Chicago Tunnel and Reservoir Plan, Mainstream and McCook Tunnels, MWRDGC, 2017

Deep Tunnels: Lessons Learned from Around the World

In Partnership With:

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Why Deep Tunnels?

Large-scale deep tunnels are increasingly used to address conveyance and storage for water, wastewater, stormwater and combined sewer systems around the world. While these mega infrastructures with 100-year plus service lives are among mission-critical assets of many utilities, there isn't a global platform for information sharing to benefit from the science and technology as well as the innovations and lessons-learned thus far.

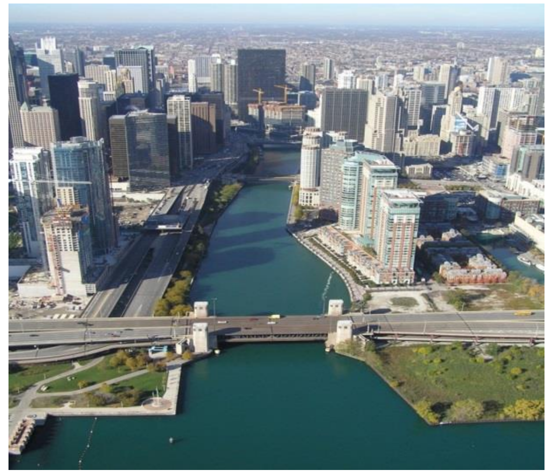

Figure 1 - Chicago's TARP Deep Tunnel protects Lake Michigan and has significantly reduced pollution in urban rivers that are now public and tourist attraction. (Photo: Provided by MWRDGC)

The Water Research Foundation (WRF), and Water Environment Federation (WEF) along with Singapore's Public Utilities Board (PUB) National Water, have recognized the gap in the industry and kicked off a special-purpose Deep Tunnels Workshop toward discussion and evaluation of design, construction, operation, and resilience of these integrated infrastructure systems.

On April 12, 2018 WRF, WEF, and PUB hosted a Deep Tunnels Workshop in conjunction with WEF's Collection Systems Conference in Virginia Beach, Virginia. The workshop was sponsored by Black & Veatch.

The participants included panelists representing five major utilities with multi-billion-dollar deep tunnel programs in Chicago, Milwaukee, Cleveland, Singapore, and London, UK. The panelists discussed their systems, overall program development experience and lessons-learned on design, construction, operation and resilience and also shared innovations and unique solutions to problems encountered. Following the workshop, the WRF, Singapore PUB, Black & Veatch, and several representatives of deep tunnel systems intend to re-organize and advance this information exchange platform with additional input, evaluations, and recommendations during the 2018 Singapore Water Week, July 8 through 12, 2018.

The Deep Tunnels Workshop and this follow-up report provide a great deal of information on design, construction, operations and maintenance, and resilience of five significant deep tunnel systems in service in the world. The report contains information on:

- Deep tunnels, part of the integrated infrastructure
- Technology and innovations
- Lessons learned

The report concludes with future discussions, acknowledgments and references.

It is our expectation that as we continue to make significant investments in deep tunnel systems, we are able to recognize opportunities to access global state-of-the-art technology, innovations and lesson-learned, and benefit from them for enabling the most efficient and resilient tunnels into the future.

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Deep Tunnels: Big Infrastructure, Big Impacts

Deep tunnel systems are used to convey water, raw sewage, stormwater, floodwater, and **combined sewer overflows (CSOs)** in many urbanized communities and large cities around the globe. Deep tunnel conveyance can be via gravity or siphon.

Deep tunnel systems are generally **10-foot (3-meter) or larger in diameter** and used for dry weather (sewage or used water), wet weather, stormwater, and CSOs.

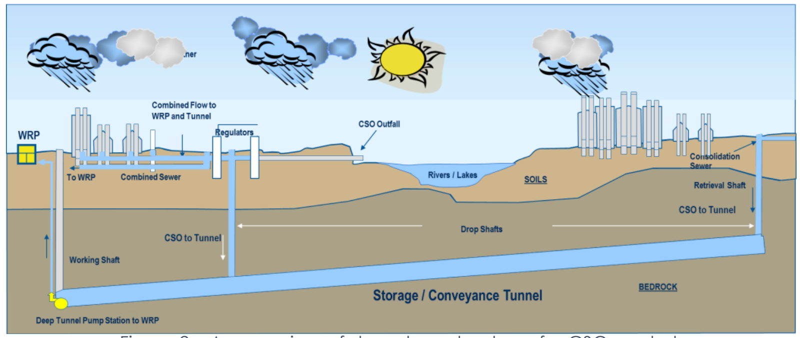

Figure 2 – An overview of deep tunnel systems for CSO control.
(Figure provided by F. Oksuz)

Most sewage and CSO deep tunnels lead to **deep tunnel pump station facilities** that are often equipped with screening and air/odor management facilities. The flows are then directed to water resource recovery facilities (WRRFs) and high rate treatment systems (HRTs) for treatment and eventual return back to surface waters and/or reuse facilities. In the case of deep tunnels dedicated to flooding and stormwater management, discharges may lead to reservoirs, streams, and other relief points to mitigate damages.

