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VORTEX DROP SHAFT STRUCTURES: STATE-OF-THE-ART AND FUTURE TRENDS

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ABSTRACT

Vortex drop shaft structures have played a critical role in hydraulic engineering; from one of their first applications in hydroelectric energy dissipation in the 1940s, to numerous contemporary installations throughout modern day urban drainage infrastructure. They are known to convey flows up to 1400 m^3/s through drop heights of 190 m and due to their small footprint, stable flow mechanics and enhanced energy dissipation, they are often considered to be the most successful form of hydraulic drop structure. There are several design questions on various aspects of vortex drop shaft structures that have not yet been addressed in the laboratory environment or at full-scale and moreover will require full appreciation by engineering practitioners in future years. This article summarizes over 75 years of research and development of vortex drop shafts including types of structure, applications, laboratory modelling techniques, physical modelling studies and recent advancements in multiphase numerical modelling. The article discusses the hydraulics of various types of vortex drop shaft structures such as the key design differences between subcritical and supercritical intakes, energy dissipation, and aeration and presents the insights gained from successful case study commercial projects. The outcomes of seminal research studies and projects are discussed in detail and areas that are deemed to require further research and development are highlighted.

Keywords: Hydraulic structures; vortex flow; energy dissipation; air entrainment; best practice guidelines

1 INTRODUCTION AND BRIEF HISTORY

Vortex drop structures are popular in sewer and hydropower systems where they are used to convey water from a higher to a lower elevation and dissipate its energy safely. In the structure, angular momentum is imparted to a linear flow at a higher elevation through a vortex intake which causes the water to travel a helicoidal path down a vertical cylindrical drop shaft whilst clinging to the wall and dissipating energy through friction. One of the earliest manifestations of the vortex drop shaft was by Drioli (1947) who provided designs as part of an energy dissipator in a hydropower project (see Figure 1). It is argued that this is the first appearance of vortex drop shafts in hydraulics; however, there are other reports that suggest they have originated in Vancouver in the mid-1930s (Motzet and Valentin, 2002). From the 1980/1990s, applications of the vortex drop shaft in urban sewerage infrastructure grew rapidly due to increased urbanization, population growth and requirements for infrastructure upgrade with climate resilience driving new design requirements (Jain and Kennedy, 1983). In the wake of this application has come extensive studies of vortex drop shafts in analytical, physical, numerical and commercial research resulting in a suite of new scientific findings, data sets and design guidelines.

As part of a collaboration between the National University of Ireland Galway and Thames Tideway (London) this paper was motivated by the need to review existing design guidelines and synthesize the findings of previous studies for the purpose of drawing high-level conclusions on design approaches and methods and identifying key gaps where future research should focus. Although the article of course cannot remark on the complete content of available literature in this field, the review focuses on seminal studies from over 75 years of research and development on vortex drop shafts together with more recent model studies undertaken for full-scale commercial projects (Plant and Crawford, 2016).

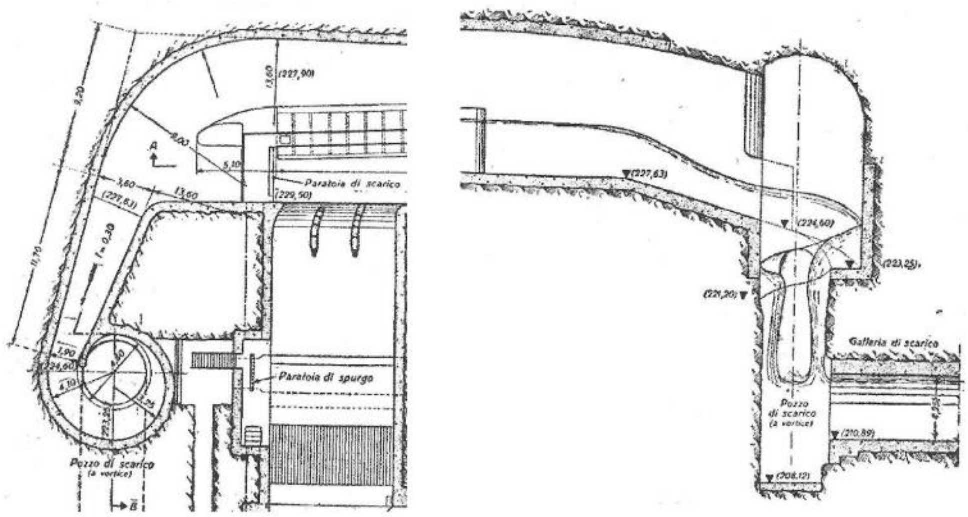

Figure 1. Plan and end view schematic of Drioli's spiral vortex drop shaft (Drioli, 1947).

2 CONFIGURATION OF VORTEX DROPSHAFTS

In general, vortex drop shaft structures can be categorised into two types depending on the approach flow Froude number condition Fri = $v_{in}/\sqrt{gh}$ where v_{in} and h are the approach flow velocity and depth respectively. Subcritical inlet structures (Fri < 1) are typically characterised by a horizontal approach invert (Knauss, 1987). The opposite case is that of a supercritical approach flow (Fri > 1) where the inertial forces at the inlet dominate. In the latter case, supercritical flows are encouraged in the inlet channel by channel taper and a positive bottom slope (β) where β values of between 10 – 20 % are optimum (Hager, 2010). In some cases, the approach flow of a horizontal invert vortex chamber can also be made supercritical via a pressure flow or high velocity inlet (Motzet and Valentin, 2002). There are several configurations for drop shaft structures and vortex chambers alike which may be classified into four broad subcategories (Jain and Kennedy, 1983; Knauss, 1987) as shown in Figure 2 and described below

