary cause of deterioration, or whether other factors (e.g., cavitation, poor grade concrete, etc.) contributed. Likewise, the author is aware of a separate installation where significant deterioration occurred in the de-aeration chamber to the drop structure. Again, insufficient data is available to determine if the cause was from biologically induced corrosion or other factors (e.g., poor grade concrete, improper installation, etc.) The author is not aware of exceptional corrosion to occur at cascade drop or helicoidal ramp drop structures.

2.9 SOLIDS MANAGEMENT

Sewage contains different types of solids, including floatables (e.g., plastic bottles, tree branches, fats, oils, grease, etc.), suspended solids, debris, and grit (e.g., sand, gravel, etc.) The drop structure must be able to accommodate all these types of solids or must be protected from the solids likely to cause problems. Of these types of solids, debris is usually the biggest concern.

For the tangential inlet vortex drop and the helicoidal ramp drop structures, there are locations where large debris could become lodged, potentially resulting in backwater conditions, overflows, and other undesirable effects. As a result, these types of drop structures are often provided with a coarse bar rack or screen to protect the drop structure, which in turn requires maintenance.

Similarly, but to a lesser degree, plunge drop structures are usually installed with an opening directly above the drop structure, to allow for removal of debris. See the "inside maintenance hole" example in Figure 6 above.

The vertical spacing between adjacent cascade shelves should exceed the largest cross-sectional dimension of the incoming sewer. If so, then the likelihood of clogging the cascade drop is de minimus, so racks or screens are not warranted.

Regardless of drop structure type, if a de-aeration chamber is provided with the drop structure, then grit deposition in the de-aeration chamber is a concern. For the de-aeration chamber to be effective, the flow must be made sufficiently quiescent so that buoyancy forces can dominate over momentum forces. Jain and Kennedy (1983) suggest that the Froude Number in the de-aeration chamber should be between 0.14 and 0.23, suggesting very small downstream velocities. The authors are aware of minor sediment deposits in one de-aeration chamber that had been operational for about a decade.

Floatables were believed to be the primary factor in the collapse of a de-aeration chamber for a tangential inlet vortex drop servicing a sanitary sewerage system. In this instance, fats, oils, and grease (FOG) floated on the water surface in the de-aeration chamber. The restriction at the downstream end of the de-aeration chamber (see Figure 8) limited that amount of FOG that could be flushed downstream. Over time, the FOG built up in the de-aeration chamber to the point where it plugged the air vent pipe. With the vent pipe sealed, the de-aeration chamber eventually failed structurally, resulting in the collapse of the chamber.

2.10 FLOW CONDITIONING

For the tangential inlet vortex drop, an approach channel and vortex generator must be constructed upstream of the drop structure. The approach channel and vortex generator are usually constructed using open-cut methods. If the local sewer is deep underground, then constructing an approach channel and vortex generator in a deep excavation is risk-laden and expensive. This problem is often less of a concern with other forms of vortex generators. In addition, a screen is often needed upstream of the vortex generator or helicoidal ramp (see discussion on "Solids Management" above). In general, no flow conditioning is warranted for either plunge drop structures or cascade (baffle) drop structures.

2.11 CONSTRUCTION COSTS

The cost to construct a drop structure depends on numerous factors, including size, depth, geology, site constraints, whether a de-aeration chamber is needed, whether the shaft will be used for other purposes during construction (e.g., a tunnel boring machine launch shaft), on-line vs. off-line construction, etc. One factor that is often overlooked in the planning of the drop structures is the need for access for personnel and equipment. For a cascade (baffle) drop structure, this access is built into the "dry side" of the shaft. For the remaining drop structures, no provisions for access are built into the designs, so a separate access shaft may be required. Often, the construction cost for the access shaft is the determining factor as to which drop structure alternative is least expensive. On at least three projects with which the author is familiar, the initial recommendation was to install tangential inlet vortex drop structures based on construction cost estimates. However, when an access shaft was added to the cost for the vortex drops structure, then the cascade (baffle) drop became the less costly alternative. On the most recent project that involves eight drop structures, switching from tangential inlet vortex drops structures to cascade (baffle) drop structures is estimated to save approximately NZD $24 million. In general, the plunge drop is usually the least expensive type of drop structure to construct and the helicoidal ramp is usually the most expensive. Often, both the plunge drop and the helicoidal ramp are eliminated from consideration for performance reasons, so the choice comes down to vortex drop or cascade drop.