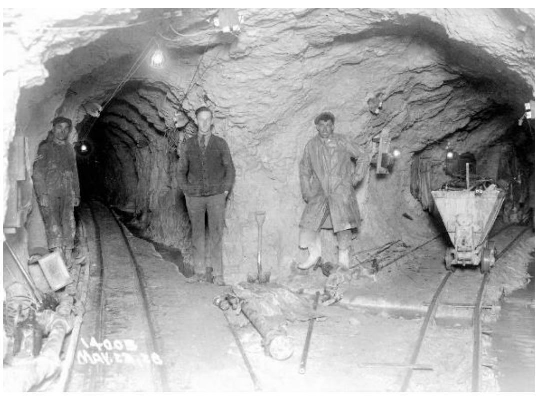
Figure 3 – Photo of workers constructing a connection between two sewer segments in an underground chamber of MWRDGC's Salt Creek Tunnel.
(Photo provided by MWRDGC)

Although largely unseen, these large infrastructures can have a big impact when considering the large storage capacity, relatively "low maintenance", reliability, and potential **service lives of over 100-years**. While many utilities, particularly those in dense urban areas, are looking at deep tunnel systems as long term-sustainable assets, tunnels have been around for decades. Long gone are the days of hand digging. With advancements in technology and a better understanding of how tunnels can be integrated with existing wastewater treatment, many utilities look at tunnels as the most reliable and sustainable fabric of urban living today.

Tunnels are **integrated infrastructure systems**. Even though tunnels are point-to-point linear facilities, the overall planning, design, construction and operation of tunnels can be highly complex, and in most cases, specific to their location and application. Tunnels not only need to act as both storage and conveyance, but they also need to be designed in consideration with:

- Consolidation/Link Sewers and Interceptors
- Drop Shafts & Diversion Structures
- Pump Stations, Lift Stations, Screening Facilities
- Water Resource Recovery Facilities
- High Rate Treatment Systems
- Dams & Reservoirs
- Intakes & Outfalls
- Hydropower Units
- Green Infrastructure and Stormwater Management
- Water Reuse/Recycling Facilities

And while tunnels must be planned out holistically, they can be built in multiple phases.

Deep Tunnel Systems Around the Globe

Just like all integrated sewer systems, no deep tunnel system is ever the same. Depending on the location, space available, purpose, and how the tunnel will work within the existing sewer system, deep tunnel systems around the globe are all different.

Some of the global deep tunnel systems that are in service include the following:

- Alcosan Dry Weather Flow Tunnel
- Atlanta Deep Tunnel
- *Chicago Tunnel and Reservoir Plan (TARP)*
- *Cleveland (NEORSD) Mill Creek Tunnel*
- Hong Kong Harbour Area Treatment System (HATS)
- *Lee Tunnel (part of Thames Tideway, London)*
- *Milwaukee Deep Tunnel*
- New York City DEP Deep Tunnels for Water
- Paris TIMA
- Portland Deep Tunnel
- Seattle Deep Tunnel
- *Singapore PUB Deep Tunnel Sewerage System (DTSS) Phase 1*
- St. Louis Deep Tunnel

Those in italics are deep tunnel systems that were represented at the April 12, 2018 workshop.

Technology and Innovations: Improving an Age-old System

While large diameter tunnels have been used throughout water's history, a resurgence in tunnels as a cost and space effective water storage alternative, has sparked technologies and innovations to help make the operations of deep tunnels more effective, reliable, and resilient.

Most innovative concepts within deep tunnels are centered around methodologies and tools for design, modeling, monitoring, inspections and maintenance of the tunnels and ancillary facilities such as gated systems and pump stations. Other technology advancements include data management innovations in the development and selection of tunnel alignment, engineering analysis, tunnel excavation, tunnel lining materials, and various mechanical, instrumentation and control (MEICA) components of deep tunnels.

While the lessons-learned and solutions are unique to each of the tunnel system, the following are some examples of the innovative approaches that are engaged throughout the tunneling industry:

- 3D and BIM modeling of tunnel diversion and hydraulic and air management structures, pump stations.
- 3D development of tunnel alignment and shaft locations alternatives and real time evaluation with the aid of GIS and aerial imaging (maps, drone data, etc.)
- Computational Fluids Dynamics (CFD) Modeling
- Structural analysis modeling using ANSYS or similar software and coupling with CFD models
- Advancements in tunnel construction and tunnel boring machines (TBMs)
- Advancements in tunnel lining methods and materials
- Tunnels inline treatment considerations
- Innovations and alternative methods in construction of drop shafts and tunnel connections
- Tunnel isolation gates for resilience, future access, and maintenance
- Advancements in remotely operated vehicles for tunnels inspections and maintenance
- Fiber optic installations for structural integrity monitoring and data transmissions in tunnels
- Drones for tunnel inspections

Many of these advancements are highlighted in the following sections.

Planning and Designing a Tunnel

As with any new integrated infrastructure, the initial planning and design phases of deep tunnel projects are crucial to the operations and success of the tunnel. With every tunnel project having a different and specific purpose, there have been several innovations seen throughout the years with the planning and design of a tunnel. These innovations and technologies have allowed engineers to examine different, not previously thought about, aspects of tunnel design, helping to optimize efficiency and reliability, as well as minimize the risk of the system.

