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EDITORIAL

Angelos N. Findikakis
Hydrolink Editor

Hydrolink publishes articles on water projects and issues of interest to a general technical audience, which includes the members of IAHR who either work on engineering design and construction of projects serving the water needs of communities and contributing to the protection and restoration of environmental systems, or are engaged in research supporting such projects. The subjects of the articles reflect the evolution of hydraulic engineering and research from being narrowly focused on flow problems for the design of hydraulic structures when IAHR was founded 88 years ago, to developing solutions to water problems in a way that serves the needs of a world that strives for sustainability. This evolution, especially over the last half century, reflects the changes in the way of thinking about growth and development, starting with recognizing the environmental impact of industrial and construction activities in the 1960s and 1970s, and continuing with the introduction of the concept of sustainable development in the late 1980s, followed by several calls for sustainability leading in 2015 to the adoption of Agenda 2030 with its 17 Sustainable Development Goals (SDGs) and 169 specific targets.

Hydrolink seeks to highlight the role of hydraulic engineering and research in achieving the SDGs and inform its readers about the latest developments in this area. This is especially important considering that according to the most recent assessment of progress towards the SDGs, the world is behind in achieving them by 2030, and that significant acceleration effort is needed. This is based on several metrics for individual SDGs targets tracked by the United Nations Water.

To better appreciate where the world stands on the road to sustainability with respect to water, we can look at the recently developed water security score for most countries. The concept of water security is closely related to that of water sustainability. A common definition of water security that is used across the UN system, defines it as the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability.

Last year the United Nations, University Institute for Water, Environment and Health (UNU INWEH) assessed water security around the world by estimating for each country a water security score on a scale from 0 to 100. This score consisted of ten components based on UN Water's indicators for several water related SDG targets. As can be seen in the plot in the next column, using the UNU INWEH's definition of water insecurity, about 60 percent of the world population is water insecure.

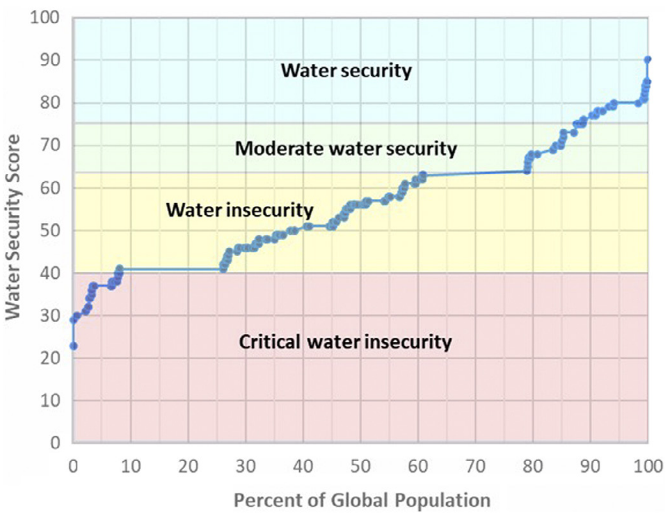
As the world is trying to attain water security and achieve the SDGs, hydraulic engineering plays a significant role through its contribution to the planning, design, construction, and operation of much needed water infrastructure. In addition, hydraulic research supports the development of nature-based solutions and aquatic ecosystem management practices.

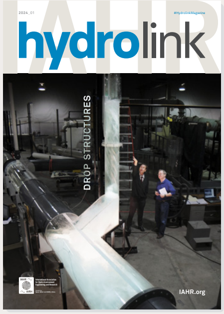
As discussed in an article by IAHR's President and its Executive Director published in Hydrolink last month, three pillars of IAHR's strategy are a) climate change adaptation and mitigation, b) energy transition, food security and nature. and c) resilient societies against water hazards and disasters, with digital transformation as an overarching component cutting across these three thematic areas.

Hydrolink informs its readers on work on these themes by publishing articles that sometimes focus on specific technical solutions and other times deal with broader issues. For example, the current issue includes several articles on drop structures, vertical shafts that are part of urban stormwater management systems designed to convey water to deep tunnels, sometimes up to 100 m below ground level. These structures are essential for preventing flooding in several large cities.

Examples of issues on broader themes, are the issue on SDGs published last year, and the issue on water and net zero with articles on the role of water in climate change mitigation, embedding low-carbon solutions into a water asset lifecycle, assessing GHG emissions for water bodies and other relevant topics.

Upcoming issues of Hydrolink will focus on lakes, water engineering pathways towards net zero, droughts, nature-based solutions and pumped storage. Hydrolink welcomes suggestions for subjects or themes to cover.





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Cover picture: 1:7 scale model at the Iowa Institute Hydraulic Research (IIHR) used to evaluate hydraulics and air management schemes for the Abu Dhabi drop structure.

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The importance of Drop Structures for Urban Hydraulic Engineering

By Sean Mulligan and Rob Ettema

Urban environments across the world are facing unprecedented challenges in the context of stormwater and wastewater management. These challenges commonly result from increased population growth and consequent urbanisation, as well as from ageing infrastructure and climate-change impacts.

Figure 1 | Image example of a drop structure (Courtesy of Thames Tideway/Jacobs)

Cities must consider novel approaches for managing stormwater storage and conveyance to support sustainable urban development and enhance resilience to climate change. Additionally, combined sewer systems (CSO) in existing urban areas are responsible for immense discharges of raw wastewater to the environment every year. Such CSO discharges are occurring more and more regularly, due to more intense rainfall events, increased urbanisation, and flows exceeding the capacity of aged infrastructure. For example, in the United States alone, it is estimated that CSOs annually result in 3.2 bn m^3 of untreated wastewater and stormwater being discharged into waterways[1].

To address these challenges, large-scale deep tunnels are increasingly being implemented around the world to cope with the conveyance and storage issues arising with the collection and treatment of stormwater and wastewater. Typically, such deep tunnels have been enabled using "Drop Structures" (see **Figure 1**) that function to convey storm or wastewater, safely and efficiently, through substantial elevation differences incurred by deep sewer schemes. Those schemes call for innovative hydraulic designs, technology, and construction methods to ensure service-life targets of more than 100 years can be attained for the infrastructure required. Aside from the significant role that large-scale drop structures have recently played in enabling deep tunnel systems, it must also be recalled that, for centuries, drop structures have played a major role in the form of smaller "back drops", "plunges" or "cascades" when the performance of water-collection systems required water energy dissipation.

This Hydrolink issue provides a brief overview of state-of-the-art developments in drop structure engineering applied in urban settings. Several live megaprojects from around the World were selected from high profile authors and organisations (including Iowa Institute of Hydraulics Research (IIHR), Jacobs, AECOM, Singapore Public Utilities Boad (PUB), and more) regarding recent advances in drop structure design and performance, along with innovations and lessons-learned thus far from both laboratory- and computer-simulation studies, and experiences gained in prototype-scale construction and case studies. The following section briefly recaps on the history and types of drop structures used in the context of urban hydraulic engineering, offers insights concerning specialised design and sustainable construction methods, and illustrates the importance of drop structures in future hydraulic engineering and sustainable urbanization.

History

Over many years, numerous drop structures have been designed and constructed to convey water and wastewater from a higher to a lower elevation. Examples exist of drop structures of various form having been used in early times (antiquity and up to the end of the Middle Ages (Chanson, 2002[2])) and those that are used today. In simple terms, whenever flow has had to be dropped in elevation with a requirement for flow energy dissipation, drop structures have been used. Early treatises on water engineering focused primarily on access, lifting, and conveying of water to enable irrigation or for domestic use (e.g., as described in Rouse and Ince 1957[3]; Garbrecht 1987[4]; and Violet 2007[5]). For example, the Romans used plunge-flow drop structures to drop water flow from a conduit to a lower one, as commonly required (sometimes in series or cascades) in the conveyance systems involving aqueducts. Roman drop structures typically were small (of the order of 4 m high and a 1 m in width), open to the air above, handled small flows (e.g., about 0.3 m^3/s, though usually less) and included a shaft pool into which the flow plunged before being decanted by a lower conduit. **Figure 2** illustrates a laboratory study examining the hydraulic performance of a typical Roman plunge-flow drop structure.

Without forgetting the past, this Hydrolink issue focuses on the contemporary and future use of drop structures, especially drop structures using vortex formation to stably drop water flows, often to elevations far beneath urban communities. An advantage of vortex formation is in its capacity to minimize the two main problems incurred with dropping flows: energy dissipation and, relatedly, air entrainment. These two problems potentially plague deep tunnels used for water storage or conveyance. The problem of energy dissipation is mentioned above, though the problems caused by air entrainment are expensive and possibly catastrophic (flow bulking, flow surging, and blowback/geyser; "air burping" may cause the latter two problems).

Figure 2 | Laboratory testing of the hydraulic performance of a Roman, plunge-flow drop structure replicated at full scale (Chanson 2002).[2]

The use of vortex-flow, drop structures for conveying substantial flows began in the late 1940s and has progressed since. Figure 3 shows progress in the development of vortex-flow drop structures through the construction of large-scale deep sewer conveyance systems globally. A rapidly increasing number of urban regions are implementing vortex flow drop structures as part of their urban drainage and storm-sewer systems.

Types of Drop Structures

Drop structures can be classified into two broad categories in accordance with the nature of flow that they convey: vortex-flow drop structures; and plunge-flow drop structures. The former category has the flow tangentially entering the drop structure through a vortex generator and remaining in contact with the drop structure's wall, and so forming an air core, as the flow descends. In the latter category, flow enters the drop structure radially and entrains air as the flow plunges downwards. The hydraulic characteristics (notably energy dissipation and air entrainment) of flow in a drop structure are quite different for the two categories. Figure 4 illustrates 5 types of inlet form that have been used to produce vortex-flows drop structures[8]. Occasionally, when weak foundation conditions require that drop structure diameters be kept small (and air entrainment and energy dissipation to be further reduced), helicoidal ramps are placed in drop structures to maintain tangential velocity and lengthen the flow path.

Early work on vortex-flow inlets for drop structures used the circular inlet form, which developed vortex flows from a sub-critical approach flow to a drop structure. This work, conducted in the late 1940s and early 1950s, sought to design a suitable inlet to pass storm-sewer flows for the Allegheny County Sanitary District of Pittsburgh, USA. In the mid-1950s, the Hydraulics Research Station of Wallingford, U.K. carried out tests of a circular inlet for storm-sewer drop structures intended for Episkopi, Cyprus. During the late 1940s and early 1950s, and generally in mountainous regions or whenever approach flows were supercritical, the spiral inlet was developed. For example, early studies of spiral-flow inlets were done in Italy, Switzerland, and Serbia, as well as for stormwater drainage at Orly Airport in Paris, France.

The scroll form of inlet is a widely used form of vortex-flow inlet, evolving from the circular form, which required substantially more head to produce the vortex flow. The hydraulic performance of scroll inlets has been widely studied where its inlet geometry was standardized. In circumstances where water depth is constrained, a partially pressurized scroll inlet can be used.

The geometry of the tangential inlet form to generate a vortex flow down a drop structure is perhaps the simplest of the vortex-generating inlets. The approach channel directly aligns with the circular drop structure walls to project flow tangentially around the walls of the drop structure's shaft. The hydraulic performance of tangential inlets has been studied

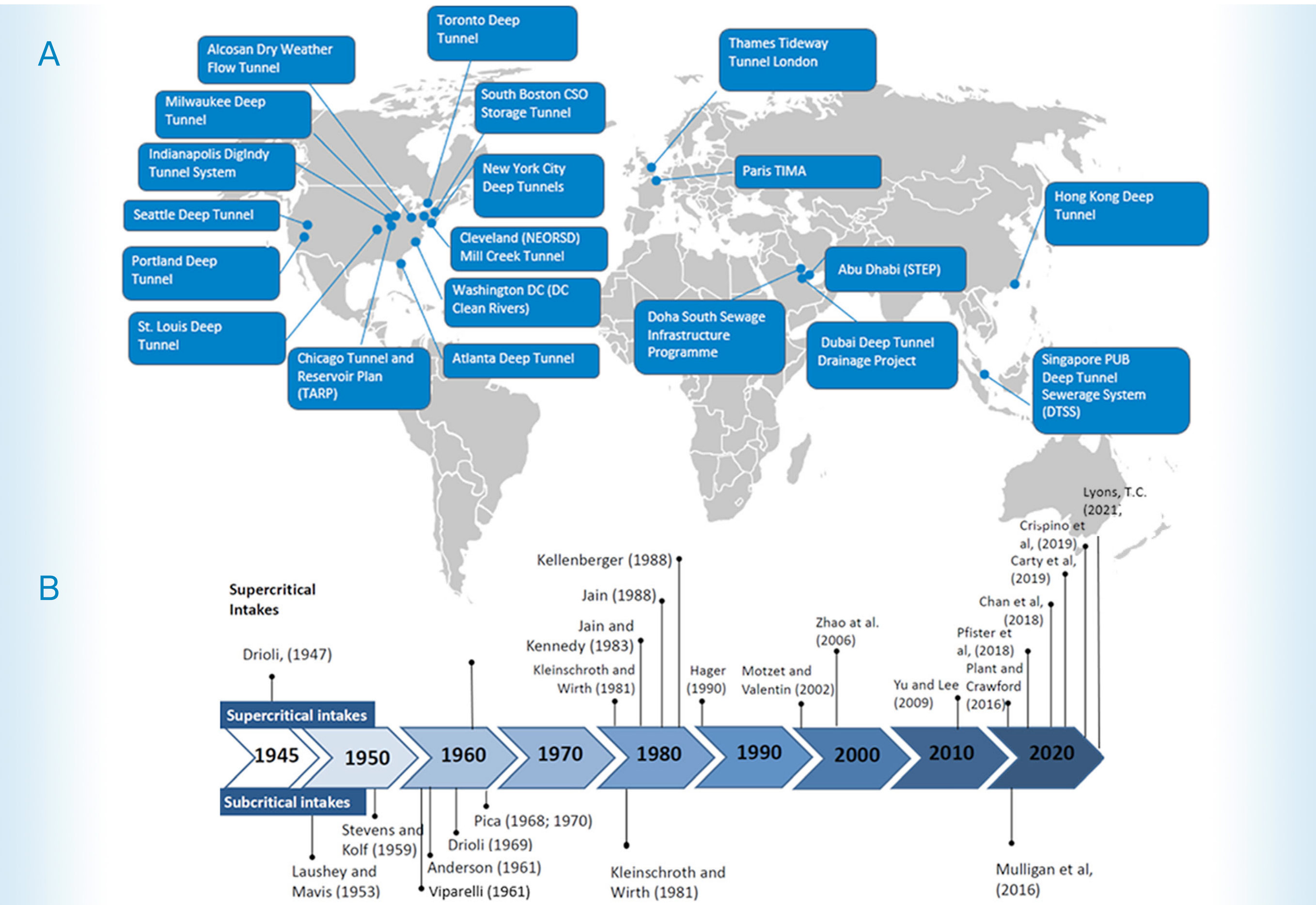

Figure 3 | (A) World map highlighting locations of major deep tunnel projects (and approximate completion dates) enabled by drop structures, and (B) historic timeline on the academic development of vortex-flow, drop structures. (see Mulligan *et al.* (2019)[6], for full references on research projects cited).

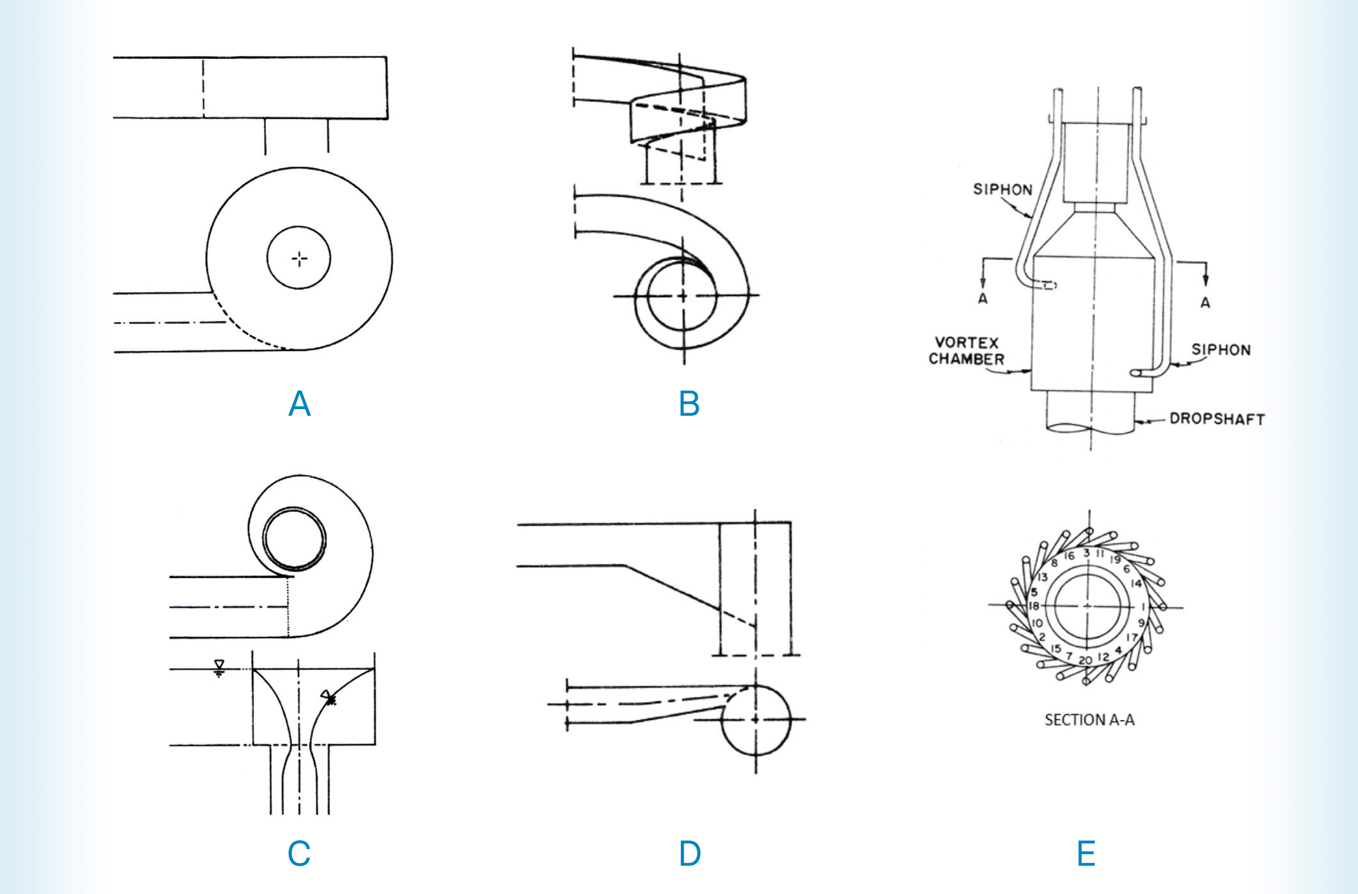

Figure 4 | Schematics of vortex-flow inlets for drop structures: (A) circular; (B) spiral; (C) scroll; (D) tangential; and (E) siphon[8].

extensively and shown to be equally effective in producing a vortex flow, as are the scroll and spiral inlets. The chief drawback of scroll and spiral inlets is that these inlet forms are larger in size and more complex in shape as compared to a tangential inlet. This drawback is significant because most drop structures used for storm-sewer flow control are in urban regions where space is very limited. At times, the tangential inlet could be assisted by a helicoidal ramp or a set of discrete baffles spiralling downwards within the drop structure. Though ramps or baffles aid continued vortex-flow down a drop structure, they considerably add to the construction cost of the drop structure and, therefore, are rarely used.