Whilst construction costs are an important consideration, the authors recommend that other factors also be included in any analysis that compares different drop structure alternatives.

2.12 SUMMARY OF FEATURES

Table 1 summarises the comparison of features for four types of drop structures.

Table 1: Comparison of features for four drop structure types

Feature	Drop Structure Type			
	Vortex	Plunge	Helicoidal	Cascade
Total number of installations	++	+++	-	+
Commonly used in sewage tunnels	+++	-	+	+++
Hydraulically efficient	+++	+++	++	+
Access for equipment/people	+	+	-	+++
Surge mitigation built-in	+	++	+	+++
Commonly built over top of tunnel	++	+	???	+++
Accommodates multiple inlets	-	+	-	+++
Reduces air entrainment	+++	-	++	+++
Reduces odours	+	-	???	++
Manages solids well	++	++	++	+++
Reduces need for flow conditioning	+	+++	+	+++
Costs less to build	++	+++	-	++

Legend for Table 1:

+++	Highly favourable / exceptionally well suited
++	Favourable / well suited
+	Acceptable
-	Unfavourable / poorly suited
???	Insufficient data to evaluate

3 RECENT ADVANCEMENTS AND INNOVATIONS IN DROP STRUCTURES

3.1 PREMANUFACTURED VORTEX DROP STRUCTURES

Three decades ago, most drop structures were made of cast-in-situ concrete. Today, there are a few manufacturers (e.g., Hydro International, Ipex, etc.) who produce premanufactured sewage drop structures. It is beyond the scope of this paper to evaluate, compare, or comment on these premanufactured drop structures.

3.2 MATERIALS OF CONSTRUCTION

Most drop structures are usually made of concrete. However, precast concrete drop structures are becoming prevalent. The first known precast concrete cascade drop structure was built as an outfall to a wastewater treatment plant in year 2010 and has been operating successfully on a continuous basis since its installation. In addition to precast concrete, the use of fibres (both steel fibres and glass fibres) is becoming commonplace for both in-situ and precast concrete construction.

Stainless steel has been used for the construction of vortex drop structures for the past twenty years. Due to the high cost of stainless steel, however, the use of stainless steel is less common.

Recently, glass reinforced plastic (GRP) has been used for cascade (baffle) drop construction. (See Figure 14)

Figure 14: Example of a glass reinforced plastic (GRP) cascade (baffle) drop structure (note "dry side" to the left and the "wet side" on the right

3.3 HYDROPOWER

In one case, the cascade (baffle) drop was located on the discharge from a wastewater treatment plant. The owner installed a small hydropower turbine on the "dry side" of the baffle drop. Normally, the plant effluent discharges through the turbine and generates electricity for the wastewater treatment plant. When the turbine needs to be taken off-line for maintenance or other reasons, the flow is switched over to the "wet side" of the cascade drop structure. Using the cascade drop for hydropower can generally be cost-justified when the flow rates are continuous (as with a wastewater treatment plant) and the flow consists of relatively clean water. The authors were part of an evaluation to consider hydropower for a sanitary sewer system, and the project was difficult to cost-justify, due to need to precondition the flow ahead of the turbines.

3.4 DROP HEIGHTS

Total vertical drop heights with cascade (baffle) drops can exceed 60 m. For the cascade drop, the sewage drops from shelf to shelf a fixed distance, often about 2 metres at a time. The pattern is repeated throughout the drop height, so, in theory, the total vertical drop height for a cascade drop is virtually unlimited. For the vortex and plunge drop structures, the flow reaches terminal velocity quickly and the flow patterns break up, resulting in massive amounts of air entrainment.