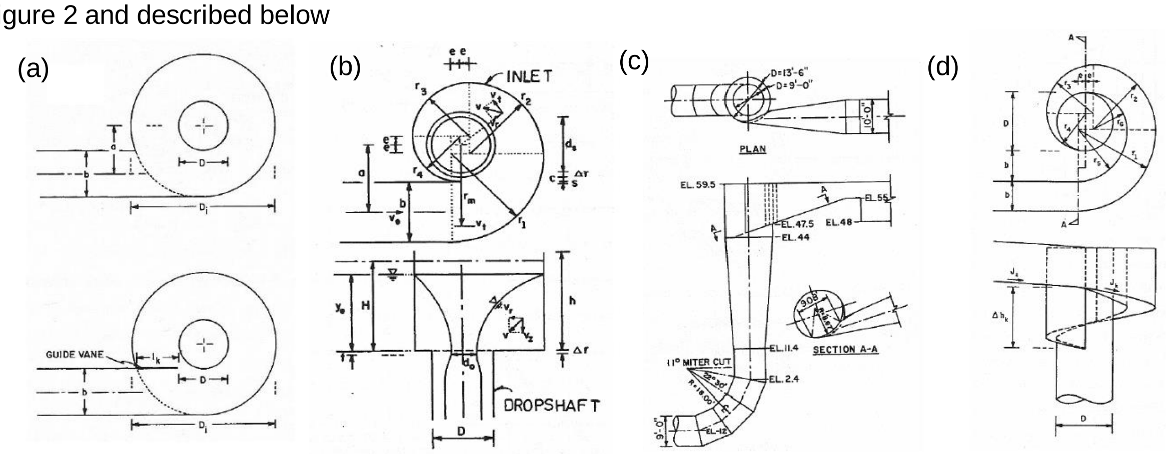

Figure 2. Schematics of (a) circular, (b) scroll, (c) tangential and (c) spiral vortex intakes reproduced from various sources

a) *Circular:* The most simplistic approach flow configuration is that of a circular inlet where the walls of the intake are concentric with the drop shaft and the floor is horizontal (β = 0). Therefore, subcritical approach flow conditions prevail for the majority of applications (Laushey, 1952; Laushey and Mavis, 1953). They can be further modified by adding a guide vane to increase the discharge capacity of the chamber for a given approach flow depth (h/d) where d is the drop shaft diameter.
b) *Scroll:* The scroll inlet increases the discharge capacity in comparison to the circular shaft by spiralling the sides of the intake towards the drop shaft or orifice. The floor in a scroll shaft is horizontal and therefore subcritical approach flow conditions prevail for the majority of applications (Mulligan et al, 2016).
c) *Spiral:* The spiral inlet has a scrolling formulation similar to b) and a sloping floor (β > 0) (Drioli, 1947; Kellenberger, 1988; Pfister et al, 2018). The approach flow conditions are then generally of the supercritical type presenting a shockwave due to bend flow and forced vortex behaviour. These can also be modified to have a banked or warped (radial sloping) approaching channel (Lee et al, 2017; Rhee et al., 2018) which limits the shockwave and increases the air core diameter.

d) *Tangential:* The tangential inlet (Jain, 1984) is a form of supercritical circular inlet and remains one of the most popular approaches due to its low footprint and high capacity (Plant and Crawford, 2016). The flow is conveyed tangentially to the circular chamber in a contracting and sloping channel. In initial designs, the commencement of the channel slope and contraction occurred at the same location (Jain, 1984; Yu and Lee, 2009). However, more recent designs by Thames Tideway (Plant and Crawford, 2016) adopted a steeper slope angle and shorter taper which achieved a compact footprint and high capacity for a wider throat width. Similarly, the vertical slot vortex chamber (Quick, 1990) is composed of a vertical pipe with a 90º rectangular slot cut into its top which is essentially another variation of the tangential inlet.

Other types of vortex intake are confined and siphonic intakes but will not be discussed in this paper due to their limited application.

3 HYDRAULIC ANALYSIS

3.1 The Hydraulic Control

The hydraulic control section (or critical section) and its transition plays a key role in vortex intakes. Hydraulic control shift occurs when the flow is forced to transition from subcritical to supercritical flow – for example due to the narrowing of a channel. In a subcritical vortex intake, the hydraulic control section resides at the critical air core diameter just downstream of the intake and may transition to the inlet channel under cases of large eccentricity and or large flow capacities causing a hydraulic jump in the inlet channel (Mulligan et al, 2016). In a supercritical inlet, the hydraulic control resides at some location in the approach flow channel (Yu and Lee, 2009). In, for example the tangential type, the hydraulic control usually resides at the crest of the sloping channel during initial conditions. As the flow increases, the control section then shifts from the crest to the throat (or junction) of the intake for most flow conditions. As the depth and discharge rises further, the control section finally shifts to the drop shaft and the approach flow to the chamber begins to flatten out and become subcritical. The control section is then pushed further downstream in the drop shaft, which may give rise to a 'choking' effect of the shaft introducing highly unstable flow phenomena.