Also rarely used in modern days are siphon inlet drop structures. They were designed to serve as reservoir outlets and comprise a set of pipes around the entrance to the inlet that draw flow, then discharge flow through an array located down in the drop structure, thereby producing a vortex flow within the drop structure. Though their main advantage is in minimization of air entrainment, siphon inlets are complex in form, expensive to construct, and subject to plugging/clogging.

Sustainable Design and Construction

Although drop structures have been in existence for millennia, developments of large-scale drop structures (cascades, plunge, and vortex type structures) have greatly increased during the last few decades, driven largely by the development of deep-sewer conveyance systems. Recent drop structures have been known to convey flows of up to 1400 m^3/s through drop heights of up to 190 m, from the dense urban settings of Hong Kong, to deep beneath the River Thames and London's 150-year-old Victorian combined sewer system. Such designs have posed a range of new hydraulic design, construction, and maintenance considerations that have sparked significant advances in innovation and technology.

- **Hybrid Hydraulic Modelling** – Laboratory modelling continues to be one of the most reliable methods of predicting flow behaviour in drop structures and verifying design criteria such as drop structure capacity, flow stability, air flow rates, energy dissipation efficiency, etc. However, with advances in multiphase numerical methods and computational power, recent commercial projects have adopted both computational fluid dynamics (CFD) and physical modelling in so called "hybrid" hydraulic modelling approaches to maximise flow insights available via a validated 3D multiphase CFD model, to enable rapid optimisation and to further derisk novel designs[8].

- **Specialized Design and Construction** – Construction and installation of these drop structures in urban environments pose significant multidisciplinary hurdles. Construction sites may face difficulties like dense traffic and pedestrian activity, small compact areas for access and construction, uncertain or varying ground conditions, etc. Nonetheless, successful developments have led to significant advances in specialised civil engineering design (including both geotechnical and structural), construction techniques and technology development such as trenchless tunnelling via Tunnel Boring Machines (TBMs), and the use of small and large diameter "sunk" caissons to house drop structures and liners (see **Figure 5** (A)). For example, recent innovative levelling systems have been developed and deployed, measuring real time caisson movements to within 1 mm via load cells to measure the soil-structure interaction during sinking[9] (see **Figure 5** (B)).

- Service Life Considerations – With colossal capital investment requirements, and significant time horizons being considered for future sustainable development, the design life of such infrastructure is typically more than 100 years. Drop structures form the backbone of many deep-sewer conveyance systems, and therefore exhibit one of the largest risks to system lifespan. This consideration is augmented by the unique characteristic flow transitions that take place between upper and lower levels of a drop structure, including hydraulic behaviour (e.g., shocks and waves, air water flows, plunging jet pools, and hydrogen sulphide emissions). To align with service life requirements, special consideration is needed for material types and construction approaches, particularly for the shaft of a drop structure. A shaft may be lined for corrosion protection. Linings can vary from cast, or precast concrete liners, stainless steel liners (see Figure 5(C)) or glass reinforced plastics (GRP) liners. Further, high strength concrete is needed for plunge pool surfaces.

- **Inspection and Maintenance Considerations** – Design criteria often require limitations to be set regarding minimum dimensions of vortex-flow drop structures (e.g., vortex generator throat width) to avoid debris clogging. Nonetheless, over their long service life, it cannot be assumed that vortex-flow drop structures will ever be "maintenance free", where large, unexpected debris accumulations (anything from railway sleepers to cars) can become lodged in vortex generators or shafts, or where sedimentation, fats, oils, greases and rag build up can cause capacity issues on approach flows or in plunge pools. As a result, accessibility for inspection (via human or artificial means: e.g., remote operating vehicles) has been high on the agenda for utilities during the design of these projects, where innovative approaches for emergency access and inspection to both upper and lower drop structure zones being accommodated with isolation or bypass structures/gates[10]. In some instances, designers have reverted to plunge-flow intakes to avoid some of these problems (e.g., extensive amounts of debris).

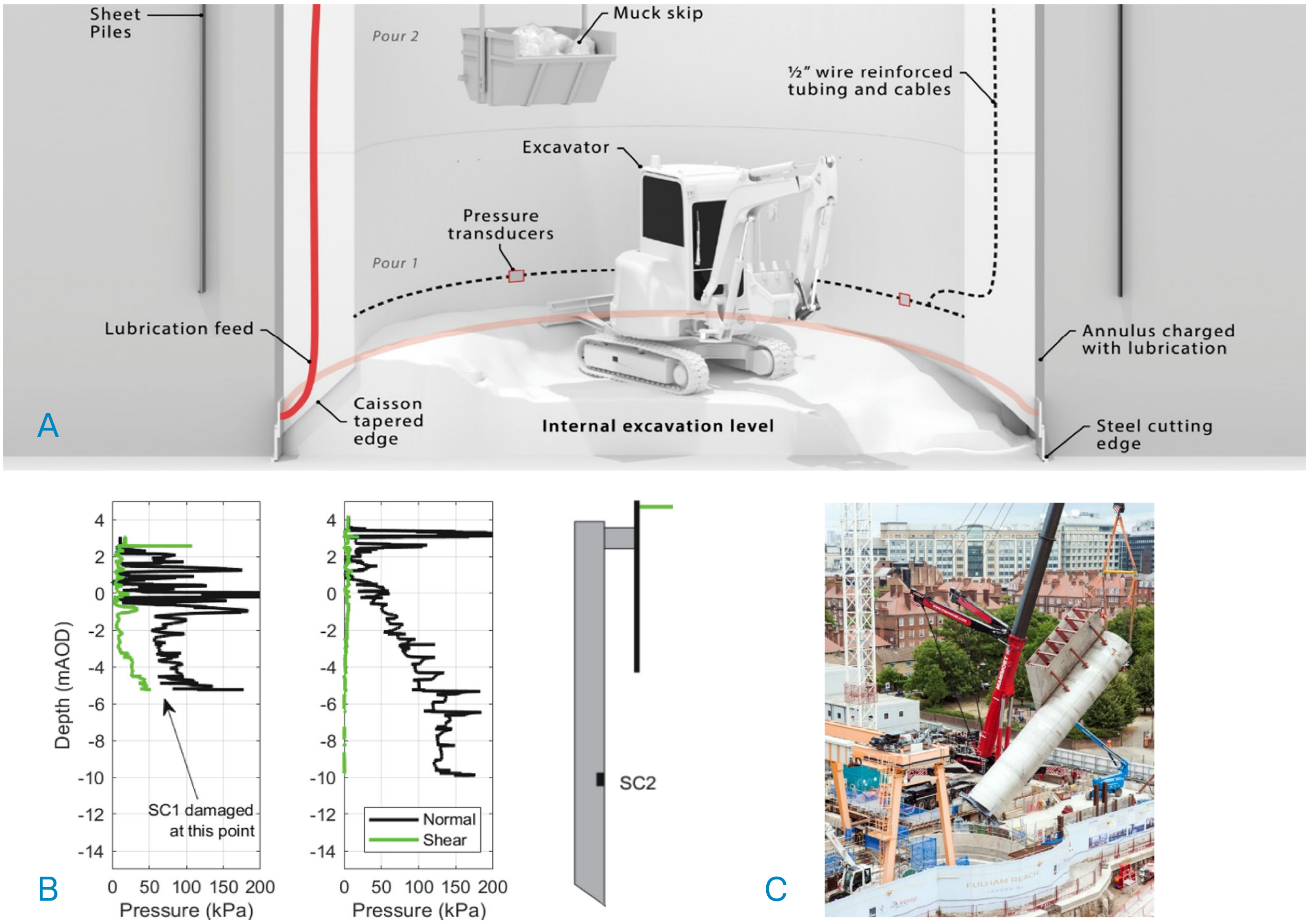

Figure 5 | Examples of construction complexities: (A) and (B) Images from www.wardandburke.com on trenchless technology and shaft/caisson construction informed by pressure monitoring/machine learning (Courtesy of Ward and Burke).; and (C) image of a stainless-steel tangential vortex generator and drop shaft liner being moved and lowered into position down the caisson shaft at Hammersmith, London. (Courtesy of Thames Tideway).

Figure 6 | Infographic outlining sustainable impact (Drop shaft with tangential inlet under construction). (Courtesy of Thames Tideway).

Sustainable Impact

Drop structures are key to enabling the performance and development of deep-sewer conveyance systems globally which have proven to significantly enhance sustainable development of cities and communities around the world.

Figure 6 provides an overview of the key Sustainable Development Goals that are impacted by the successful completion of drop structure projects:

- **SDG 6 – Clean Water and Sanitation:** Drop structures have played a fundamental role in sewer systems for centuries, in conveying wastewater and combined sewer discharges efficiently towards a wastewater treatment plant for treatment before safely discharged back to the environment.

- **SDG 9 – Industry, Innovation and Infrastructure:** Due to the complexity of drop structures, with the ambition to achieve more than 100-year service lives, drop structure development over the past few decades has resulted in significant advances in technology and innovation across the industry, including in areas of advanced hydraulic modelling, construction technology (TBMs and Caissons), data collection, machine learning and robotics for inspections.

- **SDG 11 – Sustainable Cities and Communities:** As described briefly in previous sections, and as elaborated in this issue's presentation of various case studies from around the world, drop structures and the systems of which they are part have been key in enabling sustainable development of cities, by providing flood protection and supporting treatment of wastewater and alleviating pollution from CSOs.

- **SDG 14 – Life Below Water:** CSO intercepts and drop structures are key to diverting untreated wastewater and combined sewer discharges to deep tunnels, away from the coastal and river environments safeguarding life below water and promoting ecosystem recovery.

- **SDG 15 – Life on Land:** Many recent projects have made significant strides towards enhancing life on land in the vicinity of infrastructure developments. For example, surfaces on top of flow intercepts and drop structures in cities have had developed new landscaped areas for public spaces. The iconic Thames Tideway project has integrated its vortex-flow drop structures into the public space by forming artistic ventilation columns resembling the free-surface of the vortex flow down the shaft (see **Figure 7**).

Outlook

Given the need for stormwater and wastewater infrastructure across the urbanizing world, significant developments in deep-tunnel systems and drop structures will continue to occur. These developments will bring diverse and complex considerations, such as modelling constraints, space restrictions, and underground construction.

What is clear, and indeed outlined in the various case studies and projects reported throughout this Issue, is that drop structure engineering must connect hydraulic engineers to a global network of consultant expertise, contractors, environmental protection authorities, utilities, universities, and researchers. This connection will provide shared access to state-of-the-art technology, innovations, and lessons learned from experience with the design, construction, and performance of vortex-flow drop structures.

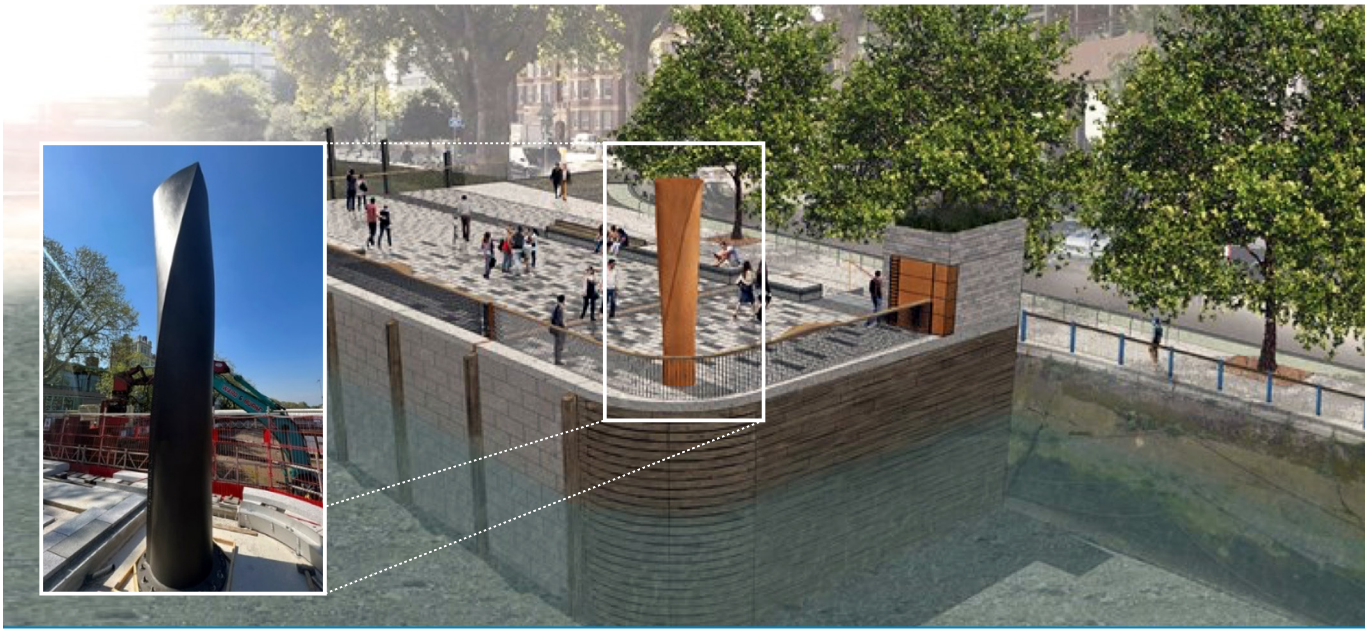

Figure 7 | SDG15 – Enhancing life on land. New river-shore developments have provided a unique opportunity to provide seven new landscaped areas above the drop structures developed in the Thames Tideway Project, including an artistic drop structure ventilation column resembling the top surface of the vortex flow passing down the drop structure below the area. (Courtesy of Thames Tideway).

References

1 | United States Environmental Protection Agency (2004). Report to congress on impacts and control of combined sewer overflows and sanitary sewer overflows. Report: 833-R-04-001.

2 | Chanson, H, (2002). An Experimental Study of Roman drop shaft Hydraulics. J. of Hydraulic Research, 40(1), 3-12. DOI: https://doi.org/10.1080/00221680209499868

3 | Rouse, H. and Ince, S. (1957). History of Hydraulics. Iowa Institute of Hydraulics, State Univ., of Iowa, Iowa City. Journal of Fluid Mechanics 4(6), pp. 655 – 657. DOI: https://doi.org/10.1017/S0022112058210732

4 | Garbrecht, G. *et al.* (1987). Hydraulics and Hydraulic Research: A Historical Review. IAHR 50th Anniversary, Balkema, Rotterdam.

5 | Viollet, P.L. (Trans by Holly, F.M.) (2007). Water Engineering in Ancient Civilizations: 5,000 Years of History. IAHR Monograph, Madrid.

6 | Mulligan, S., Plant, J., Nash, S. and Clifford, E., (2019), September. Vortex drop shaft structures: state-of-the-art and future trends. In *Proc., 38th IAHR World Congress–Water Connecting the World* (pp. 3860-3869). DOI: https://doi.org/10.3850/38WC092019-1813

7 | Ettema *et al.* (2023). Vortex-Flow Intakes. IAHR Water Monograph Series.

8 | Knauss, J. “Swirling Flow Problems at Intakes, Hydraulic Structures Design Manual”. Hydraulic design considerations. Balkema, Rotterdam (1987).

9 | Royston, R., 2018. Monitoring the construction of a large diameter caisson in clay. In Proc., 26th European Young Geotechnical Engineers Conf. London: International Society for Soil Mechanics and Geotechnical Engineering.

10 | Water Environment Federation (2018). Deep Tunnels: Lessons Learned from Around the World. Water Environment Federation. WSEC-2018-TP-002.

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Physical and Numerical Modelling Examples and Best Practices for Drop Structures

By Troy Lyons and Kevin Nielsen

Over many decades, successful and even sometimes unsuccessful designs for drop shaft arrangements have been implemented throughout the world. Today, the most common and best tools for successful hydraulic design of drop shafts are numerical and physical models. While proven designs exist and can be studied, and perhaps adapted to new sites, they usually require additional consideration and hydraulic design effort. Most projects require customizations to accommodate unique local conditions such as existing infrastructure, converging flows, varying inlet elevations, size constraints, unfavorable geological conditions, etc. Thus, hydraulic modelling remains an essential part of creating innovative designs that adequately perform under a wide variety of challenging conditions.