3.5 PEAK FLOW RATES

Vortex drop structures that can accommodate more than 50 m3/s are in successful operation. Cascade (baffle) drop structures that can accommodate more than 30 m3/s are in successful operation.

3.6 PRECAUTIONS FOR REDUCING SEDIMENT DEPOSITION

On combined sewer systems and highly responsive separate sewer systems, the drop structures must be designed to accommodate huge variations in flow rate. The drop structure must be designed to accommodate both the instantaneous peak wet weather event as well as the minimum daily dry weather event.

For the cascade drop, the shelves of the structure usually have no slope. Some practitioners have conjectured that this may lead to solids deposition on the shelves, which may putrefy over time. However, at least two cascade drop structures with horizontal shelves and conveying both dry and wet weather flows have been in successful, continuous operation for over 25 years. There have been no odour complaints and annual inspections show minimal deposition. It is likely that wet weather flows occur often enough to scour sediment from the shelves.

Nonetheless, a few investigators have sought to implement precautions to reduce sediment deposition on the shelves of cascade drop structures. Yang and Yang (2020) have investigated using sloped shelves. Three slopes were investigated: 0-degrees (i.e., level baffles), 10-degrees and 20-degrees. Of these three slopes, the 10-degree slope was selected as the best. Others have installed plunge drops within the cascade drop to accommodate low flows. Considerable hydraulic laboratory work was needed to reduce air entrainment for this configuration.

4 CASE STUDY: CENTRAL INTERCEPTOR

For the Central Interceptor (CI) project the adoption of cascade drop structures was an appropriate solution given the depth of the main tunnel and link sewers and the limited surface space for installation. Other reasons for adopting the cascade style drop structure were:

- The alternating shelves dissipate the energy from falling water,
- The ability to introduce multiple flow inputs at different levels,
- The dry side of the cascade allows for pressure equalisation, and

- The dry side provides for manned or robotic entry for inspections or maintenance.

The CI project requires 16 shafts to divert flow from the near surface networks into the deep sewer tunnels. The tender documents required two of these shafts to be prefabricated from fibre reinforced plastic (FRP), a composite material comprising polyester fibre and resin.

The CI construction contractor proposed to make eight of the sixteen shafts on this project using composite materials, which compared to the specimen design of cast in-situ reinforced concrete offered benefits in terms of off-site manufacture, light-weight construction, durability and minimising the need for workers below ground. This last feature is a key consideration for deep shafts that in the case of CI range from 25 to 75 m in depth.

The CI construction contractor engaged a subcontractor to develop the specimen design using the selected composite technology. Key variations from the specimen design included:

- Expanding the use of composites to shaft liners up to DN7500; this involved some re-tooling to manufacture the larger modules,
- Adaptation of the chosen materials to meet the 100-year design life, with thinner sections than concrete and support beams under the cascade shelves,
- Load cases developed for the in-service conditions: surge, seismic, fatigue, buoyancy, groundwater, and earth loads, and
- Designing for abrasion, including the addition of an HDPE layer on the shelves and walls.

The composite shaft liners have been designed in modules weighing up to 22 t that are flanged to provide for on-site assembly. The ends are domed for strength during transportation. The shaft liners are connected to the tunnels in a four-stage operation including:

- Demolition of the tunnel lining,
- Removal of the domed bottom of the shaft,
- Casting an in-situ concrete joint, and
- Sealing the concrete with HDPE sheet that is boned to the FRP shaft liner and the HDPE tunnel liner.

This provides an integrated, corrosion-proof connection.

CONCLUSIONS

Four types of sewage drop structures are compared. Under the proper circumstances, each can be justified; no one drop structure is the best option for every circumstance. The plunge drop remains the most popular drop structure for low flow rates and limited drop heights. On the other hand, the helicoidal ramp drop structure is less common. Worldwide, the use of cascade drops is gaining popularity, especially for deep tunnel installations. The vortex drop structure is a viable solution for many locations and circumstances. The paper provides guidance on the many construction, operational and maintenance factors need to be considered before deciding on which type of drop structure is most appropriate for a given circumstance.

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