3.2 Vortex Intake Design and Depth-Discharge

Solutions for the depth-discharge relationship in vortex intake approach flows depend on the position of the control section and, hence, the type of approach flow - supercritical or subcritical. In the supercritical case, for small discharges, the control is at the crest of the sloping channel. The depth–discharge relation is then determined by the critical depth equation (Yu and Lee, 2009):

$$y = y_{ca} = \sqrt[3]{\left(\frac{Q}{B}\right)^2 \frac{1}{g}} \quad [1]$$

where y is the channel depth, B is the channel width, Q is discharge and y_{ca} is the critical depth based on unit discharge. For large discharges, as the control shifts to the junction between the downstream end of the tapering inlet and the drop shaft, the flow at the junction becomes critical. At the junction, the critical depth becomes:

$$y = y_{cj} = \sqrt[3]{\left(\frac{Q}{e}\right)^2 \frac{1}{gCos\beta}} \quad [2]$$

where y_{cj} is the critical depth at the junction, e is the slot width at the junction and β is the slope angle (Yu and Lee, 2009). Using the specific energy equations, the following expression for the control shift discharge Q_c can then be derived:

$$Q_c = \frac{\sqrt{ge}(2z/3)^{3/2}}{(Cos^{2/3}\beta - (e/B)^{2/3})^{3/2}} \quad [3]$$

where Q_c increases with e, and most importantly z, for given β and B (Yu and Lee, 2009). Using Eq. [1], [2] and [3], it is then possible to resolve the depth discharge relationship in the approach flow based on adjusting for the drop in channel level within the vortex intake (Plant and Crawford, 2016).

Resolving the depth-discharge for the subcritical vortex intake is more difficult due to the control section residing at the vortex air core. An approximate expression for the depth-discharge relationship can be obtained by making a number of assumptions, namely, that the whole flow field is axisymmetric and fully irrotational and the velocity varies inversely by $v_\theta = \Gamma/2\pi r$ with a constant field circulation Γ assuming no losses between the inlet and intake (Ackers and Crump, 1960). Then, by applying energy principles between the inlet channel and the intake, it has been shown (Ackers and Crump, 1960; Mulligan et al, 2016) that a generalized expression for Q can be derived as follows:

$$Q = \frac{\pi}{4} d^2 (1-\lambda) \sqrt{2gE - \frac{\Gamma^2}{\pi^2 d^2 \lambda}} \quad [4]$$

where λ is the fractional air core area and is equal to a_c^2/d^2 where a_c is the air core area at the hydraulic control. Eq. [4] provides a challenge as it cannot be readily solved due to the unknowns λ, E and Γ. The equation was simplified into several analytical/semi-empirical models by various authors which are summarized by Mulligan et al. (2016).

3.3 Free-Drainage Discharge

Yu and Lee (2009) showed that under some conditions in a tangential intake, the vortex flow, after turning 360° in the drop shaft, may reenter the inlet or disturb the parallel inflow jet, creating a backflow or even a hydraulic jump in the tapering section. To avoid this condition, Yu and Lee (2009) derived an expression for the discharge when wrap-around interference occurs and defined it as the free drainage discharge, Q_f. The expression was derived based on the assumption of the flow being irrotational and axisymmetric and is expressed as:

$$Q_f = \left(tan\beta \frac{\pi D}{1 - e/D}\right)^{3/2} \sqrt{g}\, ecos^2\beta \quad [5]$$

Thus, to maintain the smooth and stable flow condition in the tapering section of a tangential inlet intake, the criterion of $Q_c < Q_f$ for the design of the tangential vortex intake can be adopted.

3.4 Vortex Chamber Velocity Distributions

The velocity distribution across the vortex intake and drop shaft has recently been a topic of interest in various studies. As was described in Sections 3.2 and 3.3, many analytical solutions for the depth-discharge relationship are dependent on ideal assumptions made on the tangential velocity profile. Thus, a poor understanding of actual velocity conditions in the intake could result in significant uncertainty resulting from assumptions made therein.

Regarding subcritical approach flows, the tangential velocity in the vortex generator can be approximated by axisymmetric and irrotational assumptions where $v_\theta = \Gamma/2\pi r$. However, numerous authors found significant discrepancies in this model near the vortex core region. Mulligan et al., (2018) studied the tangential velocity distribution extensively using particle tracking velocimetry and reported that this discrepancy was likely due to neglecting the axial flow effects in this region. To improve on this, Mulligan et al. (2018) presented a corrected equation as follows:

$$v_\theta(r) = \frac{\Gamma_\infty}{2\pi r}\left(1 - \left(\frac{h}{5\alpha d}\right)^{\frac{2r}{d}}\right) \quad [7]$$

where r is an arbitrary radius in the intake and $\alpha = r_{in}/e$. In a supercritical approach vortex generator, it has been assumed that the velocity profile also follows the ideal irrotational model, i.e. $v_\theta = \Gamma/2\pi r$ (Yu and Lee, 2009). However, more recently Chan et al. (2018) determined that the flow is better approximated using a Rankine-like combined vortex model. In this, the author determined that a large portion of the flow surrounding the air core was a rotational vortex defined by solid body rotation. This was bound by a smaller irrotational flow region closer to the walls of the chamber.

3.5 Drop Shaft Flows, Energy Dissipation and Aeration

An understanding of the hydraulics in the vertical shaft is significant for considering energy dissipation characteristics and for choosing suitable lining material for durability and wear resistance (Laushey and Mavis, 1952). The earliest studies on the drop shaft hydraulics were documented by Jain and Kennedy (1983) and Kellenberger (1988). More recently, measurements of wall pressures and flow thickness in the shaft were reported by Zhao et al. (2006).

In the drop shaft, the diameter of the vortex air core first decreases and then increases from the generator to the vertical drop shaft which forms a throat at the contracted section. In a subcritical scroll intake, the free-surface is central and vertical due to the fluid dynamics of vortex flow properly aligned with the geometry of the chamber. In the case of a tangential inlet, the free-surface is not uniform within this region due to velocity imbalances resulting from the position of the tangential inlet and thus the air core does not maintain centrality or verticality (Chen et al., 2010). As the flow discharges axially from the vortex generator into the drop shaft, the residual centrifugal forces in the flow combined with the Coanda effect cause the water to cling to the walls of the shaft on its transition to the bottom stilling basin (Weiss et al., 2010). This longer helicoidal path that the fluid takes along the walls induces energy dissipation through friction (assuming a roughness coefficient n) and aeration (Hager, 1990; Jeanpierre and Lachal, 1966). Similarly, in a scroll intake, the annular jet is axisymmetric with a uniform thickness circumferentially due to uniformity of the vortex. In the tangential or spiral intake however, flow in the intake causes a primary helical annular jet covering a thinner more uniform secondary annular jet.