The role of physical and numerical modelling in drop shaft design

In cases where hydraulic modelling is deemed beneficial or required for design development, the design team must determine the best approach for their project. Sufficient hydraulic design may be achieved with either numerical or physical modelling alone, but sometimes using both can be the most effective approach due to the combined benefits and insights gained from each. When both types of models are used, the process typically begins with numerical modelling. Because drop shafts and connected structures feature highly three-dimensional flows, the best numerical modelling tools are computational fluid dynamics (CFD) models. These tools can inform initial layout and sizing of major components and simulate flow through transitions, inlets, curves, and other complex conveyance features. They can provide essential information on water depths, flow speed, energy loss, pressure, and other flow characteristics of interest to inform design decisions. Regardless of the approach, the time and cost of hydraulic modelling efforts must be weighed with the benefits provided. CFD models continue to become more powerful and accessible, yet they require engineering and modelling expertise to properly build the model, run the simulations, and interpret the results. They also remain limited in replicating some of the more advanced flow physics due to grid size and computational resource limitations. Some of the best and most robust hydraulic designs are often achieved using CFD and physical models in a complementary fashion to support the theory.

In general, CFD models are best utilized for design development by evaluating major configuration alternatives that are being considered such as overall layouts, alignments, and other geometric features that affect hydraulic performance and would be more expensive to implement in a physical model. Alternatives include geometry upstream and downstream of the drop structure, more than what may be possible with a reasonably scaled physical model. Designs developed with CFD provide an excellent starting place for physical modelling and can make the physical modelling process more efficient and cost-effective. CFD models can and should continue to be used along with physical models during the detailed design phase to inform design decisions and potential changes to the physical model.

Physical models are suitable for replicating overall flow features but also useful at investigating detailed flow features and nuanced changes that may have impacts on system performance. Changes in physical models commonly include moving or adjusting internal walls, floors, ceilings, and adding or removing flow conditioning features such as fillets, filler plates, curves, baffles, etc. With proper design, physical models can be used swiftly and effectively to evaluate gate and trash rack performance, sediment deposition, air entrainment, and debris conveyance. Practitioners must be aware of model scale effects and their implications on full-size performance. For example, reduced-scale models don't properly replicate bubble sizes of entrained air due to improper scaling of surface tension forces which can have non-negligible effects on aeration rates and bulking of flow at full scale that need to be understood and accounted for. CFD models have the advantage of full-scale simulations but may not be able to adequately replicate the physics of complex two-phase flows.

Physical models are also useful in validating CFD results, which further enhances the usefulness of and reliability of CFD results. Physical models can be used to explore phenomena beyond CFD limitations, such as highly complex or aerated flows where CFD may not be as effective. For example, physical models are helpful tools for evaluating air entrainment, debris and grit handling, gate and screen performance, and complex flow scenarios. For non-standard designs where complex three-dimensional flows create performance concerns and pose significant risks should they fail, physical models and CFD models should both be considered.

Several major projects have extensively and successfully relied on the hydraulic modelling tools of CFD and physical models. Two examples of such projects are the Thames Tideway Tunnel (TTT) project in London and the Strategic Tunnel Enhancement Project (STEP) in the United Arab Emirate of Abu Dhabi where physical and CFD studies were carried out in collaboration

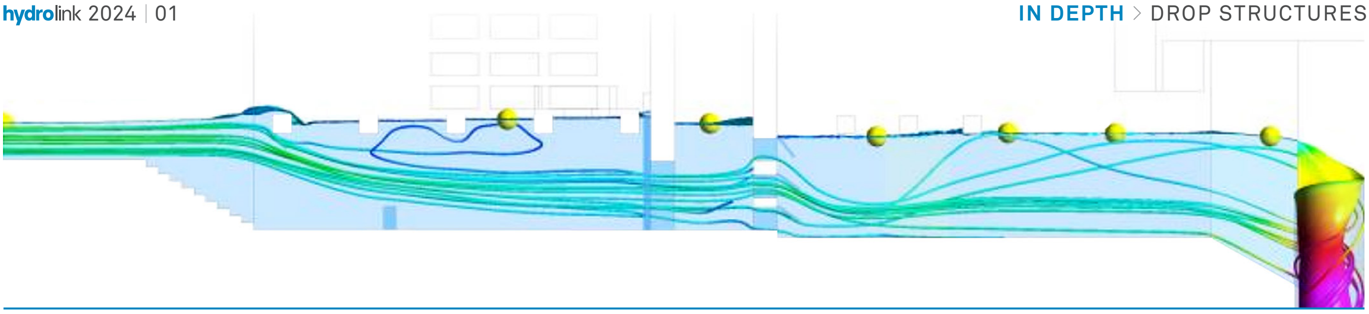

Figure 1 | Thames Tideway Tunnel CFD model used to develop initial designs.

with Jacobs Engineering, IIHR–Hydroscience and Engineering, H.R. Wallingford, and Thames Water; and CH2M, IIHR, and Abu Dhabi Sewerage Services Company, respectively.

Thames Tideway Tunnel (TTT) Project, London, UK

The TTT project, scheduled for commissioning in 2024, was a major overhaul and upgrade to London's combined sewer system that aims to reduce wet weather overflows to the Thames River by 95%. The project features over 25 kilometers of deep storage tunnel and 23 drop shafts, of which 22 are vortex-flow drop shafts. The system has many unique features, including flap gates at many of the drop shaft sites to keep river water from backflowing through the drop shafts and into the tunnel during high tide conditions. Other unique features include vertical deaeration within several shafts (Plant *et al.* 2017[3]), modified horizontal deaeration chambers, and altered tangential inlets to make the vortex inlets more efficient and compact (Plant and Crawford 2016[4]). Several of the drop shafts utilized unconventional on-tunnel arrange-ments including a one-of-a-kind double-sided baffle-type drop shaft, and most sites required unconventional interception chambers and inlets due to site grit and debris conveyance, air entrainment, and potential air constraints and tidal considerations. The uniqueness of each site posed significant logistic, structural, and hydraulic challenges. The design of each site, and its connection to the larger system, was critical to ensure that risks of backups and flooding in the city along with discharges to the river during wet weather were minimized.

To evaluate and develop the unique designs, the owner's engineers extensively used CFD and physical modelling tools. These tools were used synergistically to investigate specific design features and the performance of detailed hydraulics within the system. First, CFD models were developed to evaluate initial design ideas, siting options, and major features (**Fig. 1**). The CFD models were used to select designs for advancement and further evaluate channel slopes, elevations of features, sizing components, and then fully develop preliminary designs for each site. Certain aspects and features of those designs were then evaluated, and stress tested using physical models. Physical model evaluation included basic quantifications of water depths, velocities, head losses, and overall flow characteristics, and a more advanced evaluation of tide gate dynamics,

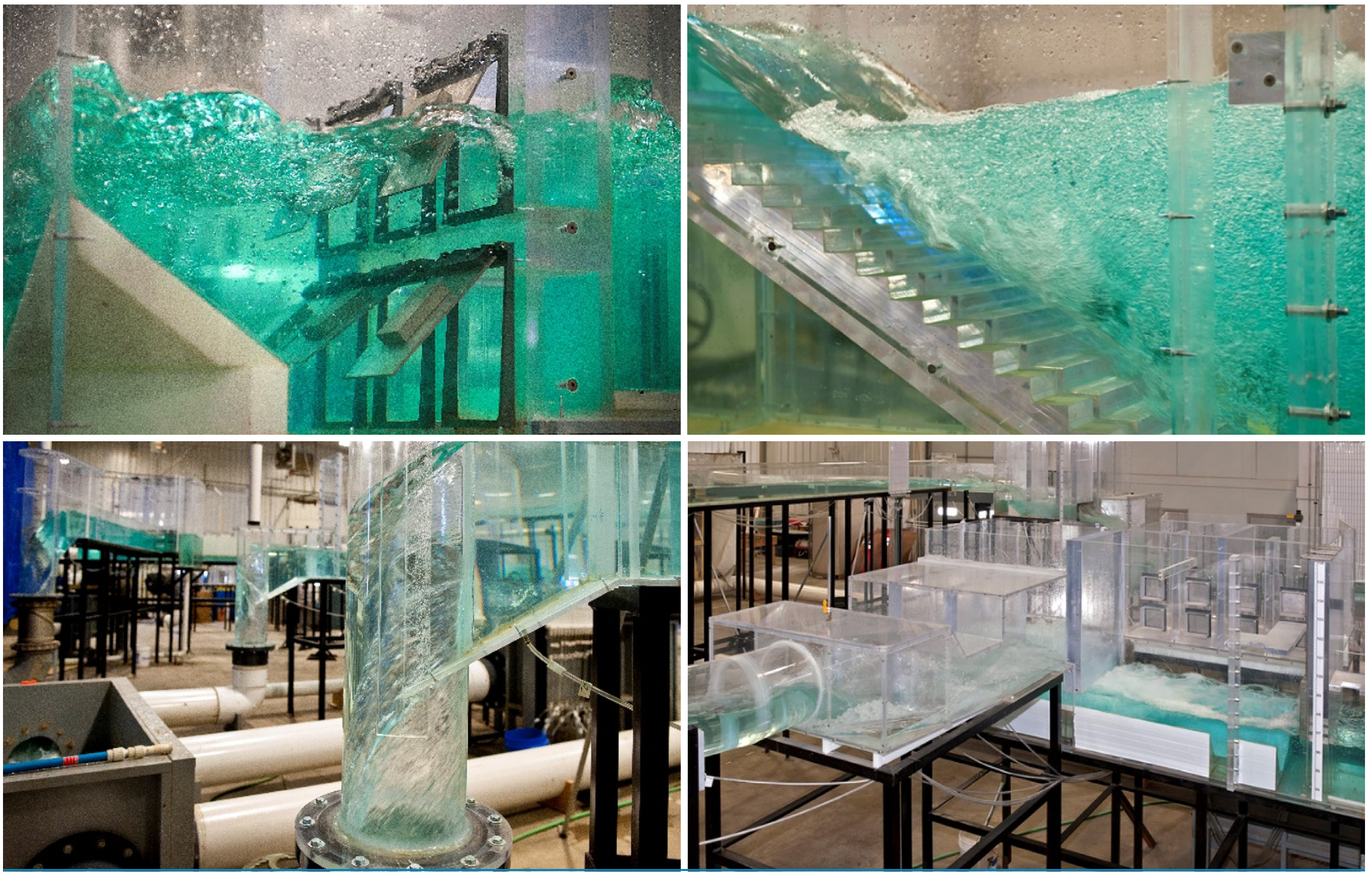

Figure 2 | Thames Tideway Tunnel 1:10 scale physical models used to improve and refine designs.

management requirements (**Figure 2**). Measurements on the physical model were compared back to the CFD simulation results to refine or validate the CFD replication of some of the more complex features such as the swirling flow inside the vortex drop shafts.

Strategic Tunnel Enhancement Project (STEP), Emirate of Abu Dhabi

The STEP project is an example of a project that relied extensively on numerical and physical modelling to evaluate complex hydraulics and the unique aspect of air management for odor control. The total system was comprised of about 40 kilometers of sewage conveyance tunnel fed by numerous drop shafts. Two particularly unique aspects of the system were (1) the replacement of rectangular approach channels with unconventional below-grade pipe connections directly connected to the tangential inlet vortex generators, and (2) the elimination of deaeration chambers and complete sealing of the system to force all air into the tunnel headspace and attempt to prevent air/odor leakage at drop shaft sites.

Computational fluid dynamics (CFD) models were developed to evaluate the proposed arrangements for the tunnel and each drop shaft (Krause *et al.* 2011[1]). Several different vortex and scroll drop shaft configurations were modeled using CFD to determine the most appropriate configuration for each drop shaft site. Many of the sites were very restrictive due to construction constraints. The evaluations focused on non-conventional inlet conditions along with air and odor management. The CFD models were used to investigate site specific modifications to typical drop shaft configurations (**Figure 3**). A 1:7 reduced-scale physical model was constructed to evaluate hydraulics and air flows through three drop shafts connected to a common tunnel (Lyons *et al.* 2011[2]). The project began by evaluating the performance of three differently sized tangential inlets fed directly by round pipes. Typically, vortex-flow drop shafts are fed by straight, rectangular channels with free surface flows that are usually open cut from the surface during construction. However, in this case, the connections were deeper underground, and this unconventional approach was implemented to avoid costly deep open cuts and to en-able easier connections to existing infrastructure. The resulting transition flow characteristics from the pipe and tangential inlet into the vortex drop shaft were initially unsatisfactory due to excessive turbulence that manifested as splash and spray that intermittently closed the throat of the vortex tube. Some geometric changes in the model cleaned up and homogenized the flow and created an acceptable, stable transition flow from the inlet pipe to the drop shaft (**Figure 4**).

Further attention was given to the transition of the drop shafts and adits (connector tunnels) into a main tunnel. The largest drop shaft was "on-tunnel", and design changes were needed to ensure splash and spray did not block the tunnel headspace through which air was extracted. The other two smaller shafts transitioned from the adit to the tunnel down a series of steps and performed well. Once hydraulic performance in the system was improved to an acceptable level, odor control (i.e., air extraction) was investigated. A "local" odor control scheme was evaluated by installing air extraction ports in the roof of each vortex-flow inlet and extracting air using a mechanical fan. Similarly, a "regional" odor control scheme was evaluated by extracting air through the tunnel headspace from the downstream end of the tunnel. Each setup enabled the control of air extraction flow rate and required measurement of the pressure gradient along the inlets and tunnel.

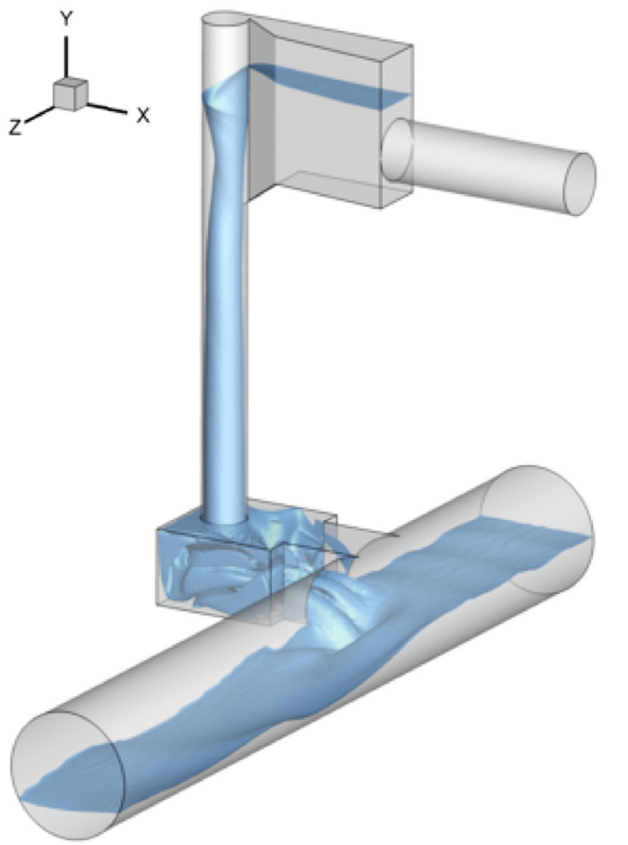

Figure 3 | Abu Dhabi CFD model used to develop initial designs.

Best Practices for Hydraulic Modelling

When determining best practices for hydraulic modelling, one must consider the unique aspects and complexities of each project and weigh the practical realities of time constraints, cost implications, and risk level. Time and cost constraints aside, the robust approach of theoretical predictions must be considered, followed by CFD modelling to develop and evaluate initial designs, and then physical modelling is implemented to refine and improve the designs, potentially coupled with more CFD simulations. Often, physical model results are used to validate and refine CFD models, improving their accuracy and reliability in the design process. Both CFD and physical models can be used early in the design process to identify potential design flaws or performance issues, reducing the risk of costly errors or failures on full-scale structures. By evaluating various design scenarios, engineers can optimize the design and improve the safety and efficiency of hydraulic structures.

There are many commercially available CFD codes that can handle the complexity of flows associated with hydraulic structures such as drop shafts and their related components. However, regardless of the code, CFD must be applied with a thorough understanding of its capabilities and limitations and should be executed by a trained CFD engineer with expertise in the chosen software. The engineer should also be overseen by an experienced engineer with knowledge in designing and evaluating hydraulic structures and interpreting model results. These aspects are critical to ensure that the model is developed properly, with appropriate boundary conditions, mesh resolution, and parameter settings, to get realistic results. Because modelling large-scale highly complex two-phase flows such as those in drop structures can be computationally expensive and time-consuming, expertise is essential to optimizing simulation setup, assessing model validity, recognizing non-physical phenomena, and accurately interpreting results. There are also many hydraulics laboratories throughout the world that can design and fabricate accurate and complex physical models that directly replicate complex fluid flows in a drop structure and can be used to effectively improve and optimize the design. Physical models are a useful tool for simulating trash, debris, and sediment movement and accumulation in the system and its components and with some design foresight, physical models can also quantify air entrainment and develop air management schemes with air vents, pipes, and other air control mechanisms. Physical models also offer the advantage of direct visualization of flow characteristics, allowing engineers to observe vortex formation, turbulence, and other flow phenomena communicating complex hydraulic concepts and engineering designs to stakeholders and the public. Experienced modelers are needed to identify suitable model boundaries, design and construct the model properly, make accurate measurements, accurately interpret the model results, and recognize and adjust for possible scale affects.