Designing for now? Or the future?

When beginning the design of a deep tunnel project for CSO and flood protection, the idea of which ultimate conditions should be considered comes up. Should the design include a 5, 10, 50, or 100-year flood and level of service? Will it be used in dry weather conditions – as a back up to existing facilities? These are just a few situations that need to be considered. Also, once in use, what if it's not enough? How do you expand?

With an expected service life of over 100 years, it is inevitable that deep tunnel systems will require some type of live taps and connections due to unplanned or uncontrolled changes over it's long service life. It is important to provide as much flexibility as possible into the design and construction of the tunnels.

One example of planning for the both situations, now and the future, is the on-going **Tunnel and Reservoir Plan (TARP) for the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC)**. Adopted in 1972, TARP was a cost-effective way to comply with Federal and State water quality standards. The plan is a system of deep, large diameter tunnels and vast reservoirs designed to reduce CSO overflows, improve water quality in Chicago area waterways and protect Lake Michigan from pollution caused by sewer overflows. It consists of two phases, Phase 1, the tunnels, which was completed in 2006 and Phase 2, the reservoirs, which will be completed in 2029. When completed the TARP project will have a CSO capacity of 20.55 billion gallons (BG).

Phase 1 of TARP consists of the 109 miles (mi.) of tunnels with a CSO capacity of 2.3 BG. It is made up of four distinct tunnel systems: Mainstream, Des Plaines, Calumet, and Upper Des Plaines, which were planned so that completed portions of the tunnel system could be put into operation as work continued elsewhere.

Phase 2 of TARP includes three reservoirs; Majewski, McCook, and Thornton, with a CSO capacity of 18.25 BG.

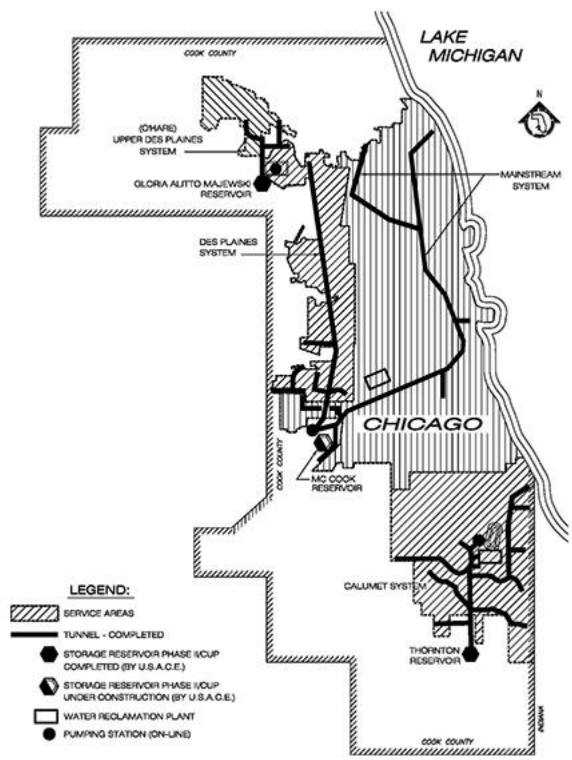

Figure 4 – Map of the MWRDGC's TARP service area. (Figure provided by: MWRDGC)

A **phased-approach** and early commissioning in sections is often desired and a recommended approach for implementation of a large and multi-billion-dollar deep tunnels program. Systems should be designed and constructed to minimize overlaps and operational interferences as much as possible as part of phased-approach.

This is big! Where's it going to go?

One obstacle that many utilities face when approaching a deep tunnel project is the question of, "Where are we putting this huge water infrastructure?". Sizing and aligning the tunnel to not only fit a city but operate efficiently requires evaluating the tunnels alignment from many different angles.

Figure 5 – 3D integrated layouts can show how the tunnels alignment will affect the community and other infrastructure. (Figure provided by: F. Oksuz)

These days modeling tools not only look at the hydraulics of the system but the horizontal and vertical alignment and can evaluate conditions such as:

- Risk (technical, third party, other)
- Shaft locations
- Easements
- Capital and operating costs
- Geotechnical considerations
- Community impacts
- Proximity to sensitive structures
- Tunneling under rivers, wetlands, etc.
- Permits
- Constructability issues

By looking at these factors from different angles and perspectives, it allows utilities and the public to get a better idea of why a large integrated tunnel is needed and how it will fit as an integrated system.

Another innovative tool, that's helped both utilities and the public better understand the tunnel design, is the development of a **3D Integrated Layout**, which can be shown in a **virtual reality environment**. It's said that "a picture is worth 1,000 words" but imagine if that picture could get even better! By utilizing tools like virtual reality and 3D layouts both at surface and below ground, it not only allows the public to visualize how this large infrastructure will be installed, but also how it will impact them and the surrounding environment.

Hydraulic Design and Modeling

Deep tunnels are integrated infrastructures, and the overall system hydraulics is the linchpin to successful design and operations. **Computational Fluid Dynamics or CFD modeling**, once an innovative approach, is now a norm in hydraulics design and optimization for deep tunnels and integrated diversion works, drop shafts, gates, valves, storage, etc. While some may view modeling as just a fancy way to show how the tunnel works, CFD and other hydraulic modeling has allowed utilities to optimize the operational efficiency and reliability of their system.