(a) (b)

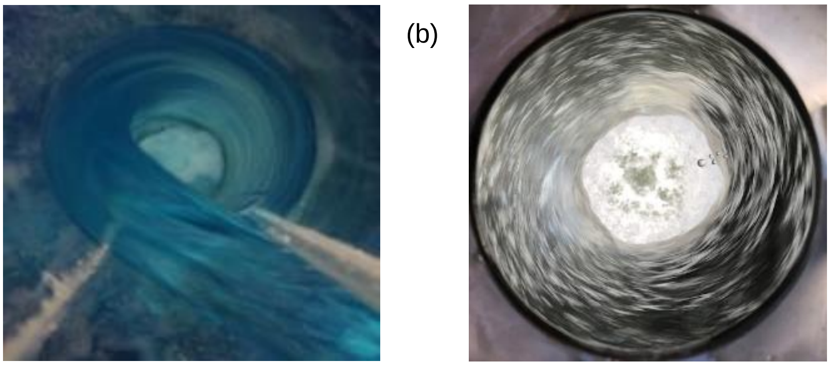

Figure 3. (a) Helical annular flow in a spiral intake drop shaft (Carty et al., 2019) and (b) uniform annular flow in a subcritical scroll intake drop shaft (NUI Galway Water Research Facility).

In each case, through assumptions of uniformity and irrotational flow, the specific energy head E along the drop shaft can be defined by:

$$E = \frac{{v_z}^2}{2g} + \frac{{v_\theta}^2}{2g} + \frac{p(r)}{\rho g} = \frac{{v_z}^2}{2g} + \frac{2\Omega^2}{gD^2\left(1 - \frac{2b}{D}\right)^2} \quad [9]$$

where $\Omega = rv_\theta$. For an axisymmetric annular flow, it can also be assumed that the axial velocity is constant over the annular cross section, thus:

$$v_z = \frac{Q}{\pi(\frac{D^2}{4} - {r_c}^2)} \quad [9]$$

Therefore, once the annular jet thickness is measured, the Energy heads $H = E + Z$ can be ascertained to determine the energy dissipation along the drop shaft through experiments. Estimates of the energy dissipation in earlier studies assumed that the drop shaft is so long that the flow reaches its terminal velocity. Vischer and Hager estimated 85% energy dissipation for $l = 50d$ where l is the length and d is the diameter of drop shafts with a Manning's n of 0.012. Jain and Kennedy (1984), predicted a 90% energy loss in a drop shaft of 100d with a friction factor of 0.03. Jeanpierre and Lachal (1966) reported 62% energy dissipation for a drop of about 9d. Zhao (2006) reported on an overall energy dissipation rate in the drop structure of 90% where the highest energy dissipation was reported in the plunge flow 'water cushion' where an annular hydraulic jump formed. Other work was undertaken on the streamline angle of the annular jet in a tangential inlet by Carty et al. (2019) which is useful for resolving the tangential component of the velocity in the drop shaft when the jet thickness is known. Carty et al. (2019) also proposed that this form of investigation is necessary to assess the hydrodynamic effects on drop shaft liners.

In terms of air entrainment, there are primarily two mechanisms: (1) within the annular jet due to free-surface instabilities and (2) impingement of the annular jet in the downstream plunge pool (Zhao et al., 2006). It has been said that vortex drop structures entrain appreciably less air than plunge flow structures (Jain and Kennedy, 1983); however, Zhao et al. (2006) states that air entrainment is primarily controlled by the jet velocity, irrespective of whether the drop shaft is of vortex or plunge-flow type. Furthermore, two regimes of air entrainment were characterized structures (Jain and Kennedy, 1983). When the lower end of the drop shaft is open to the atmosphere and the annular jet discharges freely, the air entrainment condition is said to be in Regime I. Regime II occurs when the drop shaft is flooded causing the formation of an annular hydraulic jump.

4 75 YEARS OF PHYSICAL MODELLING

From its earliest conception in 1947, extensive physical modelling studies have been undertaken on vortex drop shaft structures. These generally involve transparent acrylic models and use a range of techniques from simple flow and depth measurements to advanced instrumentation for consideration of air entrainment, pressure and velocity distributions. This section recaps on the historical progress of experimental modelling for subcritical and supercritical intakes.

4.1 Subcritical Intake Flows

Laushey and Mavis (1952) and Laushey (1953) investigated the circular inlet configuration as a means to safely drop storm-sewer flows for the Algheny County Sanitary District of Pittsburgh. In this work the authors carried out physical model studies to determine the discharge characteristics, air entrainment, pressures and dissipation of energy. The experiments were conducted in a 150 mm diameter pipe having a Lucite section of about 1.22 m length at the top. Velocities were measured using a pitot tube. Further experimental model studies were conducted on the circular intake by Anderson (1961) by analysing three tank-diameter/orifice-diameter (d/D) ratios; however, the author rejected the design due to failure to comply with design requirements and the costs associated with construction. Kleinschroth and Wirth (1981) modified the geometry with the previously described guide-wall which solves the problem low capacity. Early experimental investigations on the scroll type vortex chamber were presented by Drioli (1969) and Ackers and Crump (1960). The ETH VAW Switzerland (ETH, 1977) also performed model studies on prototypes. Stevens and Kolf (1959) conducted physical model studies on a vortex chamber based on results from dimensional analysis and considered four varying orifice diameters. More recently, Mulligan et al. (2016) undertook a study on twelve variations of the scroll chamber to develop a simple empirical model for determining the depth discharge based only on the approach flow geometry. Subsequently, Mulligan et al. (2018) investigated the tangential velocity profiles across the scroll chamber using laser particle tracking velocimetry.