References

1 | Krause, T., Orakzai, S., Marshall, R., Nielsen, K., Cowden, S., and Lyons, T. (2011). Physical Model Study Validation of Deep Tunnel Sewer Design Concepts. In WEFTEC 2011 (pp. 5911-5938). Water Environment Federation.

2 | Lyons, T. C., Odgaard, A. J., Muste, M., Cowden, S., Nielsen, K., and Orakzai, S. H. (2011). Odor Control Modeling in Sewage Drop Structures and Tunnels. In Proceedings of the 34th World Congress of the International Association for Hydro-Environment Research and Engineering: 33rd Hydrology and Water Resources Symposium and 10th Conference on Hydraulics in Water Engineering (pp. 2663-2670). Barton, ACT: Engineers Australia.

3 | Plant, J., Crawford, D., and Nielsen, K. (2017). Design Standards for In Shaft Vertical Deaeration and Energy Dissipation for Deep Storage Conveyance Tunnels. WEFTEC 2017. Water Environment Federation.

4 | Plant, J., and Crawford, D. (2016). Pushing the limits of tangential vortex intakes: Is higher capacity and flow measurement possible in a smaller footprint? WEFTEC 2016. Water Environment Federation, 2016.

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Troy Lyons focuses on hydraulic design of structures, river mechanics, sediment transport, and two-phase flows. He is a Research Engineer and serves as the Associate Director of IIHR – Hydroscience and Engineering at the University of Iowa. For more than 20 years he has applied physical and numerical modelling techniques to evaluate complex flows. He works closely with industry and has led numerous physical model studies of stormwater and sanitary systems utilizing various types and arrangements of drop structures. A few examples include the referenced TTT and STEP projects, the Anacostia River CSO project in Washington, D.C., the Forest Park intake in St. Louis, the Doan Valley Tunnel drop shafts in Cleveland, OH, and the Fall Creek/White River and Deep Rock Tunnel drop shafts in Indianapolis, IN.

Kevin Nielsen

Kevin Nielsen specializes in fluid mechanics, hydraulic design, hydrology studies, and environmental water resources project planning. He serves as Jacob's global hydraulics leader for hydraulic transient analysis, applications of computational fluid dynamics (CFD), and advanced hydraulic modelling, evaluation, and design. He has over 40 years of experience in the evaluation and design of water control and conveyance systems. He has extensive experience conducting tunnel filling transient, CFD, and physical hydraulic model analyses for CSO and tunnel projects including the analysis of numerous drop shaft types and major terminal pump stations. A few project examples include the reference design of the TTT, Combined Sewage Storage Tunnel (CSST) in Ottawa Canada, Inner Doha Resewerage Implementation Strategy (IDRIS) in Doha Qatar, and Strategic Tunnel Enhancement Programme (STEP) in Abu Dhabi, UAE.

Strategic Tunnel Enhancement Project (STEP), Emirate of Abu Dhabi.

Drop Structures for the London Tideway Tunnels

By Joss Plant

The 25-kilometer-long London Tideway Tunnels (LTT) system intercepts combined sewer overflows (CSOs) throughout central London to store, and then convey, stormwater and sewage to treatment at Beckton sewage treatment works (STW) in the east of the city. Drop structures are included at major drop shafts varying between 30-70 m in depth and at intermediate sub-surface locations. The primary drop structure types employed at the drop shafts involved tangential vortex-flow intakes, but cascades and direct drops are also utilised where applicable due to the complex and highly constrained nature of some of the sites. The types, selection process, design criteria and other salient aspects of the project's drop structure designs are discussed below.

Context

The LTT system combines the 7-kilometer-long Lee Tunnel and the 25-kilometer-long Thames Tideway Tunnels to form a single storage-conveyance system (the LTT), which will intercept CSO discharges throughout central London and deliver intercepted storm sewage to the Beckton Sewage Treatment Works (STW). As the newest major subterranean infrastructure to span central London, the LTT must pass beneath many existing structures and tunnels which necessitates a deep-tunnel system with significant drop heights. Flow gravitates from the interception locations on the existing sewer network to the terminal pumping station at Beckton, resulting in the tunnel invert dropping from around 30 m below ground level (at the head of the tunnel at Acton) down to levels of more than 70 m below ground at the terminal end in the east. The tunnel is constructed at a constant gradient with the drop structures at each interception site connecting flows from existing sewer levels down to the corresponding tunnel invert level. Along the length of the tunnel, the geology varies as shown in **Figure 1**, resulting in different considerations and constraints for the construction of subterranean structures.

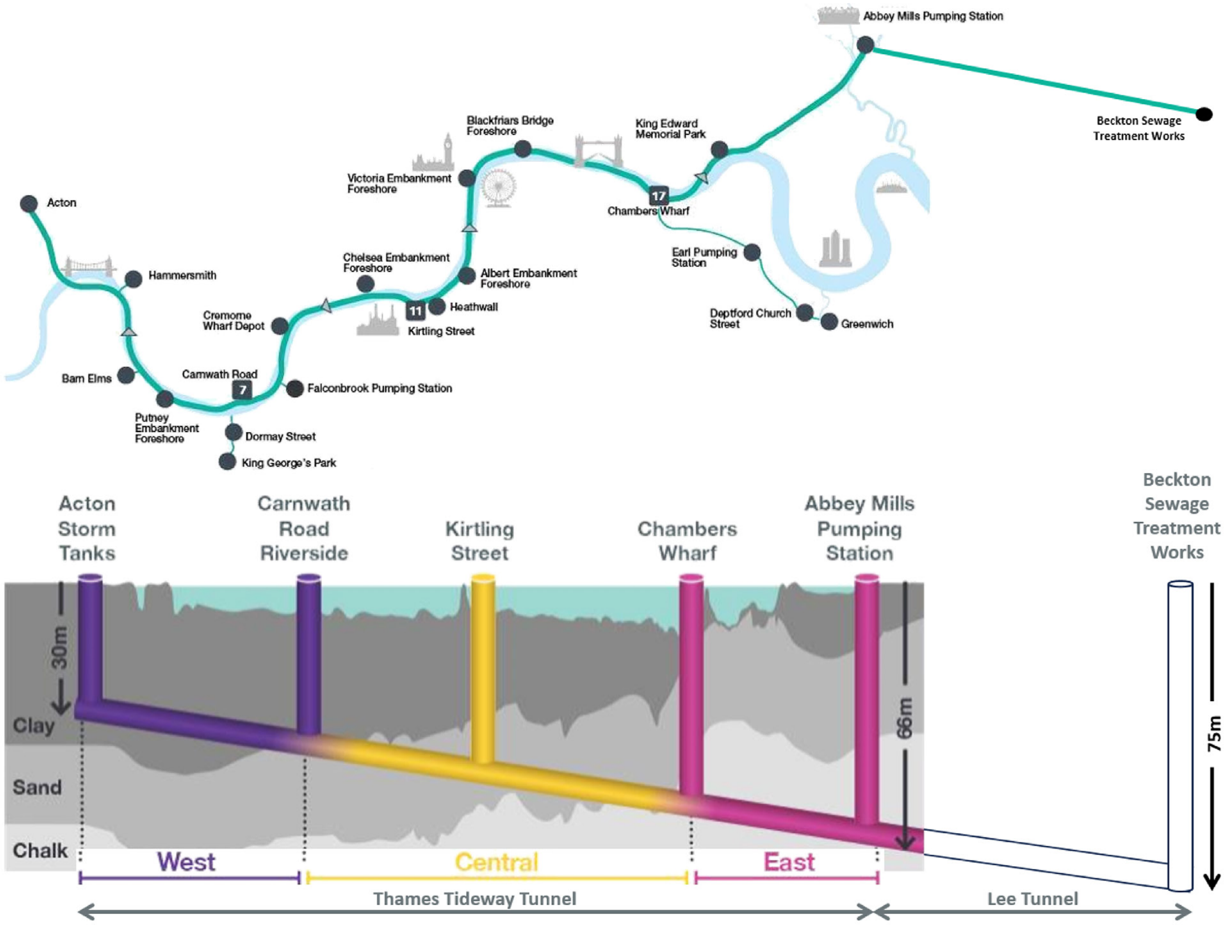

Figure 1 | London Tideway Tunnels route and sites with arrows indicating tunnel drive directions (top), main tunnel longitudinal schematic with drive/reception shafts and the prevailing geology (bottom).

Two smaller diameter branch tunnels are situated to the south of the main tunnel. The Frogmore tunnel in the west intercepts CSOs in the Wandsworth area and is situated at a higher level than the main tunnel, resulting in shallower shafts and drop structures. The Greenwich tunnel intercepts CSOs in the south-east and has drop heights like those required in the central area of the main tunnel.

Additionally, several of the interception sites require intermediate drop structures and high-level tunnels to convey flow from the interception points to the drop shafts down to the tunnel level. Each of these designs are heavily constrained by limited construction footprints and integration with existing infrastructure resulting in a variety of different requirements and designs across the project.

This article addresses both the main deep drop shafts and the bespoke sub surface drop structures.

Design requirements

The design flows at each interception site vary considerably from 1.2 m^3/s to over 40 m^3/s at the highest flow sites. Hence, the size of drop shafts and drop structures varies widely across the project.

Deep Drop Shafts

The LTT comprises deep drop shafts, as explained below.

Lee Tunnel

The Lee Tunnel features a large double cascade drop structure at its inlet shaft from Abbey Mills Pumping Station. The Abbey Mills site is owned and operated by Thames Water and hence construction of a large cascade shaft with open central vertical access to the tunnel invert was not constrained by the interface with other land uses. The Abbey Mills cascade drop design achieves the required performance and operational requirements but was not suitable as a standard design for the rest of the LTT system due to the limited space available to construct drop shafts within central London, including, in many cases, construction within foreshore areas of the River Thames.

Thames Tideway Tunnel

During the initial design and site selection for the Thames Tideway Tunnel (TTT), criteria were developed for suitable drop structure designs to enable space-proofed designs to be defined. These criteria included the following considerations:

- Small footprint: constructible within highly constrained sites
- Maximise storage volume
- High conveyance capacity
- Long design life: resistance to flows (impact damage and chemical corrosion)
- Flow measurement via defined depth-discharge rating relationships
- Effective integration with sub-surface CSO interception works:
  - Capacity to accept design flows without discharge to the river
  - Self-limiting performance
- Integration with shaft base and tunnel connections
  - Energy dissipation
  - Deaeration of flows
- Minimising maintenance: accessible components and design of hydraulic structures to minimise potential for blockage by debris conveyed by flow.

The above criteria were applied to all TTT main drop shafts and resulted in the selection of a three-part standardised solution:

1 | Open, circular drop shafts
2 | Tangential vortex-flow intakes and drop shafts
3 | Energy dissipation and deaeration systems at the base of each drop shaft

Existing literature and research provided guidance on the initial sizing of the tangential drop structure and options for deaeration[1]. However, project specific requirements drove the development of new design standards that were needed to suit the unique constraints of the TTT system.

Compact, high-capacity, vortex-flow intakes were developed with extensive Computational Fluid Dynamics (CFD) and physical hydraulic modelling[2]. Also, the intakes were matched to available drop shaft sizes. These considerations pushed the design limits of tangential vortex-flow intakes developed in previous research. The TTT system had to reduce the footprint of its intakes without compromise to intake flow capacity. CFD model testing of a drop shaft design including tangential vortex designs, and the integration with the tunnel is shown in **Figure 2.**

The development of this design also created a new variant for low flow sites with a long taper and shorter slope to achieve a compromise between flow measurement and avoiding narrow constrictions.

Throughout the system, vortex-flow intakes and drop shafts are constructed with prefabricated steel liners encased in concrete to maximise durability and design life. This design enables control of construction tolerances for extremely large structures that present challenges to construct. **Figure 3** illustrates the construction of one of the tangential vortex intakes prior to pouring the concrete and one of the finished structures.

Deep drop structures are a potentially significant source of high velocity flow at the tunnel level and of air transport into the tunnel. Control of energy and air transport into the tunnel is required to mitigate potential durability issues and mitigate the potential for entrapment and pressurisation of air in the tunnel which can result in flow unsteadiness and pneumatic effects with the potential for uncontrolled air/water release at shafts.

In the west and part of the central tunnel, horizontal deaeration and energy dissipation structures similar to those employed for previous projects[1] are utilised. However, to the east, inshaft deaeration systems were developed using physical modelling to simplify construction in challenging ground conditions, and to accommodate online tunnel connections[3].

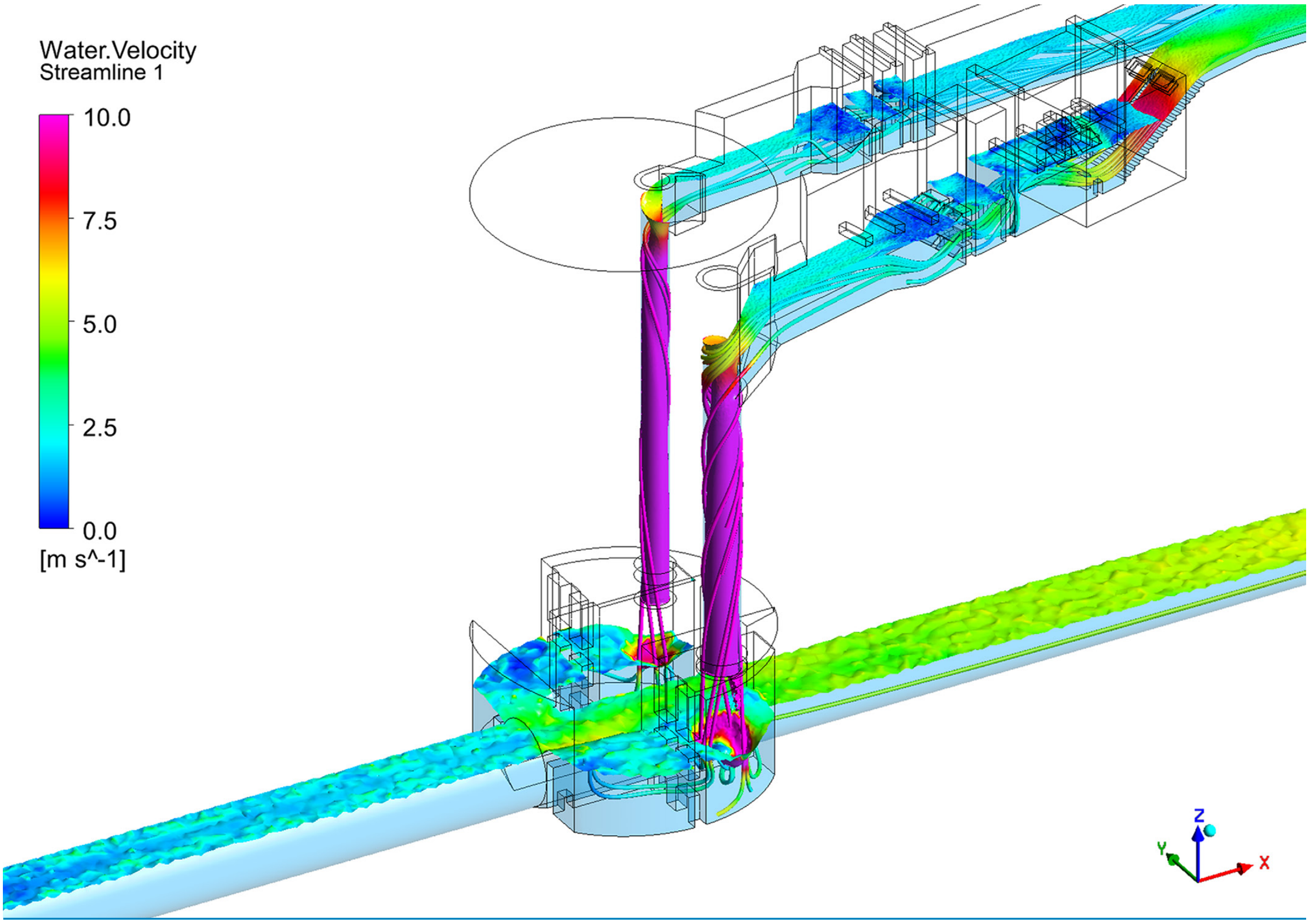

Figure 2 | CFD Model of TTT Dual Vortex Drop Interception Site (colour scale: water surface and streamlines coloured with water velocity [m/s]).

These designs feature larger drop shafts with ported baffles and weir walls to form deep plunge pools (see example in Figure 2) increasing the residence time of the flow in the drop shaft which enables effective deaeration and energy dissipation of flows prior to entering the tunnels.

The large, open drop shaft designs at all sites as seen in Figure 4 ensure that air release during filling is maximised and that any residual air from the tunnel can be released without constriction.

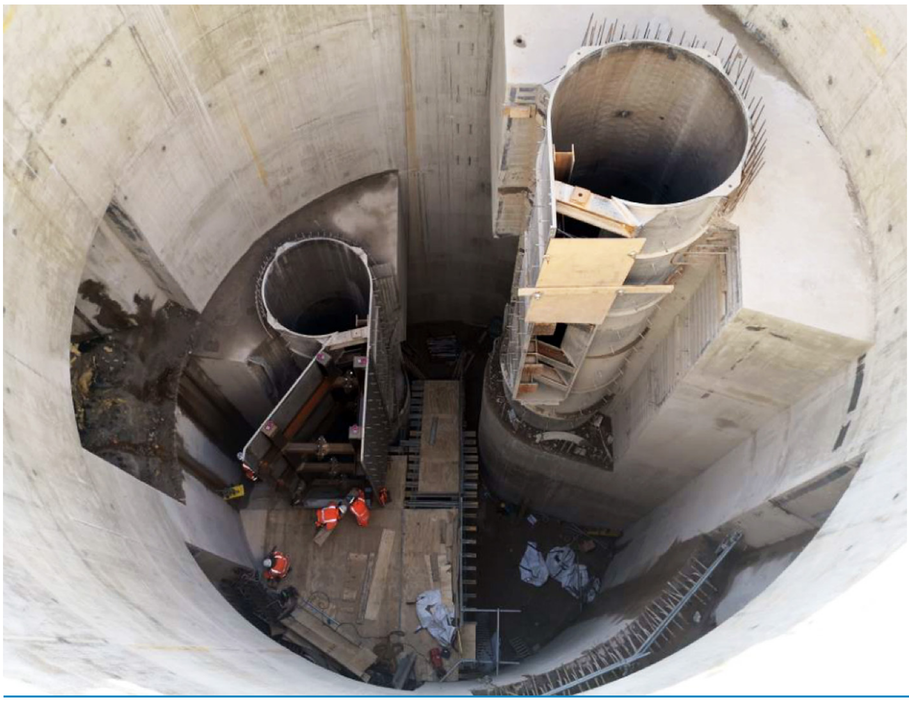

Figure 3 | Examples of steel lining of TTT tangential vortex intake during construction (left) and tangential intake with concrete encasement prior to installation of shaft covers (right).