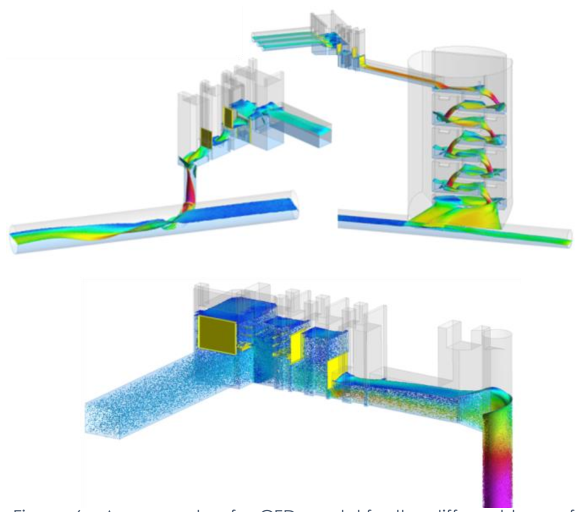

Figure 6 – An example of a CFD model for the different type of drop shaft connections. (Figure provided by F. Oksuz)

Once innovative in the 2000s, one of the most common uses for CFD modeling is the design, sizing, and layout of **drop shafts and diversion works**. Diversion works and drop shaft designs have evolved over time, with many being familiar with the three most common types:

- "Chicago" style **plunge drop shaft** – Common applications for large volume/diameter diversions and drops up to 30 ft.
- "Milwaukee" style **vortex drop shaft** – Smaller diameter shafts and footprint, efficient energy dissipation
- **Baffle drop shaft** – Used in large diameter shafts with no dedicated deaeration

Advancements in computing power have allowed CFD modeling to virtually depict and simulate any type of hydraulic structure and check operations criteria. It can also readily be coupled with and transferred into civil/structural models and design. By utilizing CFD modeling for diversion and drop shafts, it helps to maximize the operational efficiency and reliability of the shafts.

While many utilities utilize models to help with the operations and maintenance of their deep tunnels, others have seen that the use of **data analytics and predictive operations** have not been advanced enough for any deep tunnel systems in design or operations.

At Milwaukee MSD's 521 MG wet weather Inline Storage System (ISS), both combined and separate sewer flows are collected during wet weather events. When a severe wet-weather event occurs, operations staff has to decide, "*To prevent an SSO and possibly cause a CSO, when do we shut off CSO flow to the tunnel?*".

The problem with **volume reserve for separate sewage (VRSS)** is one that utilities with both combined and separate sewer flows sometimes encounter. Operations staff have a hard-balancing act to decide how much space should be reserved in the tunnel for separate sewage inflow. At Milwaukee, the fact that the separate sewage inflow lags the combined sewer inflow, makes the balance that much more difficult and requires on-call staff to actively manage rainfall during the wet-weather event. With zero SSOs permitted on their consent decree, the VRSS predictive tool used at Milwaukee is helpful, but experienced staff have been seen as more important.

Green's Not Bad!

Contrary to popular belief, green infrastructure is not a competition feature to tunnels, but is a catalyst and companion. Green infrastructure cannot match conveyance and storage capabilities of tunnels. Tunnels, however, can be categorized and qualified for lower-cost green infrastructure bonding when properly demonstrated that they allow for expansion of green space and are integrated with a number of green infrastructure and materials reuse and recycling concepts.

An example of embracing green infrastructure in tunnel projects can be seen at **Thames Water in London, England**. During the planning and design of the Thames Tideway Tunnel, the project team went through a rigorous public outreach program, promoting the construction of the tunnel as both a community improvement project and a project to help preserve and prolong the Victorian sewer network, by another 100 years.

By engaging the community and utilizing green infrastructure as a component of the tunnels design, Thames not only left a beneficial legacy for the community, but also helped fund the project. With the incorporation of green infrastructure, Thames Water was able to obtain the largest Stirling Green Bond (£250M) from the S&P's Green Bond process (with a score of 95/100 from the S&P's Green Evaluation Tool).

Figure 7 – Before and after for the Blackfriar drop shaft location along the Tideway Tunnel. Thames Water utilized green infrastructure to provide both a community walkway and tunnel access for operations staff. (Photo's provided by D. Crawford)

That's a Big Hole! Tunnel Boring Machines (TBMs) and Lining Systems

There are several different methods for constructing large infrastructure tunnels, the most popular being **Tunnel Boring Machines (TBMs)**. TBMs have been around since the 1970s and have advanced in their ability to bore larger diameters and longer lengths, as well as integrate with tunnel lining systems.

To get an idea of TBMs advancements in tunnel length and daily average, MWRDGC compared the capabilities of TBMs used during the construction of their tunnel system throughout TARP (dating all the way back to 1977).