4.2 Supercritical Intake Flows

Drioli (1947) was the first to perform experimental analysis on drop shaft structures which were typically that of the spiral inlet design. Kleinscroth and Wirth (1981) as well as Kellenberger (1988) introduced design procedures as well as results on physical model experiments for spiral inlets. Small and large scale model studies were performed by Jain and Kennedy (1983) and suggestions were made on similarity and optimum length of the de-aeration chamber. Jain (1984) conducted a laboratory study to develop and test tangential-inlet drop structures for an in-line storage system proposed by the Milwaukee Metropolitan Sewerage District. The experimental data was used to predict analytical models proposed by the author. Subsequent work was carried out by Jain (1988) to assess air transport in the annular jet of a vortex drop shaft. Hager (1990) optimised the spiral inlet based on data collected from various inlet geometries. The surface profile along the outer guiding wall was analysed. It was found that the Froude number of the approach flow and the radius of the outer inlet wall influence the maximum standing wave height. More recently, Motzet and Valentin (2002) assessed the efficiency of a horizontal bottom vortex chamber (scroll type) when used to convey a supercritical approach flow. Zhao at al. (2006) undertook model studies to provide design guidance for a Chinese power station where a large vortex-flow drop shaft was proposed to convey water to an existing diversion tunnel. In this study, the authors focused on energy dissipation along the drop shaft by measuring the wall pressure using a total of 50 piezocrystal pressure sensors arranged at 13 sections and the annular jet thickness using a specially designed L-shaped probe. The probe consisted of a horizontal pipe of 3 mm in diameter and a small inlet tube 1.5 mm in height and 1.2 mm in diameter which encountered sensitivity in detecting the air-water interface with errors of up to 2 mm in jet thickness entrained. Yu and Lee (2009) carried out extensive experimental work in order to progress towards general and robust design criteria which were not available for supercritical drop shafts. Fifteen experimental models were investigated, and the authors noted their observations agreed well with the theoretical prediction. Plant and Crawford (2016) however investigated Yu and Lee's (2009) relationships for the tangential inlet and observed significant discrepancies. Chan et al. (2018) and Chan et al. (2019) appear to be the only studies that focused on velocity measurements in the complex flow of the vortex intake. Here they employed laser doppler anemometry (LDA) for a wide range of inflow conditions to resolve a Rankine like vortex distribution radially across the intake.

5 ADVANCEMENTS IN NUMERICAL METHODS

Flows in a vortex drop shaft structure are highly three-dimensional exhibiting various intensities of turbulence and instability, particularly in the vicinity of the free-surface. It was shown by Plant and Crawford (2016) that in many cases the use of one-dimensional approaches to resolve depth-discharge relationships can severely impact final designs. With advancements in the field of computational fluid dynamics (CFD) in recent years, attempts have been made to provide accurate simulations of drop shaft flows to enhance insight into their performance from a research and design perspective.

The two-phase fluid domain is commonly modelled using a homogeneous Eulerian-Eulerian multiphase or Volume of Fluid (VOF) method (Hirt and Nicholas, 1981). The tracking of the interface between the phases is accomplished by solving the volume fraction equation for one of the phases based on the VOF approach. In supercritical vortex generators, due to their popularity in recent years, a number of studies have been undertaken. Plant and Crawford (2016) reported on the use of ANSYS CFX for analyzing tangential intakes pre- and post-physical modelling stages. In their studies, the authors adopted an inhomogeneous multiphase approach to model interphase momentum transfer between air and water with homogeneous turbulence using shear stress transport (SST). The simulations involved steady flow and used a 0.1 s time step and an unstructured mesh with inflation layers applied to the walls. A fine mesh (9 million elements) produced a prediction of free surface very close to the physical model prediction, whereas a course mesh (1.5 million elements) showed noticeable divergence from the physical model. A similar physical-numerical model study was undertaken by Carty et al. (2019). Although similar boundary conditions were employed in the ANSYS CFX model, the study used a transient model (0.01 s timesteps) and adopted a homogeneous multiphase approach and various turbulence models. In the homogenous approach, both phases are treated as interpenetrating continua parted by a well-defined interface and share common velocity, pressure and turbulence field. The authors reported on similar levels of accuracy (≤ 5% error) in modeling the free surface using the SST model and found that significant errors can be introduced to the free-surface when inflation layers are omitted from the mesh structure. Carty et al. (2018) also reported on the hydrodynamics for the extent of the drop shaft, however their results could not be validated in this region.

Chan et al. (2018) and Chan et al. (2019) advanced on the previous free-surface comparisons by also validating the CFD model predictions against detailed point velocity measurements using LDA for a wide range of inflow conditions. In their simulations, the governing equations were solved numerically using the "interFoam" solver in OpenFOAM 4.0 for two incompressible, immiscible fluids based on the interface capturing approach. The good agreement between the numerical and experimental velocity profiles for the inlet channel and vortex generator confirmed that the multiphase CFD simulation was capable of accurately capturing the velocity field in the tangential intake structure. Zhang et al. (2018) undertook another study on the tangential inlet drop structure using Flow 3D and the VOF method where they reported again on good agreements with experimental and numerical velocity and pressure distributions.