Figure 4 | Examples of TTT drop shafts during construction with base of vortex drop tube and horizontal deaeration tunnel visible (Left) and full height of a finished vortex drop (right).

Subsurface Interception Works

In addition to the vortex-flow drop structures, the TTT works include numerous smaller drops to convey flow down from sewer level to the interception structures to facilitate flow conveyance to the deep vortex drop shafts without causing overflows to the River Thames. These structures have been developed in coordination with individual site constraints and, hence, vary on a site-by-site basis. The forms employed are consistent with conventional wastewater engineering designs, including the following aspects:

For drop heights of up to 10m

- Straight drop shaft chambers
- Drop shaft chambers with vertical baffles
- Cascade steps

For drop heights greater than 10m

- Cascade shelves
- Shorter intermediate vortex drop shafts

In all cases, 3D CFD modelling was used to test and optimise the designs with the same principles of effective energy dissipation and deaeration of flows into tunnels observed as for the deep drops. This process resulted in various measures being incorporated to ensure optimum hydraulic performance such as utilisation of baffle blocks, and, where necessary, deaeration systems to control high velocity flows and air transport.

Conclusions

Following an extensive multi-stage design process, drop structure designs have been implemented through a standardised deep drop design and numerous bespoke site-specific configurations for the interception works. For all sites, these structures passively control the potential for high energy and air entrainment aspects of water flow. At the time of writing, construction of the LTT is largely complete with initial operation and commissioning due to commence in 2024. A detailed monitoring and regular inspection programme will be undertaken during initial operation and throughout the lifetime of the system. This will provide valuable insight into the operation of the system including the effective long-term operation of the project's drop structures and should aid in informing design and construction of other similar systems in the future.

References

1 | Jain, S.C. and Kennedy, J.F., 1983. *Vortex-flow drop structures for the Milwaukee metropolitan sewerage district inline storage system* (No. 264). Iowa City, IA: Iowa Institute of Hydraulic Research, The University of Iowa.

2 | Plant, J. and Crawford, D., 2016, September. Pushing the limits of tangential vortex intakes: Is higher capacity and flow measurement possible in a smaller footprint?. In *WEFTEC 2016.* Water Environment Federation.

3 | Plant, J., Crawford, D. and Nielsen, K., 2017, September. Design Standards for In Shaft Vertical Deaeration and Energy Dissipation for Deep Storage Conveyance Tunnels. In *WEFTEC 2017.* Water Environment Federation.

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Hong Kong Island West Drainage Tunnel for Urban Flood Management

By Joseph Hun-wei Lee, Tree S.N. Chan, Brian W.H. Choi, Andy Kwok and John Ackers

Over the past decades, rapid urbanization and global climate change has resulted in a significant increase in flood risks in the urban areas of Hong Kong. In the early 2000s, the Drainage Services Department proposed an innovative "Upstream Interception" scheme, namely The Hong Kong West Drainage Tunnel (HKWDT) to improve the flood protection standard for the western areas around northern Hong Kong Island. The engineering challenge was how to effectively intercept and transfer the supercritical (high speed) flow from the steep, natural watercourses located in the densely populated Mid-Levels district to the drainage tunnel located about 100 m below ground. The challenge was overcome by the development of a compact bottom rack and vortex-intake system to stably decelerate the supercritical approach flow, with efficient energy dissipation, for smooth conveyance of flow from a high elevation to the deep, drainage tunnel and discharge to the sea. Through a combination of theory, heuristic design, and physical model tests, both spiral shaped and tangential vortex intakes have been designed. Since the commissioning of HKWDT in 2012, with its vortex-flow intake system, the HKWDT has successfully protected the downhill urban areas of Hong Kong Island from flooding.

Introduction

Hong Kong is frequented by tropical cyclones and experiences an average annual rainfall of 2,400 mm. Of growing concern, global climate change has resulted in extreme rainfall intensity. In times of heavy rainfall before commissioning of the HKWDT, the mid-levels and downstream areas of northern Hong Kong Island were prone to flooding. Torrents of mud-laden and highly aerated storm flows could overshoot stream channels into roads and cause hazardous traffic conditions.

Protection of urban infrastructure from flooding is of foremost importance for the sustainable development of Hong Kong. Substantially upgrading the existing drainage systems in densely populated and commercial districts using traditional pipe installation methods is extremely difficult due to site constraints, such as congested underground utilities. Traditional methods for drainage improvement cause traffic disruptions and inconvenience to the public and commercial activities.

In the early 2000s, the Drainage Services Department (DSD) proposed an innovative "upstream interception" scheme that would greatly enhance flood protection levels of urban areas. The Hong Kong West Drainage Tunnel (HKWDT) was planned to intercept runoff through intakes located on the main drainage paths for direct discharge to the sea, thus diverting the runoff away from the downhill urban areas and effectively alleviating flood risks. The design consists of a 10.5-kilometer-long drainage tunnel (maximum diameter 7.25 m) that extends from Tai Hang on the east to Cyberport on the west (**Figure 1** (a) and **Figure 1** (b)). About 30 percent of the stormwater in northern Hong Kong Island is collected via 34 storm-water intakes located in the densely populated hillside, amid residential blocks including some premium properties (**Figure 1** (b). The project provides a safe conduit to convey stormwater through the tunnel to an outfall structure at Cyberport.

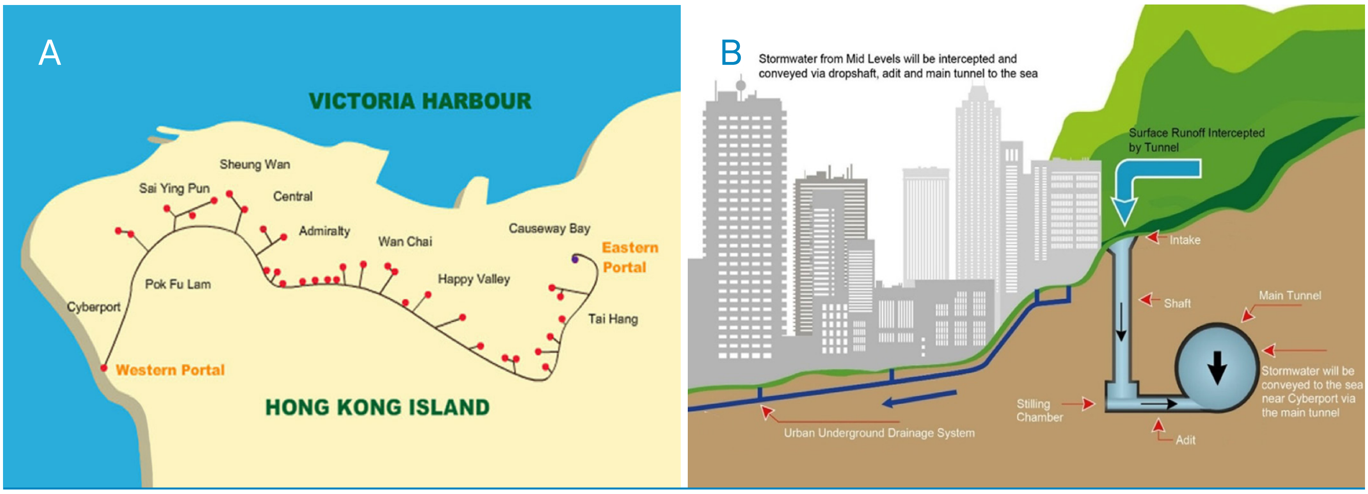

Figure 1 | Hong Kong West Drainage Tunnel System for urban flood management: (A) Layout of system of 34 supercritical vortex intakes; (B) upstream interception and diversion into tunnel.

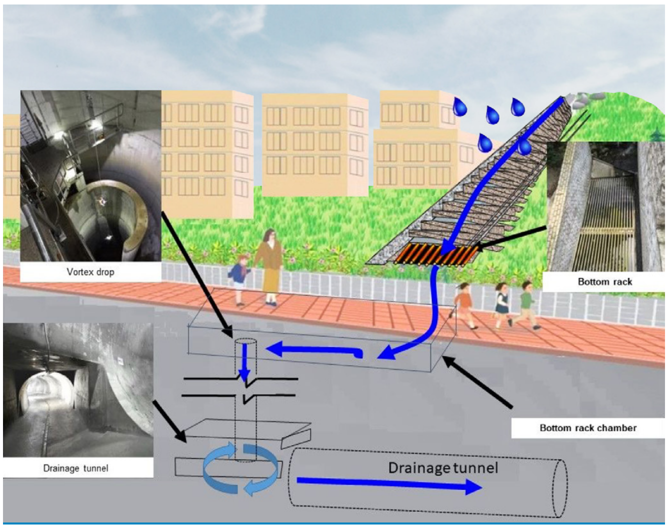

Figure 2 | Design of integrated bottom rack-vortex intake system for stormwater interception (inset: constructed vortex drop and drainage tunnel).

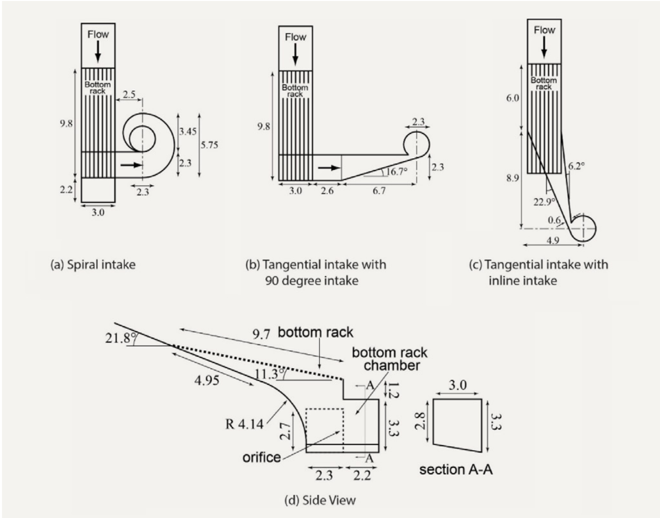

Figure 3 | Integrated vortex intake designs for supercritical flow diversion (prototype dimensions shown in m).

Engineering challenges

The 34 stormwater intakes are located on steep hill-slope watercourses (average slope of 40%) with supercritical flow regimes characterized by velocities of the order of 10 m/s and Froude numbers of 3 to 8. Each intake intercepts and transfers runoff to the main tunnel through a vertical drop shaft. The system is intended to convey a 1-in-200-year return period rainstorm event, with an intake design flow of up to 18 m^3/s. Central to the success of the HKWDT is a vortex-flow intake system for diversion of the high velocity supercritical flows stably and smoothly to the drop shaft in a helical flow, thus leaving a core of air in the middle of the drop shaft and preventing negative pressure build-up in the tunnel. The design of a compact intake structure adjacent to the densely populated residential areas is a challenging aspect of the project.

Figure 2 shows the conceptual design of the intake structure. A bottom rack intake is used to screen off large sediment debris, rocks, and vegetation. The intercepted flow passes the bottom racks into a bottom rack chamber, which is connected to a vortex drop shaft through a link channel (Figure 3). The change in flow direction is required because of site constraints. A vortex-flow dropshaft transfers the flow vertically from an open channel to a lower level in the form of a swirling annular jet. A stable swirling flow with an adequate central air core (for continuous release of entrained air within the dropshaft) results in substantial energy dissipation.

The HKWDT vortex intake design was developed through a combination of theory, heuristic reasoning and physical model experiments. Extensive experiments were performed in an undistorted Froude scale model at two model-length scales (1:24.5 and 1:9.5 [model/prototype]) for the: (i) bottom rack intake; (ii) spiral or tangential vortex inlet; and (iii) an integrated bottom rack – vortex intake. The flow in the bottom rack chamber and link channel, and water-profile and air core ratio in the vortex inlet were studied. The physical model was supplemented by a 3D numerical model of the vortex-flow intakes.

Design of Bottom Rack – Vortex Intake System

The turbulent flow in the bottom rack – vortex-flow drop-structure system is a highly complex, 3D, two-phase (air-water) flow, for which robust computational fluid dynamics (CFD) predictions were not available. Unstable flows were observed in physical model tests for many unsuccessful initial designs. The essential flow features of each component are outlined below; more details can be found in the references.

Flow Interception by Bottom Rack

The complex flow in the bottom rack chamber was studied for six designs (with different bottom rack slopes and lengths), for flows in the range of 1 to 18 m^3/s. Different shapes of the rack bars were also studied: including circular, diamond, I beam and trapezoidal bars. The flow behaviour depended on (i) the length and slope of the approach channel; (ii) the slope, length and arrangement of the bottom rack bars; and (iii) the length and slope of the channel bed, and the volume and geometry of the rack chamber. For many designs, the flow in the bottom rack chamber was highly fluctuating and unsteady with large unstable rollers. In the final design (Figure 3 (d) and Figure 4 (a)), the intercepted flow follows the bottom slope and curved surface stably into the chamber. The bottom part of this flow hits the far end of the chamber and is redirected towards the inside of the chamber. The momentum of the top part of the bottom rack flow is partly offset by this opposing jet stream from the downstream end of the enlarged chamber; the combined flow is stably re-directed onto the link channel. Additional details on the experimental and 3D numerical modelling aspects of the supercritical bottom rack can be found in Chan *et al.* (2018a)[2].

Spiral and Tangential Vortex Intakes

Figure 3 shows two main types of vortex-flow inlets: spiral intake (Hager 1990[4]), and tangential slot intake (Jain 1984[5]). Under the action of the centrifugal force, most of the flow is concentrated towards the outer wall and piles up against that surface as a coherent stream, creating a standing wave (shock wave).

Figure 4 (A) | Bottom rack intake for supercritical flow diversion; observed flow at Q = 53.9 l/s.

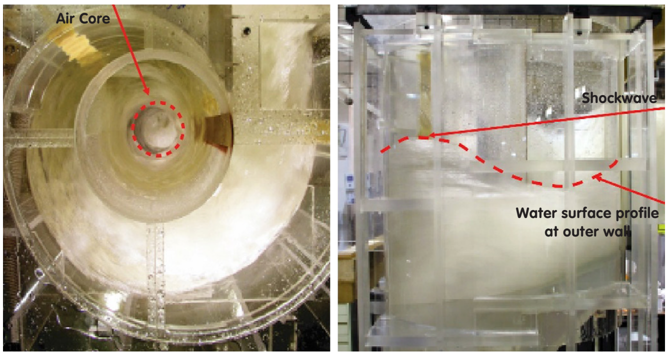

Figure 4 (B) | Spiral vortex intake with warp invert for supercritical flow diversion.

The design objective was to ensure a stable supercritical flow with minimum shockwave height, with a minimum air core area to dropshaft area ratio of 25 % and avoiding flow back up or blockage at junctions. Experiments showed that for spiral intakes with flat inverts, the inlet flow could become subcritical due to the backwater effect induced by the vortex structure; a highly unstable flow with a fluctuating air core can result under certain inflow conditions. In view of the unstable condition, the optimum spiral vortex inlet with warped invert was developed (**Figure 3** (A) and **Figure 4** (B)).

Tangential Slot Intake

The tangential vortex intake (**Figure 3** (b) and **Figure 3** (c)) is a compact-size alternative to the spiral vortex intake. Unlike the spiral vortex inlet, the inflow enters the dropshaft via a steep sloping and tapering (laterally converging) tangential inlet. The inflow impinges onto the inner surface of the dropshaft as a tangential jet with angular momentum, and a vortex flow is established without the need for a complex spiral arrangement (Jain and Ettema 1987[6]). It is suited for small discharges.

A general design theory was developed (Yu and Lee 2009[8]; Chan *et al.* 2023[1]) which provides a basis for the design of a tangential vortex intake without the need of unguided trial-and-error physical modeling.

Final Integrated Design

A study showed that the spiral intake with warped invert performed best in terms of the minimum shock wave height and maximum air core area ratio. The tangential vortex intake was found to be a compact-size alternative, especially for low flows. As a result, these two types of vortex intakes were adopted with proven performance in the HKWDT (Lee *et al.* 2018[7]). **Figures 4** (a) and (b) show the observed flow in a 1:9.5 model of the final design. The significant air-entrainment in the large-scale stable roller in the bottom rack chamber can be clearly seen (**Figure 4** (a)) along with the standing wave and air core in the spiral vortex inlet with warped invert (**Figure 4** (b)).