Award Year	Mined Diameter (ft)	Tunnel Length (ft)	Daily Average (LF)
1977	32.25	24,692	48
1988	32.25	24,024	78
1977	21.25	42,154	76
1995	24.25	35,575	161
1978	15.25	6,889	38
2001	14.17	6,485	103
1988	12.00	6,745	12
1992	10.67	6,156	51

Table 1 - TBM performance throughout TARP

As more tunneling specifications are written based on risk, utilities are putting in the effort for more in-depth **geotechnical investigations to help mitigate that risk**. With more information about the geotechnical conditions and TBMs advancements with open/closed mode operations to effectively manage variable (mixed) ground conditions, TBMs contractors have been able to be more accurate with estimating TBM advance rates and costs.

Figure 8 – Evolution and advancement of TBMs from early to modern.
(Figure provided by F. Oksuz)

As owners and contractors aim for less risk and expect more out of TBMs, TBMs are continuing to benefit from technology advancements including:

- Variable drive and larger diameter TBM cutterheads with less frequent need for "intervention" to replace cutters
- Tighter turn radius's for TBMs
- TBM control systems are linked to surface monitoring in real time
- Muck balance in Earth Pressure Balance Machines (EPBMs) is fully automated
- Slurry circuits have flow and nuclear density meters

Tunneling advancements also go beyond TBMs, and **tunnel lining systems** have also evolved beyond conventional cast-in-place concrete and corrosion protection liners (CPLs). Other lining systems include:

- Precast Segmental Lining
  - Precast concrete segments with gasketed/bolted connections
  - Steel or polymer/steel fiber reinforced concrete gaskets/seals are extruded and molded onto segments during manufacturing
  - Ethylene polythene diene monomer (EPDM) composite gaskets
- Steel Lining with Corrosion Protection
- CombiSegments

Advancements in TBMs and tunnel lining systems continue to help reduce tunneling risks associated with challenging ground conditions and groundwater.

Accessing and Inspecting

One of the biggest challenges for utilities is how to inspect and access these large diameter tunnels. While many are aware of the tunnels presence during design and construction, once in the ground, tunnels can sometimes become a "forgotten" infrastructure due to their long service life and sometimes infrequent use. Because of this, many tunnels are not frequently accessed or inspected, and when they are, utilities struggle to find ways to inspect the condition.

A great example of innovating for the purpose of accessing and inspecting a tunnel is at **Singapore PUB's Deep Tunnel Sewerage System (DTSS)**. During the construction of the DTSS Phase 2, the issue of accessing parts of the tunnel during dry weather flow management without a redundancy or backup came up. Singapore PUB developed an innovative approach to address resilience using **link sewers** (or shallow interceptors) bypass and **isolation gates** for the DTSS Phase 2 that would allow the operators to take sections of tunnel out of service for planned or emergency inspections and maintenance.

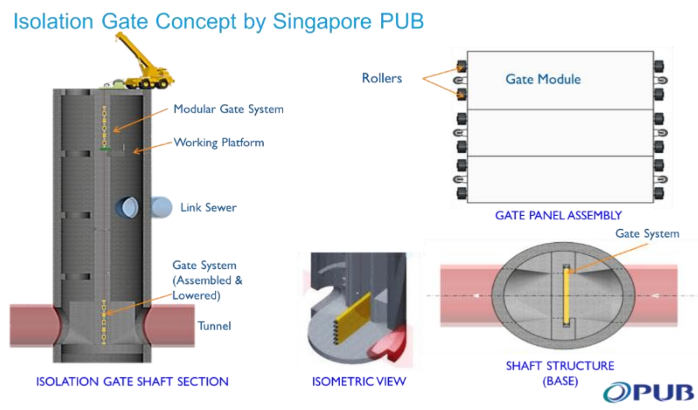

Figure 9 – Roller isolation gates concept developed by Singapore PUB. (Figure provided by Singapore PUB)

While access can be a challenge, inspecting and cleaning of tunnels has also had a surge of innovations with technology advancements in things like **fiber optic monitoring** and **remotely operating vehicles (ROVs)**.

With limited accessibility, the use of **fiber optic monitoring** has been a great innovation for deep tunnel systems. Fiber optic monitoring and communications are based on distributed fiber optic sensing (strain and temperature) and monitoring of linear integrity, in response to movements (settlements and earthquakes) and leakages. With the data transmitting and communicating with operations staff (including data on flow, velocity, metering, etc.), it allows utilities an "inside look" at the condition of the tunnels without entering.

Another field of innovation that has taken off in the inspection realm is the use of **remotely operating vehicles (ROVs)**. ROVs can be floating, crawling, or even flying (drones) with tethering that are chosen based on tunnel characteristics like water depth, flow velocity, data needed and accuracy, etc. These ROVs allow inspections to be done remotely through shaft access/hatches without the need to dewater the tunnel. ROV technology continues to rapidly advance with things like **Autonomous Underwater Vehicles (AUV)**, which are gaining wider applications in long and pressurized water transmission tunnels.

Figure 10 – An example of a crawling ROV which is inspecting the structural integrity of the tunnel. (Photo: Courtesy of Redzone Robotics, ASI Marine)

Floatables, Debris, and Grit

Figure 11 – Photo of operations staff removing floatables from a tunnel at Milwaukee MSD. (Photo provided by MMSD)

A concern that utilities have throughout tunnels is the build up of sediment, debris, grit, and floatables. While all debris and grit must be dealt with, floatables are an important consideration since if not flushed through the systems, they can form a mat on the surface of the water. This could interfere with real time control equipment or could eventually sink during dewatering and leave deposits at the tunnel inverts.