Regarding subcritical vortex drop shafts, very few studies have been carried out on these structures, most likely due to their limited application. Mulligan et al. (2019) undertook multiphase simulations on the subcritical vortex generator using a homogeneous Eulerian-Eulerian model. Despite the differences in modelling, both studies found that the standard eddy viscosity models significantly overestimate turbulence production in the vortex core which is suspected to be as a result of strong curvature and rotation in this region. Both studies also concluded that the results can be significantly improved through implementation of curvature correction in standard eddy viscosity models (e.g. SST) which reduces the production of turbulent kinetic energy and increases its rate of dissipation in regions of streamline curvature. Mulligan et al. (2019) also concluded that in order to accurately model the free-surface and depth discharge relationship in a subcritical vortex chamber, it was necessary to resolve the mesh in radial fashion to avoid false diffusion. Finally, a first attempt of modelling the subcritical vortex drop shaft with smoothed particle hydrodynamics was presented by Macherel et al. (2019). Although a comparison between the simulation data and physical model in this study was qualitative, the good agreements in free-surface obtained bode well for the use of this simulation approach in future years.

6 COMMERCIAL CASE STUDIES

There have been several commercial research investigations undertaken on vortex drop shaft structures internationally over the past twenty years following the increased number of deep sewer conveyance systems developed to alleviate combined sewer overflow and to increase climate resilience. Some of the noteworthy projects are the Milwaukee Metropolitan Sewerage District Inline Storage System (17 drop structures) (Jain and Kennedy, 1983), Thames Tideway Tunnel (22 tangential vortex drop structures) (Plant and Crawford, 2016), Hong Kong West Drainage Tunnel (34 intakes) (Lee et al., 2017) and Singapore Deep Tunnel Sewerage System (DTSS2) –17 vortex drops (Brocard et al., 2019).

(a) (b)

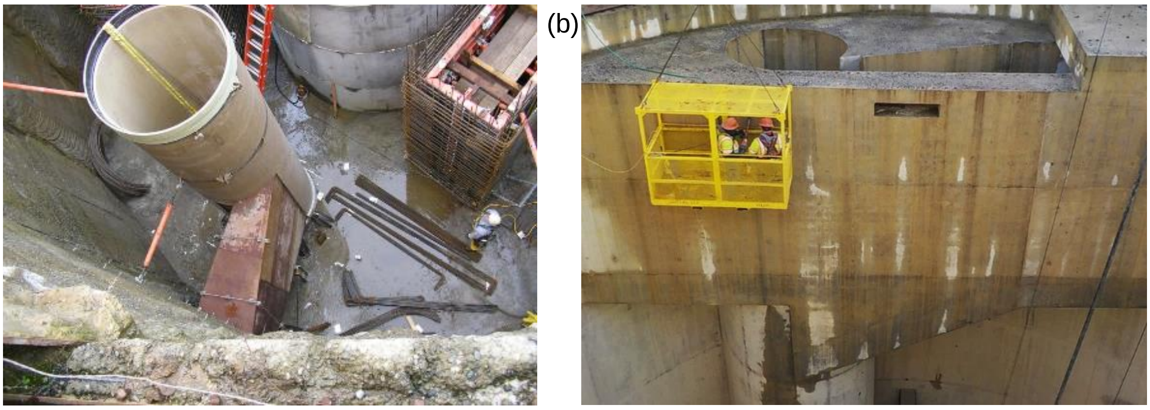

Figure 4. Image of a tangential inlet and drop shaft liner during installation ((image courtesy of Jacobs / Thames Tideway Tunnel)) and (b) image of a concrete tangential inlet (image courtesy of the District of Columbia Water and Sewer Authority)

As a result, extensive stress testing was necessary at the design stage to guarantee the reliability and robustness of the structure's operation for a lifespan of up to 100-years. During physical modelling of the Thames Tideway schemes' tangential inlets, the effect of these real-world constraints on performance were investigated extensively. For example, self-limiting conditions are often required on inlet channels to vortex generators (usually via overflow flap valves) to provide sufficient freeboard in the approach flow channel.

However, a secondary (emergency) self-limiting operation may be required when the vortex intake overtops. In the Tideway study, Plant and Crawford (2016) found that at, and beyond, the onset of overtopping of the structure (at approximately 130% design flow), the structure continued effective operation up to 150% design flow with the vortex air core remaining intact. This demonstrated the performance resilience of the structure even under the most extreme conditions.

Other effects that were observed in the Tideway studies were those due to upstream hydraulic appurtenances such as flap valves and gates which can disrupt ideal flow conditions in the approach flow. For example, considerable disturbance, turbulence and non-uniform conditions were observed in the approach flow including air entrainment and surcharge of the valve apertures and connection orifices in one case study by Plant and Crawford (2016). These effects were particularly apparent at higher flow rates where horizontal bias in the flow, arising from the sharp bend into the interception structures, was observed through the uneven opening in upstream flap valves. The authors concluded that this may be a contributing factor to the large variations between experimental data and the analytical model proposed by Yu and Lee (2009). When studying comparisons of all their datasets, at low flows ($\leq Q_f$) significant variation between the observed and predicted depths of the order of 65% were observed. The magnitude of this percentage variation was deemed to be affected by shallow supercritical flows in the drop shaft which can be directly influenced by hydraulic features upstream of the vortex intakes. Beyond the free-drainage discharge, the analytical model consistently underestimated the actual depth-discharge relationship. This analysis indicated the divergence in predicted and observed performance was caused by increasing levels of wrap-around interference restricting flow through the vortex intake slot as flow increased above Q_f. In summary, physical and numerical modeling of Tideway designs indicated that Q_f occurred significantly lower in the flow range than predicted through Yu and Lee's (2009) model and hence all designs experienced wrap-around interference. However, wrap-around interference did not detrimentally affect the performance of the drop shaft (Plant and Crawford, 2019).