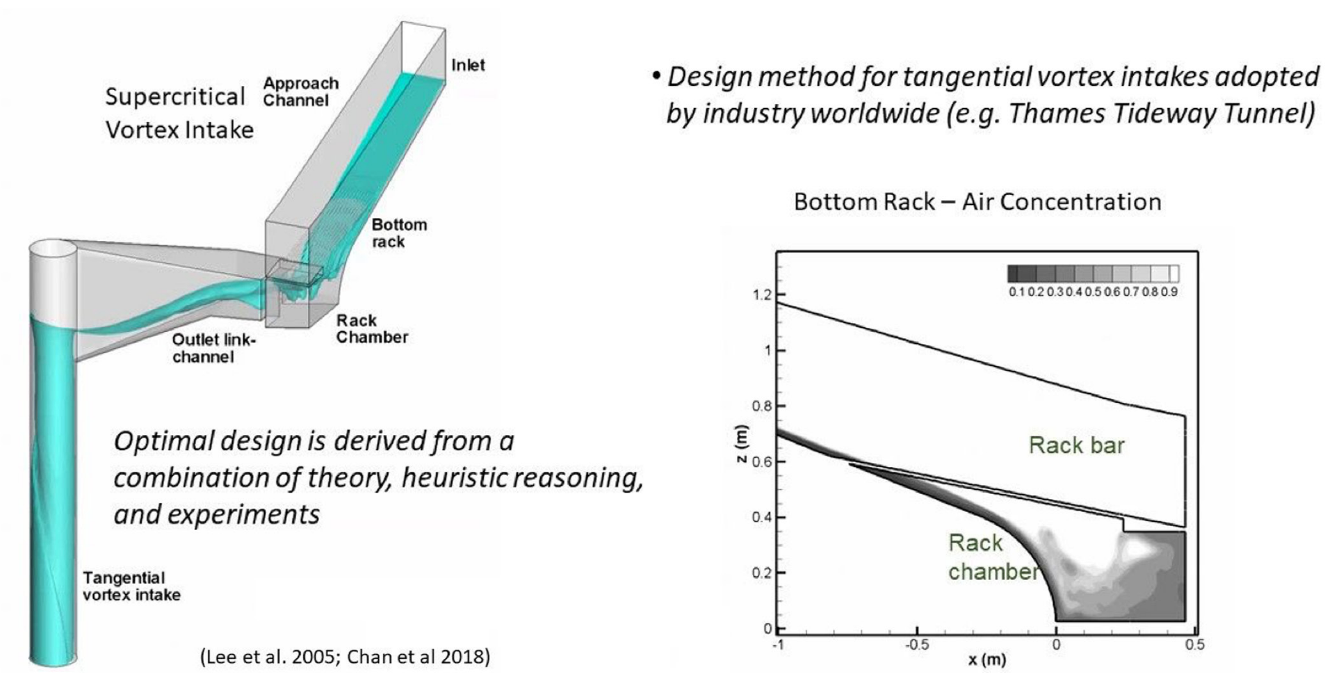

Figure 5 | CFD simulation of the 3D air-water flow in a tangential vortex intake (Chan *et al.* 2018b3).

Figure 6 | Example of compact tangential vortex intake in HKWDT system.

Concluding Remarks

A supercritical vortex intake system for interception and diversion of fast moving turbulent two-phase flows in the HKWDT is presented. The design consists of a unique bottom-rack integrated with a spiral vortex-flow intake design for supercritical flow diversion. The design was recognized by a First Prize (Sustainability Category) in the 2017 Hong Kong Construction Industry Council (CIC) Innovation Award after an international assessment. Together with the storage schemes at Happy Valley and Sheung Wan, this interception system has protected downstream urban areas of Hong Kong from flooding during extreme weather. In addition, the precision engineering means that the celebrated historic Wednesday night horse-racing events at Happy Valley in Hong Kong (billion-dollar gaming income per race for philanthropy) need not be cancelled during moderate rain events (yellow rain storms), thereby creating great public benefit. This project's success is a testament to the long-term collaboration amongst academia, industry and government.

References

1 | Chan, S.N., Lyons, T.C., Zhu, D. Z., and Lee, J.H.W., ``Vortex-intake drop structures'', in Vortex-flow intakes (ed. Ettema, R. and Zhu, D.), IAHR Water Monographs, International Association for Hydro-environment Engineering and Research, Spain, August 2023, pp.61-86 (ISBN: IS978-90-833476-1-5). Doi: 10.3850/978-90-833476-0-8_IAHR_Watermonograph_002.

2 | Chan, S.N., Wong, K.C. and Lee, J.H.W., "Hydraulics of air-water flow in a supercritical bottom rack intake", Journal of Hydro-Environment Research, Vol. 21, pp. 60-75, Oct 2018, Doi: 10.1016/j.jher.2018.08.001.

3 | Chan, S.N., Qiao, Q.S. and Lee, J.H.W., "On the three-dimensional flow of a stable tangential vortex intake", Journal of Hydro-Environment Research, Vol. 21, pp. 29-42, Oct 2018, Doi: 10.1016/j.jher.2018.07.001.

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

5 | Jain, S. C. (1984) Tangential vortex-inlet, Journal of Hydraulic Engineering, ASCE, 110(12), 1693–1699.

6 | Jain, S.C. and Ettema, R. (1987) Vortex-flow intakes, In Knauss J, ed. Swirling Flow Problems at Intakes, Rotterdam, Netherlands: A.A. Balkema.

7 | Lee, J.H.W., Tsang, K.L., Kwok, A. and Ackers, J., "Supercritical vortex intakes for urban storm water management", Innovation in Construction Journal, Hong Kong Construction Industry Council, Nov. 2018, pp. 84-93.

8 | Yu, D.Y. and Lee, J.H.W. "Hydraulics of tangential vortex intake for urban drainage", Journal of Hydraulic Engineering, ASCE, Vol.135, No.3, pp.164-174, Mar 2009, Doi: 10.1061/(ASCE)0733-9429(2009)135:3(164).

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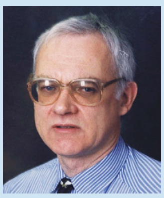

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Singapore's Deep Tunnel Sewerage System–Phase 2

By Dominique Brocard

Singapore's Deep Tunnel Sewerage System (DTSS) aims to provide a robust and efficient means of meeting Singapore's used-water needs. DTSS2, the second phase of this project, comprises two tunnels, multiple link sewers and a new water reclamation plant. DTSS2 includes numerous vortex drop structures. For the final design, all the vortex drop structures were modelled using Computational Fluid Dynamics (CFD) to refine the designs developed during preliminary design. Particular features of the DTSS system include Air Jumpers (AJs) to avoid odours at ground level and Roller Gates to isolate tunnel sections, should maintenance ever be needed.

Introduction

DTSS2 includes a 30-kilometer-long South Tunnel (3.0 m to 6.0 m in diameter), a 10-kilometer-long Industrial Tunnel (3.3 m to 4.0 m in diameter), 60 km of Link Sewers and a new Water Reclamation Plant (WRP), as shown in **Figure 1**. The previous DTSS phase, DTSS1, included (among other elements) the north tunnel and the Changi WRP. For DTSS2, there was a large focus on resilience, as well as application of lessons learnt from DTSS1.

To achieve the desired level of resilience for the DTSS system, several options for the hydraulic structures were considered and optimized using a hydraulic model of the entire system. For example, extending the existing spur tunnel provided resilience to the system, by allowing a portion of the flow to transfer from the North Tunnel to the South Tunnel. Additional measures were implemented to meet the system containment criteria set by Singapore National Water Agency, Public Utilities Board (PUB). A set of 11 tunnel-failure scenarios were developed. Additionally, extreme wet weather events were identified and were considered in the design. Different failure scenarios were simulated individually and in combination in the hydraulic model, which then was used to identify the optimum set of resilience measures.

The project was divided into Design & Build for the Tunnel Contracts and Design, Bid & Build for the Link Sewers and Tuas Water Reclamation Plant Contracts. The project is now under construction.

Vortex Drop Shafts

Several designs have been developed to safely drop flows (of up to 55 meters) from the link sewers to the tunnels (Williamson, 2011[1]). Vortex drop shafts were selected for DTSS2, because of their efficient design in terms of diameter, good inspection accessibility and the extensive local experience with this type of drop structure. The South and Industrial tunnels have 17 tangential inlet, vortex drop structures conveying design flows of 3 to 40 m^3/s. Further, the link sewers have several in-line vortex drops with scroll inlets. The basic tangential inlet vortex drop shaft is generally referred to as the H4 design, as per the Iowa Institute of Hydraulic Research (IIHR) (Jain and Kennedy, 1983[2]). Since then, the H4 design has been subjected to several physical model tests and theoretical analyses to understand further the flow processes and to develop refinements (Lee *et al.*, 2006[3]; Lyons and Odgaard, 2010[4]; Yu and Lee, 2009[5]).

At the bottom of the drop shafts, deaeration chambers are required to release the entrained air as flow swirls down the drop shafts. The basic H4 drop shaft design involves horizontal deaeration chambers connected to the tunnel by smaller diameter adits. Air vents are also provided to recirculate the entrained air back to the top of the drop shaft.

The basic vortex drop shaft dimensions were developed during the preliminary design using the H4 and other design guidelines. However, the design-build contractors selected throughout the project were required to undertake Computational Fluid

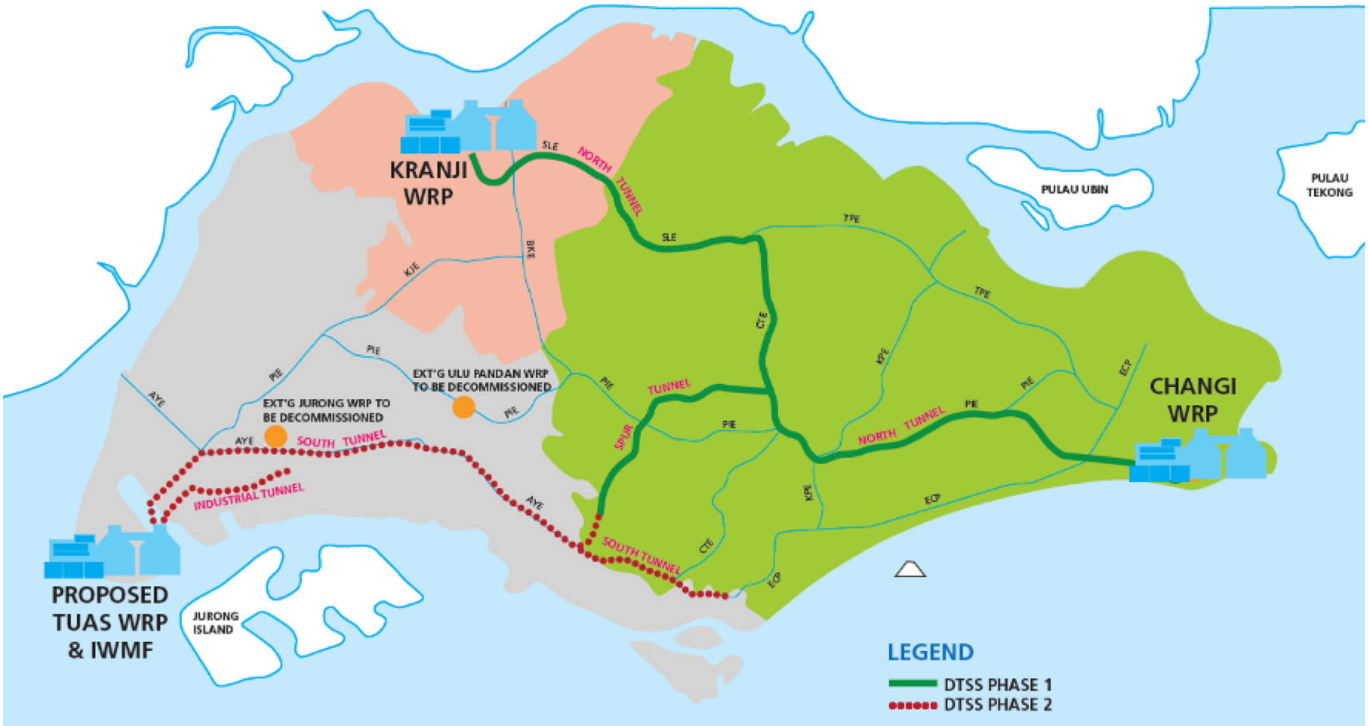

Figure 1 | DTSS Concept (WRP = Water Reclamation Plant, IWMF = Integrated Waste Management Facility).

Dynamics (CFD) models to verify and potentially refine the designs. One reason for this requirement was that the approach to the vortex-inlet drop structures could not always meet the design guidelines and several drops involved more than one influent link sewer. Therefore, a more detailed three-dimensional understanding of the flow processes was required to account for the heterogeneous design nature of the hydraulic structures throughout the scheme. The features that needed to be demonstrated by the CFD campaigns that were conducted were as follow:

- Diversion chamber: Required a stable, steady flow with no hydraulic jump.
- Approach channel: Required a stable, steady flow, no hydraulic jump, and sufficient freeboard.
- Drop shaft: Required a stable helical flow, an air core exhibiting at least 25% in cross-sectional area, calculated pressure and shear stress distribution (to inform structural designs for drop shaft longevity).
- Deaeration chamber: 1 m/s minimum speed at design flow.
- Air vent: Required demonstration of ability to convey air back to the top of the vortex drop.
- Adit: 1 m/s minimum water speed at design flow.

Air Management

One of the mandates of the DTSS is the management of odour during operation, to minimise the occurrence of any adverse smell at ground level. Meeting this mandate required pro-active air management to avoid air pressure build-up that could result in odorous air escaping to the ground level. The access manholes along the deep tunnels will largely be sealed. However, over time, air-escape pathways may develop. In addition, the link sewers upstream will offer more opportunities for air escape if pressure build-up occurs.

The approach selected for DTSS2 involves the extraction and treatment of odorous air at Odour Control Facilities (OCFs), and Air Jumpers (AJs) to convey air from the incoming link sewer to the deep tunnel and to push air along the tunnel to the next available OCF. The OCFs will treat the air extracted from the deep tunnel at that shaft including air from the incoming link sewers, as shown in **Fig. 3**. The AJs, also shown in **Fig. 3**, will be located at sites where OCFs would not be feasible due to existing land use, for example in built-up areas. In total, 12 AJs and 4 OCFs were identified for the DTSS2 tunnel and link sewer network.

Vortex drop structures naturally draw air due to air entrainment mechanisms and, if the air flow driven by the vortex flow of water is equal to or greater than the incoming air flow in the link sewers, AJs may not be necessary. However, estimates of these air flows suggested that fan-enabled AJs are needed. Air jumpers also have the benefit of providing flexibility relative to a fully passive approach relying solely on the air-pulling capacity of the vortex flow of water.

Figure 2 | Vortex generator and drop structure under construction.

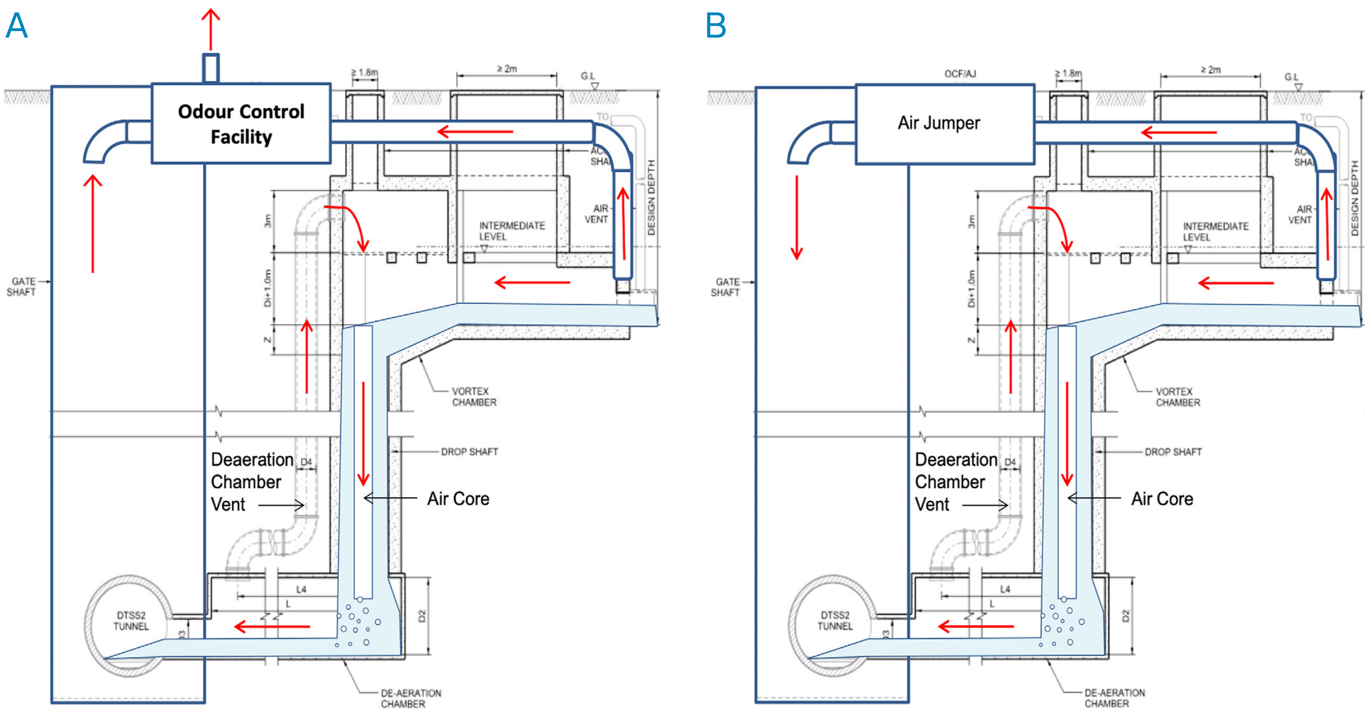

Figure 3 | (A) Odour Control Facility (OCF) and (B) Air Jumper (AJ) Schematics.