Many utilities have discovered different innovative ways to deal with floatables and debris including MWRDGC which has developed a "clamshell" basket to retrieve sediment before it reaches pumping stations and others like Connecticut Department of Energy and Environmental Protection (DEEP) which has designed its tunnel system to allow back flow from a nearby water resource recovery facility (WRRF) as a way to flush it's tunnel of grit and debris. In many instances floatables and other debris are caught and removed at screening facilities before reaching the pumping station or WRRF, it is important to look at nearby access points when deciding where to "catch" the debris/floatables.

A unique solution to the debris problem is at the **Northeast Ohio Regional Sewer District (NEORSD)** in Cleveland, OH. During their Project Clean Lake (NEORSD's CSO consent decree project), about two-thirds of their $3.0B capital improvement budget has been dedicated to tunnel systems. During the design of these tunnels, with floatables and debris collection in mind, they designed **near surface facilities** which are installed at every drop gate along the tunnel to help alleviate debris and grit. These near surface facilities (Figure 12) include:

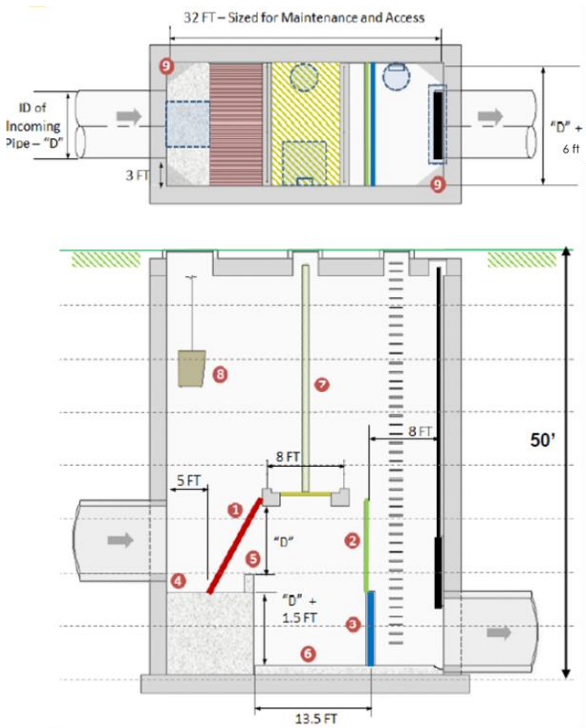

Figure 12 – Design for NEORSD's Near Surface Facilities which are installed at each drop gate along new tunnels. (Figure provided by NEORSD)

1. **Trash Rack** – To capture large debris and floatables.
2. **Floatable Bar Rack** - To capture floatables and solids prior to entering the tunnel.
3. **Wedge Wire Screen** – To prevent large cobbles, gravel, and grit from entering the tunnel.
4. **Inflow Drops with Extended Entrance Shelf** – Dissipates kinetic energy, reduces flow velocity, and allows flow to spread.
5. **Curb/Overflow Weir -** Curb on downstream end of entrance shelf dissipates energy and spreads flow horizontally as it approaches trash rack.
6. **Grit Sump** – Drop into grit sump further dissipates flow energy, allowing large grit to settle behind wedge wire screen.
7. **Vacuum Truck Connection** - Vacuum truck standpipe, for easy grit removal.
8. **Debris Hopper** – Debris hopper for easy debris and floatables removal.
9. **Fillets** – To create positive hydraulic characteristics.

While there are many innovations for collecting floatables and debris, sometimes the most effective alternative is to remove them by hand. Like tunnel designs, not every innovation and technology can be applied by every utility, but it is important to learn what is happening at other utilities and how these technologies might best fit your organization's situation.

Lessons Learned from Across the Globe

One of the benefits of having a workshop is the wealth of knowledge and conversation in the room. Throughout the Deep Tunnel Workshop on April 12, 2018, many of the utilities in attendance shared some of the 'lessons learned' that they've experienced throughout their time planning, designing, and operating deep tunnel systems. Some of the lessons learned mentioned included:

- New tunnels does not equal no CSOs. Important to manage the public's perception.
- Importance of conducting **geotechnical investigations** during the planning and design phases of the tunnel system. This helps mitigate risks during the tunnel's specification and construction contract writing.
- Tunnels asset management, reliability and redundancy studies are crucial to record and keep for operations staff.
- **Tunnel access** is a necessity for future inspections and maintenance.
- **Corrosion protection for tunnel liners**, mechanical components, etc. are important. But tunnel liners can fail due to aging, loading, pressures, or other factors.
- Transient flows and surges in deep tunnels and avoidance of geysering.
- Energy use with deep tunnel pump stations should be optimized based on evaluation of both gravity and siphon flow modes.

- **Odor management and ventilation is crucial**. Shafts in public places may cause community concerns about "breathing" when there are odors. Have covered shafts in public areas and allow those not in public to "breath".
- Deep tunnel systems are not only for storage, sometimes operational objectives need to be revised and changed to be conveyance tunnels.

While these are just some of the important lessons learned, the following sections continue to highlight useful lessons the participant utilities have learned.