7 DISCUSSION AND OUTLOOK

With the demonstrated levels of vortex drop shaft performance to date and the likely increase in the need for larger urban drainage systems, vortex drop shaft structure installations should continue to grow. That said, this review shows that there is still significant scope for improved understanding of these structures to help design safer, more long-lived efficient structures and infrastructure, improve the design stage and ultimately enhance the economics of new projects. Based on the academic and industrial experience and perspectives of the authors, a number of these areas will be discussed briefly.

7.1 Performance of Vortex Drop Structures

Performance differences between types of structure differs largely in terms of the type of vortex intake which is either a subcritical or supercritical approach flow type. Though subcritical vortex intakes have served their purpose in earlier designs, it is apparent that they have largely been displaced by the supercritical vortex intake which offers higher flow capacities and smaller footprints to suit the broader range of applications in sewer infrastructure. This is particularly true for tangential inlets which have seen widespread adoption in recent years. There have been firm conclusions on the energy dissipation rates of the structure which can be of the order of 60 to 90%. However, it is unclear on whether a certain intake type, either subcritical or supercritical, produces higher energy dissipation efficiencies over the other.

7.2 Vortex Intake Hydraulics

In subcritical approach flow generators, the depth-discharge relationship and its dependency on geometry and vortex core is well understood with many semi-empirical models available. The velocity field, in particular the tangential velocity profile, in the chamber have also been a recent topic of study which provides additional insight. On the other hand, supercritical drop shafts rely on three hydraulic equations depending on the location of the hydraulic control. It was shown that significant discrepancy between the theoretical and actual depth-discharge relationships can result in up to 65 % errors in depth measurement (Plant and Crawford, 2016). It is recommended that the hydraulics of the depth-discharge relationship in a tangential inlet is revisited to attempt to revise a more accurate relationship for future design purposes.

7.3 Drop Shaft Hydraulics

There have been only a few studies that conclude generically on hydraulic behavior inside the drop shaft and therefore more parametric studies are required. Hydrodynamic variables inside the drop shaft such as jet thickness, tangential and axial velocity and pressure distributions are necessary to the practitioner for sizing the downstream energy dissipation structure, predicting aeration rates and choosing suitable liner materials. Often, these liners have been fabricated from costly materials such as stainless-steel which indeed may be excessive but nonetheless conservative given the lack of design guidelines available on this matter. Thus, there is a requirement to substantiate the semi-empirical and numerical models proposed in past literature to permit accurate predictions on the hydrodynamics within these structures which will aid in sensible material choice to improve the economy of the structure in future years.

7.4 Further Physical Model Investigations

A number of practical outcomes have been derived from physical models of vortex drops shaft structures to date. The authors recommend the following studies in future years:

- Further studies on the three-dimensional velocity distribution in the supercritical vortex generator and drop shaft structure. Currently, several models developed with regards to depth-discharge, annular jet flows and energy dissipation are dependent on the assumption of free-vortex theory which requires further experimental validation
- Analysis of spatial (axial and circumferential) and temporal (steady and transient) pressure distributions in the vortex drop tube for various vortex intake types
- Comparisons of energy dissipation and aeration rates for subcritical and supercritical intakes for varying drop heights and roughness coefficients
- A comprehensive study on scale effects on vortex drops shafts, (apart from the work of Jain and Kennedy (1983)) is so far absent. Given that there is now an abundance of working prototypes and laboratory models, an investigation to determine conditions for the onset of scale effects in Froude similitude would be a very useful study.
- Explore new tools and instruments to resolve three dimensional free-surface data in the vortex generator and drop shaft, for example Light Detection and Ranging (LIDAR) which is actively being used to monitor hydraulic jump free-surface flows
- A systematic air entrainment study should be performed to substantiate air flow requirements in these structures for Regime I and II flows in subcritical and supercritical intakes.

7.5 CFD investigations

Computational fluid dynamics has now reached maturity for application in complex free-surface flows such as in a vortex drop shaft. Significant errors are still present in simulating subcritical vortex generators due to sensitivity surrounding the prediction of the turbulence and free surfaces near the air core; however, this uncertainty can be overcome with higher computational power. Contrary to this, simulations on supercritical generators, particularly the tangential type, have produced highly credible results requiring only modest computational resources. In general, civil engineering on a whole has been slow to adopt CFD. Evidence of this is the “graveyard” of old acrylic vortex models at various laboratories around the world where numerous design iterations have been largely tested physically. It is recommended that more confidence should be put in CFD models in the case of tangential inlets during the preliminary design stages of futures projects; notwithstanding the requirement for an initial validation study to be performed.

8 CONCLUSIONS

This study provides a review of 75 years of vortex drop shaft research and development where considerable work has been undertaken on hydraulic approaches, seminal physical model studies, numerical modelling and insights from commercial projects. The following presents high-level conclusions from the study:

(1) Vortex drop shafts are reliable, highly efficient structures. With the effects of climate change coupled with increased urbanization, more extreme rain fall events will challenge existing infrastructure and the design of new infrastructure to cope with significant hydraulic loads, larger than those previously predicted. This should see significant growth in the use of the structure

(2) There is a need to further close the gap between the experimental work and full-scale developments. This will better inform design and will also mean that the research will enable better implementation in practice and thus better system performance.

(3) Point 2 will inform the accuracy of computational models which will in turn help designers address the issues such as designing for scenarios mentioned in point 1.

(4) There is a need for improved and more efficient design of the structures themselves by better understanding the structural forces they experience in order to reduce or optimize costs and quantities of materials required.

(5) The authors propose that a new complete international design standard should be developed, perhaps in the form of a monograph, to compile the findings of the past 75 years of vortex drop shaft research and of course to set the foundations for the next 75 years.

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REFERENCES

Ackers, P., Crump, E.S., Hrs and Bernoulli, 1960. The Vortex Drop, *Proceedings of the Institution of Civil Engineers*, *16*(4), pp.433-442.