Tunnel-Section Isolation

Unlike rail or road tunnels, which can be easily accessed for inspection and maintenance, sewer tunnels constantly conveying water are relatively difficult to access. The design of DTSS2 took the unique step of using large drop-in roller gates (estimated weight of approximately 30 tonnes) to isolate sections of the tunnel and, thereby, enable interventions for inspection and any necessary repairs. In-line gate shafts with facilities to lower roller gates, cross connecting link sewers, and bypass facilities at drop structures were included to facilitate tunnel-section isolation.

The isolation gates will be required to withstand an unbalanced load of up to 55 m of water depth. To provide the required structural strength and to facilitate deployment, stainless steel gates with guide wheels will be lowered into guide channels. This roller gate system will ensure proper gate alignment and guide channel installation to minimise frictional forces when lowering or raising the gates. When a section of tunnel requires isolation, gate modules will be transported to site, assembled, and lowered into the gate shafts.

A significant hydraulic issue associated with the isolation gates is their removal. As the gates are lifted, used water will rush under the gate at high speed. With a head of 43 to 50 m upstream, the velocity of the flow under the gate will be of the order of 30 m/s which requires special attention to ensure that damage to the tunnel liner does not occur. To assess the situation, including the length of tunnel affected by the high velocities, CFD modelling and physical modelling were conducted. A sample of the CFD modelling is shown in **Figure 4**. Velocities exceeding 28 m/s are found downstream of the gate and, because of the transition between the flat floor at the gate to the circular tunnel, significant splashing was observed.

A physical model of the gate opening was also conducted at Nanyang Technological University. The physical model covered the gate shaft and approximately 300 m of the downstream tunnel at a length scale of 31.5 to 1 (prototype/model). Velocity and pressure measurements were conducted. The pressure measurements sought to address the concern that the high velocities could generate low pressures that could pull the liner off the tunnel wall. Based on the CFD modeling, stainless steel cladding was specified immediately downstream of the gates to protect against the high velocities. No negative pressures were identified by the modeling activities. Therefore, the tunnel section downstream of the steel cladding will be lined with High Density Polyethylene (HDPE) as the risk of HDPE delamination due to cavitation is negligible.

More details on the hydraulic basis of the project are provided by Brocard *et al.,* 2018[6].

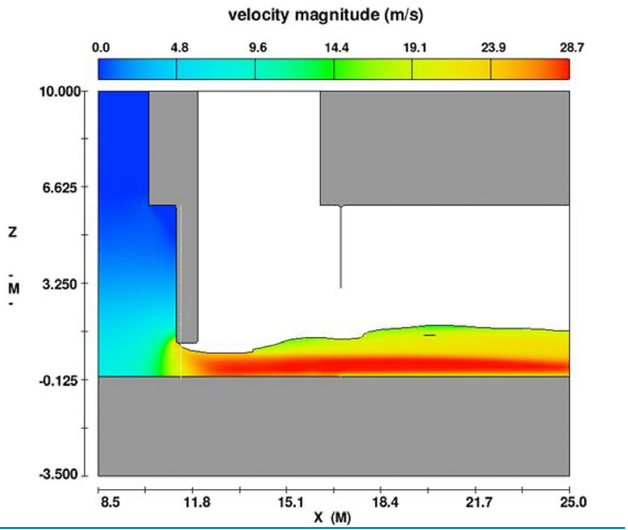

Figure 4 | Longitudinal profile of water level and velocities 4 minutes after start of gate opening.

References

1 | Williamson, S. 2001. Drop Structure Design for Wastewater and Storm water Collection and Systems Parsons Brinkerhoff Monograph 14.

2 | Jain, S.C. and Kennedy, J.F. 1983. Vortex-Flow Drop Structures For the Milwaukee Metropolitan Sewerage District Inline Storage System Iowa Institute of Hydraulic Research, Report No. 264.

3 | Lee, J.H.W, Yu, D and Choi K.W. 2006. Physical Hydraulic Model Tests for the Lai Chi Kok Transfer Scheme Intake Structure. Croucher Laboratory of Environmental Hydraulics, The University of Hong Kong.

4 | Lyons, T. C. and Odgaard, A.J. 2010. Hydraulic Model Study for the City of Indianapolis' Deep Rock Tunnel Connector Drop Structures. Iowan Institute of Hydraulic Research.

5 | Yu, D. and Lee, J.H.W. 2009. Hydraulics of Tangential Vortex Intake for Urban Drainage. ASCE Journal of Hydraulic Engineering, Vol 135, No.3.

6 | D. 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. 2018. Deep Tunnel Sewerage System Phase 2 – Hydraulics. Water Practice and Technology, International Water Association.

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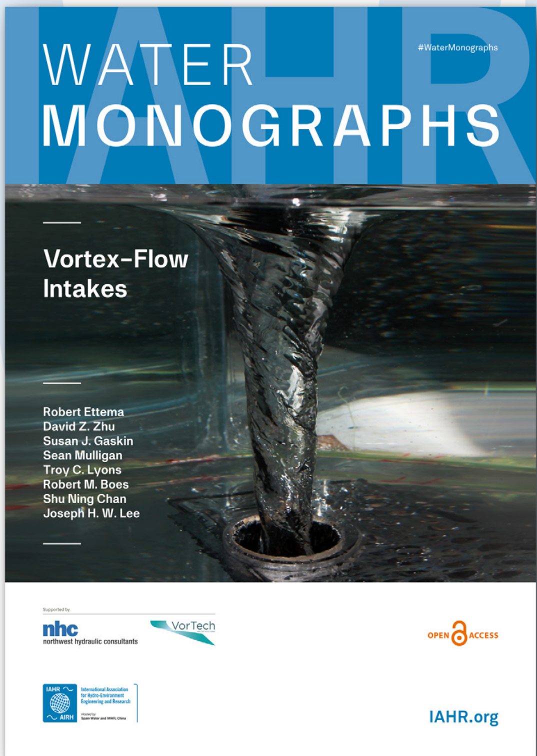


Drop Structures across (and under) the United States of America

By Rob Ettema, Troy Lyons, Dominique Brocard and Sean Mulligan

Across (and under) the United States of America are many examples of vortex-flow intakes to drop structures comprising drop shafts to deep tunnels used to collect and store volumes of stormwater or combined sewer overflows (CSOs) in urban areas. From such storage tunnels, the CSO water is typically stored until the storm event (responsible for creating greatly increased flowrates) has subsided. This water is then pumped to wastewater treatment facilities, where the flows are treated before being released into nearby natural water bodies (rivers, lakes and marine coasts). Although the number of examples of this type of infrastructure is increasing, especially in the past few decades, the brief examples given here for the cities of Milwaukee, Boston, St. Louis, and Indianapolis are representative of projects that feature drop shafts feeding water to large, conveyance and storage tunnels underlying many cities across the United States.

These examples use drop shafts with vortex flow intakes as these offer several advantages over plunge type drop structures including minimising the amount of air entrained due to the water flow into water collection and storage tunnels in addition to high energy dissipation efficiency required for flows descending to the tunnels. Such benefits thereby reduce the cross-section size and complexity of components of the drop structures. Air entrainment usually has the undesirable consequences of increasing odour problems, bulking conveyed flows of water, causing outbursts of entrapped air, water-flow unsteadiness, and de-aeration complexities.

Also, each example involved the use of a large Tunnel Boring Machine (a TBM) to overcome some of the challenges of constructing deep tunnels in urban environments and below or around numerous existing utilities, and in coordination with other municipal projects. Considerations of constructability and cost are briefly discussed here.

It is worth mentioning that plunge-flow drop shafts are still used, notably when factors such as debris ingestion must be considered. The main U.S. example of a plunge-flow intake, in which the CSO flow radially enters the drop shaft to a drop structure, is operated by Metropolitan Sanitary District of Greater Chicago and is known by the acronym TARP (Tunnel and Reservoir Project). In plunge-flow drop shafts, relatively large volumes of air bulk the flow in the tunnel and its connections, and energy-dissipation issues may be associated with the radial entry of flow into a drop shaft. Such drop shafts require large de-aeration chambers and sundry devices for flow-energy dissipation.

Milwaukee

Heavy rain and melting snow caused problems for Milwaukee Metropolitan Sewerage District (MMSD), which was struggling with problematic overflows of its CSO load (25 mm of runoff from Milwaukee requires MMSD to handle a volume of about 2.7 x 107 m³). The overflows would enter Lake Michigan. In the 1980's, MMSD addressed these problems by starting work on its Deep Tunnel Project. The Project, implemented in the mid-1990s, comprises two tunnels bored in rock approximately 100 m below the city.

The tunnels connected to the existing near-surface CSO system, 45.4 km long with diameters varying from 5.2-9.8 m, are central to MMSD's Inline Storage System. The System is an example emulated since by other cities in the U.S.

The system has seventeen drop shafts, each with a tangential, vortex-flow inlet, to feed CSO water to the two tunnels. The eventual design of the drop shafts (diameters of about 0.8-3.0 m) and the deaeration configuration adopted were guided using two physical hydraulic models to determine possible scale effects, especially regarding air entrainment. These models included a small-scale model for preliminary screening of designs (length-scale variable, as drop shaft diameters varied in prototype), then a model of larger scale (2.3 times larger than the small-scale model) to fine-tune and confirm the design. Results from the physical models showed that the flows were stable, dissipating between 46 to 91% of the approach flow energy, and that the air entering the storage tunnels was about 0.2% of water volume during design flow events. Figure 1 shows the larger model. To date, the Inline Storage System, and various other improvements, has enabled MMSD to collect and treat approximately 99% of all CSO water that has entered MMSD's sewer system since 1994. The U.S. national goal is to capture and clean 85% of water for more than 700 cities with systems like that in Milwaukee.

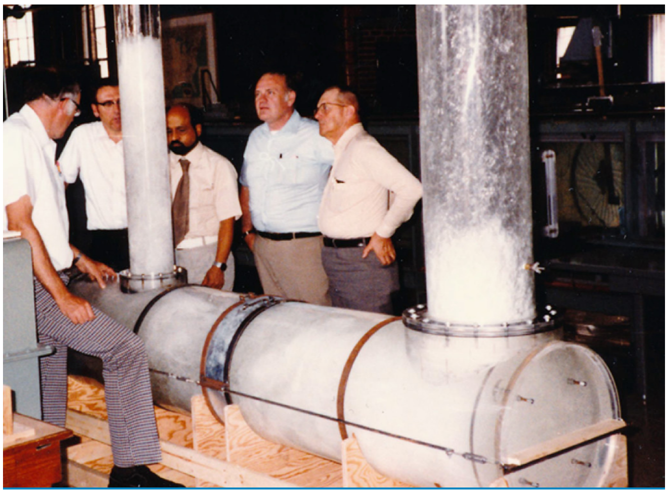


Figure 1 | The large-scale, physical model of the tangential, vortex-flow intake and de-aeration tunnel. The model was used to aid the design of the Milwaukee drop shafts. The 1982 model included a tangential form of vortex-flow intake and a de-aeration outlet. (Image, courtesy of IIHR; Jain is in the middle of the group).

Boston

The Massachusetts Water Resources Authority (MWRA) developed the North Dorchester Bay CSO Storage Tunnel within the densely developed South Boston neighbourhood just south of Boston's Logan Airport. The project is known also as the South Boston CSO Storage Tunnel. The nearly 4.0 km long, almost 5.2 m diameter storage tunnel, and associated piping captures the CSO flow from a 25-year, 24-hour design storm, thereby effectively eliminating CSO flow into North Dorchester Bay, which forms part of Boston's Harbor. After the design storm is over, the tunnel is dewatered at a rate that the Boston's Deer Island Waste Water Treatment Plant (second largest in U.S.) can handle. Boston Harbor has a well-known outfall diffuser pipe extending from the Deer Island facility.

The construction project for the tunnel was the largest in MWRA's history. The Tunnel's layout included a 56,780 m^3/day dewatering pump station located at the downstream end of the tunnel. The station sends stored water to the Deer Island facility. The tunnel comprises seven, 1.83 m to 2.6 m diameter, vortex-flow drop shafts. Opened in 2011, the Tunnel is functioning as expected.

Tangential vortex-flow intakes fitted with helical ramps (helical drop shafts) were recommended for this project, largely because of space and construction constraints associated with the location formed mainly in soft ground, consisting of mostly glacial outwash sand and gravel and glacial marine clay. These considerations meant that the drop shaft design used for Milwaukee led to drop shafts that were overly difficult and expensive to construct. The use of ramps decreased air entrainment and increased energy dissipation, thereby negating the need for deaeration chambers, an important and costly construction consideration. The ramps were made of epoxy-coated steel and inserted into the concrete drop shafts and generally conformed to the dimensions shown in the illustration given in Figure 2.

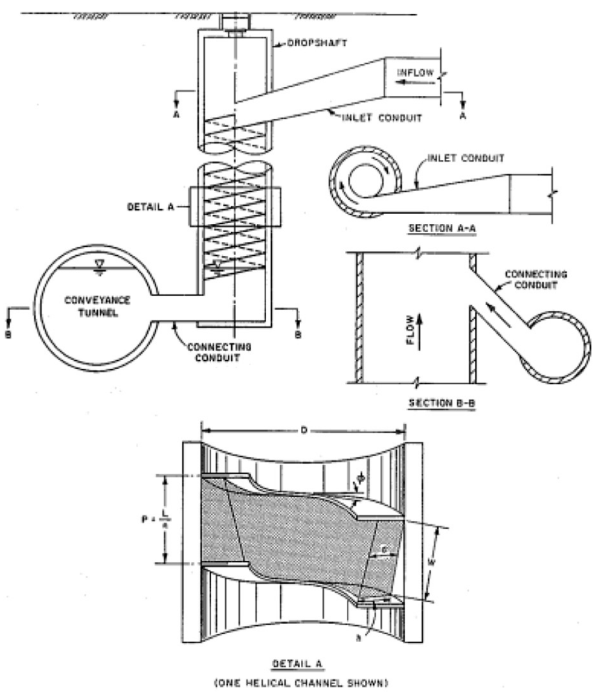


Figure 2 | Details of the helicoidal drop shafts in Kennedy *et al.* (1988).

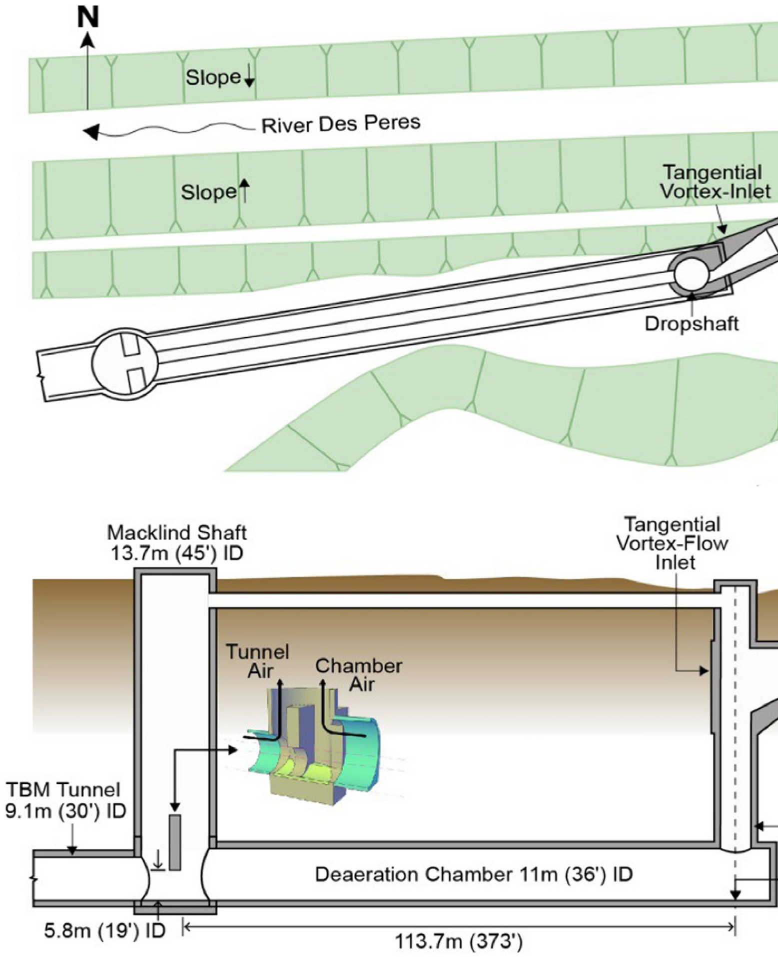


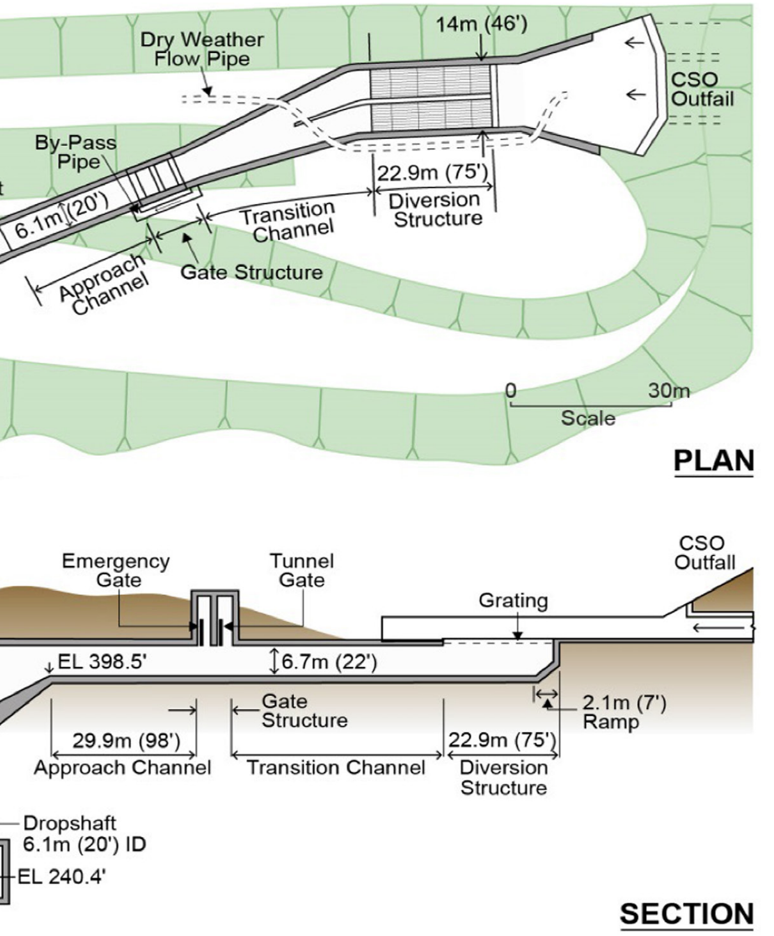
Figure 3 | Final layout configuration of the Forest Park Intake.