A Tunnel ≠ Zero Overflows

One of the popular myths among communities (and rate payers) is that these large diameter deep tunnel systems will make all the separated and combined sewer overflows disappear. **Managing the public's expectations** of the long-term purpose and significant investment in deep tunnel systems is crucial in planning and operations.

Owners and operators of deep tunnels must understand and address public expectations of deep tunnels. Keeping public informed during all phases of program/project development and garnering public and politicians' support are among keys to success. For example, most local sewer backups and basement flooding are not addressed by deep tunnel systems, however, public perception strongly suggests that they should be after spending millions, if not billions, in these systems.

It is also important to explain that while deep tunnel systems are an excellent way to help store significant amounts of flow during wet-weather events, but sometimes, even with new predictive computer models, weather cannot be predicted and there just isn't enough storage available. Utilities like Milwaukee MSD shared that when full, it can take up to 4-5 days to pump out their deep tunnel system completely. This can be a problem when there are back-to-back storms which cannot be predicted.

Figure 13 -A screenshot of DC Water's TBM, @LadyBirdTBM's Twitter account.

Besides extensive public meetings (like those done at Thames Water in London, England), some utilities take unique approaches to get the public interested and invested in the design and construction of the deep tunnel systems. One example that has recently gained traction is **naming a TBM**. Many utilities have naming competitions and have naming ceremonies as a way to get the community interested and engaged in the construction of the tunnel. DC Water in Washington, DC has even gone as far as having a Twitter account for one of their TBMs, @LadyBirdTBM, to keep the public engaged and up-to-date about the tunnel's progress. It's also a great way to start the conversation about the purpose and importance of the large investment.

On-Boarding and Operations Staff

Once the tunnel is constructed, the process of "starting-up" a tunnel can be a challenge. With a phased-approach, sections of a deep tunnel system can be rolled out at different times. Since a wet-weather event is hard to predict, there were several suggestions for the "roll-out" including:

- Have a **set "start-up" period**, some suggest between 1-3 years to test and check components of the deep tunnel system. Since a wet-weather event cannot always be predicted for a definitive start-up date, by allowing for a period of time to be the "start-up" it allows utilities to test and check the system.
- Deep tunnel system can also be tested by filling the tunnel with plant effluent.
- Unlike the "start-up" of a WRRF, during wet-weather events, flow quality is not consistent.
- You can plan and study for a "start-up", but during the first wet-weather event, you need to collect and analyze as much data as possible.
- There is not much of a manual for starting up a tunnel, since there are not many moving parts. Operators may not have much to learn.
- Have constant feedback between the consulting and operating staff during "start-up" period to ensure that the system is properly working for its intended design.

Utility leaders also stressed the importance of **keeping records**! Tunnels have 100 years plus service life and utilities will go through multiple staff successions and turnovers. Improve overall program, design, construction and operations record-keeping, commissioning, startup, and aftercare practices, including up-to-date Operations and Maintenance (O&M) Manuals and staff training. The records should include warrantees and guarantees.

It was also stressed that since there is **no special operations and maintenance crews** dedicated to operating the tunnels, i.e., controls for diversion structures, gates, valves, etc., any SCADA controls for such should be compliant and consistent with those used at the water reclamation plants and by the trained plant operators. Better yet, all operator interference should be minimized in operations of tunnels to the extent possible.

Other utilities like Milwaukee MSD have **outsourced the operations** of the wastewater system and tunnels except for needed capital improvements and major repairs/rehabilitation. These outsourced contracts are for 5-year cycles after which, the agency has the option to renew the contract. No major concerns were identified in deep tunnels, and they undergo visual inspections at about every 5 to 10 years depending on segments.

When looking at the operation of deep tunnel systems, there were three big take-aways from participants:

- Keep it simple!
- It's a challenge with the changing workforce and retirement, so be sure to keep records and develop a standard of procedures (SOP) if possible.
- There is not a book that explains how to build or operate a great tunnel. Each system is unique!

Tunnels are never "Maintenance Free"

When Singapore PUB began the design of their Phase 2 DTSS project, they wanted to know the condition of their Phase 1 tunnel which had been in operation for 10 years. When asking the operations team how the tunnel looked they were shocked to get the response that this tunnel was "Maintenance Free" and had no access points.

Tunnels are never maintenance free. While deep tunnels have a long service life and are generally reliable, they are never maintenance free, although they can be designed and operated with minimal maintenance. It is important that all future tunnel systems be designed and constructed with **access provisions for tunnel inspections and maintenance**, and if known, for future expansions and connections, etc.

Since access into a tunnel can be difficult, it is also important to keep in mind some of the inspecting and maintenance problems, including:

- **Groundwater inflow/infiltration** into tunnels can vary based on tunnel lining systems and surrounding hydrogeologic conditions. There are no significant cost or operational impacts unless inflows become excessive as to be determined for each case.
- There is **no Pipeline Assessment Certification Program (PACP)** standard for inspecting and identifying defects within a tunnel. Recommend geotechnical and structural engineers be a part of the inspection team.
- Inspecting and maintaining a tunnel is hard, it's even harder when it's underwater. Working under live conditions is difficult, have a plan for **dewatering** and gates to isolate parts of the tunnel and try to coordinate with weather (when possible).
- These are big tunnels, which require **big isolation gates**, be sure that gates and stoplogs are stored properly and accessible.
- Be sure to maintain and test your isolation gates and stop-logs periodically, so that they are easy to install and effective when used.