Brocard, D., Gan, S.J., Koh, L.Y., Tan, T.W., Cox, W.I., Schellhase, T., Woo, L.L., Lo, S.H., Cheng, S., Loh, S.H. and Perumal, V., 2019. Deep tunnel sewerage system phase 2–hydraulics. *Water Practice and Technology*.

Bart, A., Macherel, T., De Cesare, G., Mulligan, S. and Essyad, K. 2019. Vortex Siphon – From 1:1 Scale physical model to SPH simulation and prototype. *Proceedings of SimHydro 2019: 14-16 June 2019*

Chen, H.Y., Xu, W.L., Deng, J., Niu, Z.P., Liu, S.J. and Wang, W., 2010. Theoretical and experimental studies of hydraulic characteristics of discharge tunnel with vortex drop. *Journal of Hydrodynamics*, *22*(4), pp.582-589.

Chan, S.N., Qiao, Q.S. and Lee, J.H., 2018. On the three-dimensional flow of a stable tangential vortex intake. *Journal of Hydro-environment Research*, *21*, pp.29-42.

Chan, S.N., Qiao, Q.S. and Lee, J.H.W., 2018, September. Flow Features of an Unstable Tangential Vortex Intake. In *International Conference on Urban Drainage Modelling* (pp. 328-333). Springer, Cham.

Carty, A., O'Neill, C., Nash, S., Clifford, E. and Mulligan, S. (2019) Hydrodynamic modelling approaches to assess mechanisms affecting the structural performance and maintenance of vortex drops shaft structures. *Journal of Structural Integrity and Maintenance* (awaiting publication)

Drioli, C., 1947. Su un particolare tipo di imbocco per pozzi di scarico (scaricatore idraulico a vortice). *L'Energia Elettrica*, *24*(10), pp.447-452.

Hager, W.H., 1990. Vortex drop inlet for supercritical approaching flow. *Journal of Hydraulic Engineering*, *116*(8), pp.1048-1054.

Hager, W.H., 2010. Wastewater hydraulics: Theory and practice. Springer Science & Business Media.

Jeanpierre, D. and Lachal, A., 1966. Dissipation d'énergie dans un puits à vortex. *La Houille Blanche*, (7), pp.823-832.

Jain, S.C., 1984. Tangential vortex-inlet. Journal of hydraulic engineering, 110(12), pp.1693-1699.

Knauss, J. E. (1987) Swirling flow problems at intakes. A A Balkema.

Kellenberger, M.H. (1988). Wirbelfallschächte in der Kanalisationstechnik. Mitteilung 98. Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie. ETH- Zurich [in German].

Kleinschroth, A. and Wirth, H., 1981. *Dimensionierung von Wirbelfallschächten unter Berücksichtigung verschiedener Zuflussbedingungen*. Lehrstuhl für Hydraulik u. Gewässerkunde, Techn. Univ. München.

Laushey, L.M., 1952. Flow in vertical shafts. Carnegie Institute of Technology, Department of Civil Engineering.

Laushey, L.M. and Mavis, F.T., 1953, August. Air entrained by water flowing down vertical shafts. In *Proceedings: Minnesota International Hydraulic Convention* (pp. 483-487). ASCE.

Lee, J., Tsang. A., Kwok, A., Ackers, J. 2017. Supercritical vortex intakes for urban stormwater management The Hong Kong University of Science and Technology

Motzet, K.M. and Valentin, F., 2002. Efficiency of a vortex chamber with horizontal bottom under supercritical flow. *Global Solutions for Urban Drainage: 9 ICUD*.

Mulligan, S., Creedon, L., Casserly, J. and Sherlock, R., 2018. An improved model for the tangential velocity distribution in strong free-surface vortices: an experimental and theoretical study. Journal of Hydraulic Research, pp.1-14.

Mulligan, S., Casserly, J. and Sherlock, R., 2016. Effects of geometry on strong free-surface vortices in subcritical approach flows. Journal of Hydraulic Engineering, 142(11), p.04016051.

Mulligan, S., Casserly, J. and Sherlock, R., 2019. Investigation of free-surface vortices using multiphase numerical models: The effect of transience and turbulent closure. To be submitted to the Journal of Multiphase Flow

Plant, J. and Crawford, D., 2016. Pushing The Limits Of Tangential Vortex Intakes: Is Higher Capacity And Flow Measurement Possible In A Smaller Footprint?. *Proceedings of the Water Environment Federation*, *2016*(12), pp.4108-4136.

Pfister, M., Crispino, G., Fuchsmann, T., Ribi, J.M. and Gisonni, C., 2018. Multiple Inflow Branches at Supercritical-Type Vortex Drop Shaft. Journal of Hydraulic Engineering, 144(11), p.05018008.

Quick, M.C., 1990. Analysis of spiral vortex and vertical slot vortex drop shafts. *Journal of Hydraulic Engineering*, *116*(3), pp.309-325.

Rhee, D.S., Park, Y.S. and Park, I., 2018. Effects of the bottom slope and guiding wall length on the performance of a vortex drop inlet. *Water Science and Technology*, *78*(6), pp.1287-1295.

Stevens, J.C. and Kolf, R.C., 1957. Vortex flow through horizontal orifices. *Journal of the Sanitary Engineering Division*, *83*(6), pp.1-22.

Weiss, G., Brombach, H. and Hohl, E., 2010. Hydraulic model tests on a stormwater vortex drop shaft: Verification of special conditions. *NOVATECH 2010*.

Vischer, D.L. and Hager, W.H., 2018. Vortex drops. In Energy dissipators (pp. 167-181). Routledge.

Yu, D. and Lee, J.H., 2009. Hydraulics of tangential vortex intake for urban drainage. Journal of hydraulic engineering, 135(3), pp.164-174.