St. Louis

The Metropolitan St. Louis Sewer District (MSD) manages the fourth largest sewer collection system in the U.S. The biggest component of the system, the Lower and Middle River Des Peres (LMRDP), includes a 14.5 km long, 9.1 m diameter storage tunnel, which follows the alignment of the channelized LMRDP. The collector tunnel is bult in rock. The first part of LMRDP has been in service since 2014, with other parts completed since 2020.

The LMRDP CSO Storage Tunnel significantly reduces the frequency of CSOs entering the LMRDP by capturing most of the excess sewage and stormwater flow during heavy rains and storing it in the tunnel prior to treatment. The tunnel will receive CSO flows from 36 tangential, vortex-flow drop shafts located in a 116 km^2 area. The largest drop shaft is the Forest Park Intake, located at the upstream end of the tunnel. This intake has a design peak flowrate of 16.7 x 10^6 m^3/day (193 m^3/s), and to date (as the writers understand) is the largest diameter tangential vortex-flow intake with a diameter of 6.1 m. Figure 3 depicts the intake in plan and elevation.

Besides testing and adjustments using a physical model, hydraulic evaluation was undertaken using Computational Fluid Dynamics (CFD) modeling followed by construction and comprehensive testing of a 1:16-scale, physical model at IIHR – Hydroscience and Engineering (IIHR).



The layout is shown in plan and section elevation views.

Figure 4 | The 1:16-scale hydraulic model of the tangential, vortex-flow intake used for the Forest Park Intake drop shaft. (Image courtesy of Jacqueline Stolze of IIHR).

Figure 4 shows the model. The CFD code STAR-CCM+, from Siemens, was used for CFD modelling, which with the physical modelling, led to design adjustments, including an increase in diameter to the deaeration chamber (Klecan *et al.* 2017).

Indianapolis

Located more than 76 m in rock below ground, the DigIndy Tunnel System will store more than 0.95 x 10^6 m^3 of CSO flows and will subsequently release the CSO to a wastewater treatment plant, where the CSO water is treated before being released into natural waterways. The DigIndy Tunnel System will capture up to 95% of CSOs along Indianapolis' waterways. Before the tunnel, an annual average of 30 x 10^6 m^3 of untreated wastewater spilled to those waterways from the CSOs.

The tunnel system comprises about 46 km of 5.5-meter-diameter, concrete-lined tunnels, branched in five tunnel segments linked to a Deep Rock Tunnel Connector, about 12.5 km long (Maynard and Glover 2020). Each tunnel branch has one or more tangential vortex-flow drop shafts. A total of about 32 drop shafts (about a 60 m drop, and 1-2m in diameter) feed CSO flows into the tunnels, which convey water to the Tunnel Connector. The maximum flowrate into a drop shaft exceeded about 13 m^3/s.

The designs of the drop shafts and the CSO tunnels were aided using physical and numerical models. The initial designs were obtained using FLOW-3D and theory, enabling the tangential inlets, drop shaft, and tunnel to be chosen and sized. **Figure 5** indicates various iterations of intake modelled numerically. These initial results formed the dimensions used to develop a 1:10 scale physical model of a selected drop shaft, as **Figure 6a** illustrates. Among the design questions was the adequacy of the size of the approach channel (flow stability was an issue) and the drop shaft, minimization of turbulence in the storage tunnel, sufficient water attachment to the drop shaft wall, and removal of air entrained by flow in the drop shaft. Figure 6a shows the operation of the drop shaft running a prototype flowrate of 15.8 m^3/s in a 2.1 m diameter drop shaft. The vortex development shows good rotation and attachment to the drop shaft wall down to the deaeration chamber. **Figure 6b** gives an impression of the size of a DigIndy branch tunnel. Further information on the DigIndy System can be obtained, for example, from AECOM (various internet sites), Citizens Energy Group (various internet sites), Lewis and Hawbaker (2020), and Lyons and Odgaard (2010).

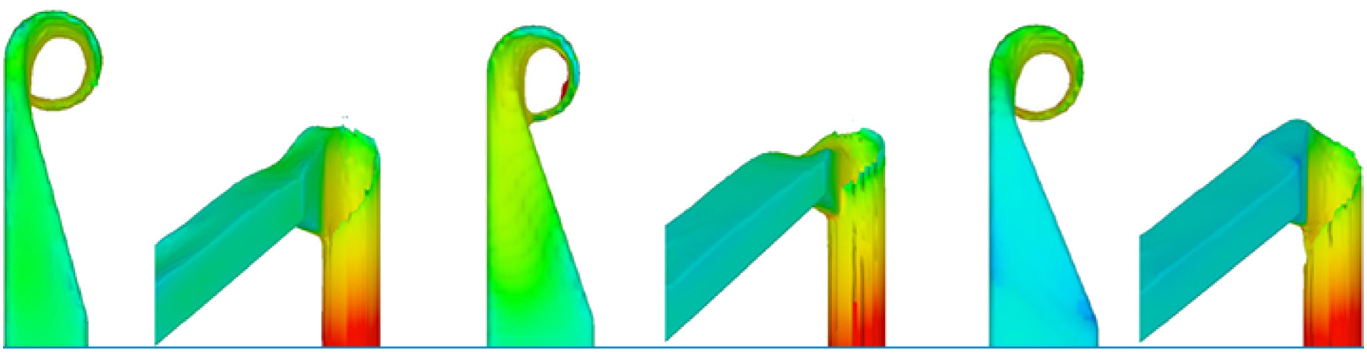


Figure 5 | Plan and elevation views from CFD modelling of several, approach-channel iterations (to tangential intake). (Image courtesy of AECOM).

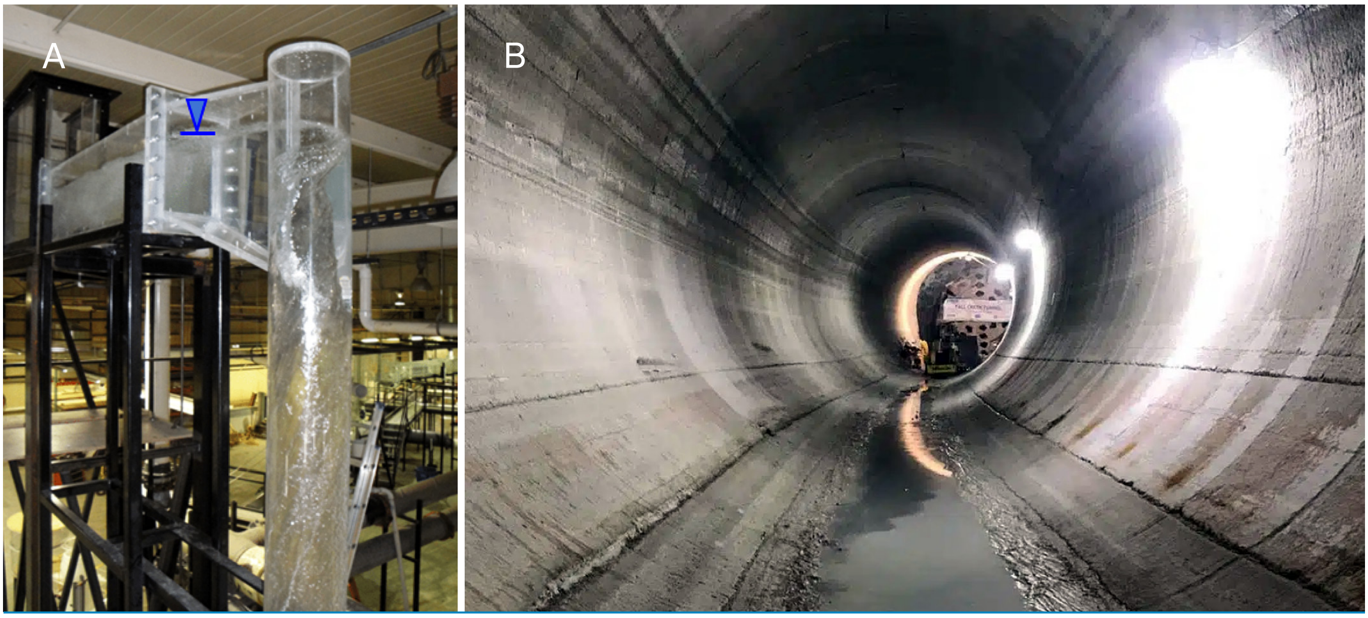


Figure 6 | The 1:10 scale physical model of the tangential, vortex-flow intake, drop shaft, and tunnel for DigIndy Tunnel System: (A) operation of the drop shaft for a test run for the prototype flowrate of 15.8 m^3/s (dropping 50.6 m in a 2.1 m diameter drop shaft); and (B) a view along one of the 5.5-meter diameter branch tunnels. (Photos courtesy of Troy Lyons of IIHR and AECOM).

Concluding Remarks

Many cities in the U.S. face pressure to intercept releases of stormwater and combined sewer overflow (CSOs) into natural water bodies and redivert instead to wastewater treatment facilities. The provided examples were motivated by this concern, pressed by local or regional interests, and eventually required by the U.S. Environmental Protection Agency. Over 100 urban communities in the U.S. have responded to this requirement, and other communities soon will need to respond as releasing polluted waters into natural water bodies is no longer acceptable.

However, the construction works entailed in collecting and treating, before releasing, polluted waters such as CSO flows involves significant investments. Many, if not all, of the examples cited here were the largest infrastructure or public works projects of the urban communities (cities) involved. Such works typically required that the drainage and conveyance systems be situated deep below the urban communities to move polluted water to treatment facilities located within an urban community. Underground construction is difficult technically, legally, and societally, and is therefore very expensive. Nonetheless, though construction and cost concerns are significant, these challenges must be overcome as urban communities continue to grow and require solutions that future proof developments and safeguard the environment.

A key component to stormwater and CSO control in urban settings are drop shafts and the use of vortex-flow intakes. The hydraulic engineering of drop structures requires further attention where the examples presented herein illustrate areas that require further research and development. For instance, concerns for air entrainment and odour continue to linger. Such concerns increasingly are being tackled using contemporary tools, including ever-improving numerical methods, instrumentation (in laboratory models and prototype situations), and innovative designs.

References

Craig, A. J., Lyons, T. C., and Knox, J. (2016). *Hydraulic Model Studies for the Design of Vortex Dropshafts for the Metropolitan St. Louis Sewer District: Lower Middle River Des Peres CSO Storage Tunnel - Forest Park Intake.* IIHR Limited Distribution Report No. 413, IIHR – Hydroscience & Engineering, The University of Iowa, Iowa City, Iowa.

Jain, S.C., (1998). *Hydraulic Design of Vertical Drop Structures.* Consultant' Report, Metcalf & Eddy, Wakefield, Massachusetts.

Jain, S. C., and Kennedy, J. F. (1983). *Vortex-Flow Drop Structures for the Milwaukee Metropolitan Sewerage District Inline Storage System.* IIHR Report No. 264, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa.

Kennedy, John F., Subhash C. Jain, and R. Rafael Quinones. *"Helicoidal-ramp dropshaft." Journal of Hydraulic Engineering* 114, no. 3 (1988): 315-325.

Klecan, W., P. Pride, J. Hallsten, A. Craig, T. Lyons, and A. Kharazi. (2017) "Diverting 4400 MGD into a Deep CSO Tunnel: Forest Park Intake Design." In WEFTEC. Water Environment Federation, 2017.

Lyons, T.C. and Odgaard, A.J. (2010). *Hydraulic Model Studies for the City of Indianapolis' Deep Rock Tunnel Connector Drop Structures.* IIHR Limited Distribution Report No. 370, IIHR – Hydroscience & Engineering, The University of Iowa, Iowa City, Iowa.

United States Environmental Protection Agency (2004). Report to congress on impacts and control of combined sewer overflows and sanitary sewer overflows. Report: 833-R-04-001.

2024/2025 IAHR Events Calendar

IAHR World Congresses | IAHR Regional Congresses | IAHR Technical Congresses | IAHR Young Professionals | IAHR National Chapters Events

2024 | March	**4th IAHR Young Professionals Hydro-Environment Challenge** 1 Mar–31 May 2024 | **Online**
2024 | April	**Young Professionals Webinar Series: Seaweed nature-based solutions for coastal resilience** 17 Apr 2024 | **Online**
2024 | May	**15th International Symposium on Ecohydraulics** 5–9 May 2024 | **Quebec, Canada**
	IAHR Africa Scholars Meeting 6, 13, 21 May 2024 | **Online**
	9th Conference on Physical Modelling in Coastal Engineering (Coastlab24) 13–16 May 2024 | **Delft, The Netherlands**
	2nd IAHR International Workshop on Scour around Hydraulic and Coastal Structures 20–23 May 2024 | **Chengdu, China** 1st Event of new IAHR Working Group on Scour
	15th International Conference on Hydroinformatics (HIC 2024) 27–31 May 2024 | **Beijing, China**
2024 | June	**8th IAHR Europe Congress 'Water–Across Boundaries'** 4–7 Jun 2024 | **Lisbon, Portugal**
	27th IAHR International Symposium on Ice 9–13 Jun 2024 | **Gdansk, Poland**
	16th International Conference on Urban Drainage (ICUD 2024) 9–14 Jun 2024 | **Delft, The Netherlands**
	10th IAHR International Symposium on Hydraulic Structures (ISHS 2024) 17–19 Jun 2024 | **Zurich, Switzerland**
	9th International Junior Researcher and Engineer Workshop on Hydraulic Structures 20 Jun 2024 | **Zurich, Switzerland**
	10th International Symposium on Environmental Hydraulics (ISEH 2024) 25–27 Jun 2024 | **Aberdeen, United Kingdom**
2024 | July	**8th W.A.T.E.R. Summer School–Workshop on Advanced Measurement Techniques and Experimental Research** 1–5 Jul 2024 | **Strasbourg, France**
2024 | August	**7th IAHR/WMO/IAHS International Stream Gauging Course** 31 Ago–2 Sep 2024 | **Liverpool, United Kingdom**
2024 | September	**12th International Conference on Fluvial Hydraulics (River Flow 2024)** 2–6 Sep 2024 | **Liverpool, United Kingdom**
	32nd IAHR Symposium on Hydraulic Machinery and Systems 11–14 Sep 2024 | **Roorke, India**
2024 | October	**31st IAHR Latin America Regional Division Congress** 1–4 Oct 2024 | **Medellin, Colombia**
	24th IAHR Asia and Pacific Division Congress 'Water for a Changing Future' 14–17 Oct 2024 | **Wuhan, China**
2024 | November	**5th IAHR Young Professionals Online Congress** Nov–Dec 2024 | **Online**
2024 | December	**6th IAHR Africa Division Congress** 9–12 Dec 2024 | **Benguerir and Marrakech, Morocco**
2025 | June	**41st IAHR World Congress "Innovative Water Engineering for Sustainable Development"** 22–27 Jun 2025 | **Singapore, Singapore**
2025 | October	**IAHR Spain Chapter Water Engineering Workshop "Jornadas Ingeniería del Agua" (JIA 2025)** 22–23 Oct 2025 | **Zaragoza, Spain**

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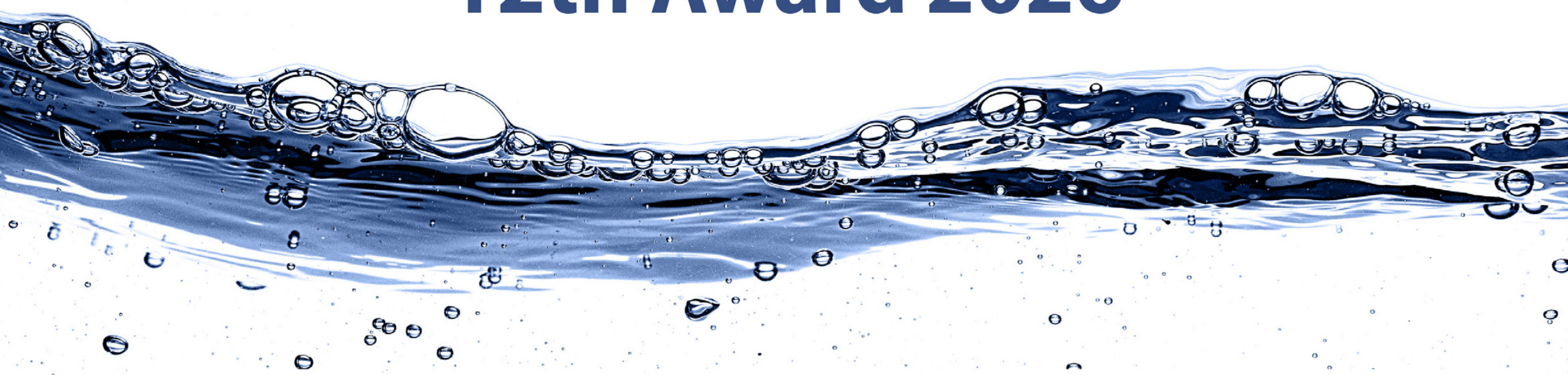

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