Figure 14 – High head wheel gates for tunnels. (Photo provided by F. Oksuz)

Tunnel maintenance can also go beyond just the tunnels themselves. **Deep tunnel pump stations** should also have redundancy or backup valves to allow servicing of primary valves and pumps.

What or who's in my Tunnel?

Once on-line, while tunnels may seem "low maintenance", there is always a concern for what or who is in my tunnel?

One of the main concerns for many utilities are floatables, sediment and grit. Utilities noted that f**loatables** (primarily plastic bottles) management at screening facilities are cumbersome and typically require remote or manned access for removal.

While other utilities like Milwaukee MSD shared that during the planning phase of their deep tunnel system, they were very concerned about **solids and sediment control**. This led them to construct an inline solids handling facility. But, since the tunnel has been in use, there has been some sediment depositions in the tunnel, but not enough to warrant removal. Unfortunately, this meant that the entire facility had to be mothballed since the anticipated solids never materialized.

Other utilities like NEORSD in Cleveland, OH shared that sometimes you have to **revise the operational objectives** of the tunnel when not in use. Deep tunnels can be multi-purpose or have alternate use among CSOs, stormwater and dry weather flows, and this should be in mind for design, construction, and operation. This was seen at NEORSD when they changed one of their tunnels, Mill Creek Tunnel, from a wet-weather storage tunnel to a conveyance tunnel after an adjacent CSO interceptor collapsed.

Sometimes, it's not a matter of what, but who is in or near a deep tunnel access shaft. At Singapore PUB they have a surveillance regime to carry out surveillance and inspection to construction site within the vicinity of the tunnel. Since most of the tunnels run along the road and may be affected by future construction activities, Singapore PUB has required specific construction activities to make submission with Construction Impact Assessment Report. It is an offence to carry out specific construction activity within the vicinity of the tunnel without obtaining PUB's approval and an enforcement action, will be dealt with accordingly.

Air Entrapment: Insurance Nightmare

Nothing gets you on the news quite like a geysering manhole (well maybe an SSO or CSO). **Transient flows (waves) and geysering** in tunnels must be addressed. Surges and geysering can result in loss of life and damages to property and installations.

Air entrapment typically occurs at drop shafts and during tunnel filling. Many utilities shared that geysering was a large concern when rolling-out their tunnel. To address both pressure and waves created during wet-weather event utilities suggested:

- Slowing the rate of inflow before pressuring the system
- Installing large diameter **surge shafts**, when able. Surge shafts while useful are not always practical due to the land space needed for construction and surge.
- Incorporating **air vent shafts** into diversion works for controlled release
- Using **deaeration chambers** which are connections above the tunnel invert level to assist draining but also protect vortex drops from geysering.

Figure 15 – Geysering is one of the many concerns utilities have during wet-weather events due to pressure and waves. (Photo provided by F. Oksuz)

Another concern that many utilities have, especially those in densely populated areas, is **odor control**. Drop shafts and pump stations should be properly **ventilated** and installations should be protected against corrosion and corrosive gases, such as hydrogen sulfide emitted in sewage tunnels. While a utility may not get a complaint if a drop shaft is "breathing" when no one is around, it is suggested that drop shafts in public spaces be covered to prevent odor complaints.

Continuing the Conversation: Future Collaborations and Efforts

While this report attempts to cover a wide array of baseline information and characteristics for deep tunnel systems, this is not an all-inclusive list. Many deep tunnel systems have their own unique purpose, regional, regulatory, geographical, political, etc. constraints and considerations that are generally evaluated by scientists and engineers on a case by case basis.

While many topics where covered, more communication between utilities world-wide with deep tunnel systems needs to occur to get a better understanding of the:

PLANNING & DESIGN

- PLANNING OF THE TUNNEL SYSTEMS
- FLOW AND HYDRAULICS
- DESIGNING OF THE TUNNEL SYSTEM
- PUMP STATIONS

CONSTRUCTION & COMMISSIONING

- CONSTRUCTION
- COMISSIONING

OPERATIONS, MONITORING, INSPECTIONS & MAINTENANCE

- OPERATIONS
- MONITORING & INSPECTIONS

RESILIENCE

- RESILIENCE AGAINST POTENTIAL DAMAGES AND FAILURES
- FUTURE EXPANSIONS AND ADAPTABILITY
- OTHER LONG-TERM USE AND LIFE-CYCLE BENEFITS

Through programs like the WRF/WEF **Leaders Innovation Forum for Technology (LIFT)**, we intend to engage utilities in conversations about their existing or future deep tunnels systems to form a dynamic network for future collaboration efforts and information exchange. More specifically, it is our expectation that the LIFT participants will be able to use this outline to share, capture and search for innovations and unique lessons-learned and solutions to problems on deep tunnels and its integrated infrastructure systems in a meaningful way.

The WRF and WEF will continue to collect and share information on innovations and lessons-learned for both systems in operation and those in planning, design, and under construction wherever provided by owners, designers, operators, contractors, and vendors.

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