LARGE WATER CONVEYANCE TUNNELS

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Large Water Tunnel Systems + Many Others

- Chicago Tunnel & Reservoir Plan (TARP)
- Milwaukee CSO/SSO Tunnels
- Singapore PUB Tunnel System (DTSS) Phases I & II
- Lee Tunnel (part of Thames Tideway, London)
- Cleveland (NEORSD) CSO Tunnels
- Hong Kong Harbour Area Treatment System (HATS)
- Indianapolis CSO Tunnels
- Atlanta CSO Tunnels
- St. Louis CSO Tunnels
- Seattle CSO Tunnels
- Portland CSO Tunnels
- Washington DC CSO Tunnels
- Toronto CSO Tunnels
- Dallas Storm Water Tunnel

*Large Tunnel Systems are Common Solutions to Address Environmental and Flooding Concerns*
Tunnels are Long Term & Sustainable Assets

- Tunnels are designed (and operated) with 100 years + service life expectancy
- Most optimum means to convey/consolidate flows without interfering with surface land features, rivers, roadways, railways and utilities
- Gravity conveyance benefits are maximized - no pumping or energy needed except at terminus
- Tunnels are a significant reliable and sustainable fabric of urban living today…and into the future

Tunnels are integral part of water, sewer, and storm/flood management
Best Practices for Planning & Design of Large Water Tunnels

- System Components
- Planning & Design Approach
- Operational Considerations
- Unique Features
Tunnels Program Development / Design Process

Planning & Engineering Design Roadmap

Understand Concepts › Validate How Project Works › Study Feasibility & Alternatives › Optimization & Preliminary Design › Contract Documents

GATHER CRITICAL INPUT
- System-wide
- Hydraulic Modeling & Optimization
- Permitting & Land Constraints
- Geotechnical & Environmental Investigation

Cost Savings & Value Creation Opportunities

Tech Memos & Feasibility Studies

Component Level Analysis

TRIPLE BOTTOM LINE WORKSHOPS

Communications & Consensus with Stakeholders

Establish Systems Operating Strategy

Refinements

Cost Savings & Value Creation Opportunities

Preliminary Design & Packages

Provide Detailed Reliable Cost Estimates/Schedules

OPTIMIZED OPERATIONS

Risk Management & Consensus Building, Stakeholder Interactions

Cost Savings & Value Creation Opportunities
Unique Considerations for Large Water Tunnels

- System Sizing – Hydraulics & Level of Protection
- Flow Management
- Screening and Pump Station Facilities
- Sediment, floatables and scum build up management
- Surges, air management, odor control
- Corrosion protection
- Instrumentation, monitoring and inspections

O&M Considerations Must be at the Forefront of Planning and Design Decisions
Hydraulic Modeling is a Complex Undertaking

- Layout and storage/conveyance sizing of facilities
- Operations strategy (diversions, pumping, gated/ungated controls, etc.)
- Transients / Surge control
- Odor management
- Sediment management
- Future connection, alternative use/operating schemes
Tunnel Sizing and Alignment Selection

- System Hydraulics & Operational Flexibility
- Horizontal/Vertical Alignment Evaluation:
  - Risks (technical, third party, other)
  - Shaft locations
  - Easements
  - Capital and operating costs
  - Geotechnical considerations
  - Community impacts
  - Proximity to sensitive structures
  - Permits
  - Constructability issues

Tunnel alignment and shaft location selections can benefit from innovative tools and solutions in a virtual reality environment.
Laying out Tunnel Alignment to Reduce Costs and Ensure Operational Efficiency

**Critical Alignment Considerations**

- Effectively Relieve Sewer Capacity Problems
  - Evaluated location and number of diversion structures/drop shafts
  - Consolidate sewers
  - Limit drop shafts
  - Limit public disruption
  - Route tunnel near sewer relief need
- Route Tunnel for High Productivity Excavation
  - Maximize straight runs
  - Utilize curves for direction changes
  - Site tunnel in high-quality rock
- Minimize Public Disruption
  - Follow existing right-of-ways
  - Avoid sensitive structures (hospitals, laser eye centers, etc.)
  - Minimize property acquisition needs
  - Site drop shafts in open/available land
- Provide Construction and Operational Flexibility
  - Route tunnel and site shafts to allow tunnel to be constructed and operated in phases
  - Flexible alignment to allow 2 to 4 tunnel construction phases
Vertical Profile Considerations

Geotechnical Investigations and Geotechnical Data & Baseline Reports
Tunnel Flow Concepts

• CSO Tunnel Flow
  - Open channel and full flow
  - Deep - high head pumping required
  - Sediment/grit moved to pump station
  - Can be pressurized, leading to exfiltration
  - Inflow/infiltration possible when not full

• Storm Water Tunnel Flow
  - Exposed Portal or Siphon flow
  - Siphon - no air space thus minimal or no corrosion - if not dewatered
  - Possible sediment/grit handling at large diversions into tunnel
  - Some exfiltration but no infiltration if not dewatered

St. Louis Tunnel Pump Station
Dallas – Mill Creek Tunnel Starter Tunnel
Diversion Works & Drop Shafts Designs Evolved Overtime

Plunge Drop Shaft (Chicago, 1980’s)  Vortex Drop Shaft (Milwaukee, 1990s)
Once an innovation in 2000, the Computational Fluids Dynamic (CFD) modeling is now the standard of practice for sizing and laying out the diversions and drop shafts.
Advancement in computing power allowed CFD modeling virtually to depict and simulate any type of hydraulic structure and check operations criteria (flow, velocity, pressure change, sediment, etc.)

CFD simulations can readily be coupled with and transferred into civil/structural (BIM and ANSYS) models and designs

Physical modeling is still popular

CFD helps to maximize operational efficiency and reliability
Plunge Drop Shafts

Common applications for large volume/diameter diversions and drops - there are many variants that accommodate site/infrastructure layout & constraints
Vortex Drop Shafts

Smaller diameter shafts and footprint, efficient energy dissipation, a widely used type for deep tunnels
Baffle Drop Shafts

- Large diameter shafts
- No dedicated shaft for deaeration

A baffle drop CFD simulation compared to scaled physical model (above)
Sediment/Grit Management in Tunnels

- Excluding - keeping sediments out - as much as possible at the diversion works
- Traditional adoption of a ‘self-cleansing’ velocity
- Tunnel slope management - steep enough to keep sediment moving, typically 0.1 percent or steeper slopes for CSO systems
- Means for flushing and cleaning - pump station operations, flush flows from upstream shafts
- Future access provisions for maintenance and removal of sediments

Sediment deposition modeling can help to assess trouble spots.
Hydraulic Effects of Sediment

• With full suspension (no deposition), “sediment drag” can result in a 4% loss of flow capacity

• With deposition amounting to 5% of conduit diameter, effect of sediment can be typically 20 to 25% loss (if dunes are formed in the bed deposits
  • Vast majority of effect is due to roughness of deposited bed

• Current Best Practice ~2% bed deposit = optimized sediment and hydraulic transport

Operational practices vary in sewer, stormwater, and CSO tunnels for handling of sediment/grit laden flows in tunnels.
Tunnel Flushing Concept - Charleston SC

- Inlet flow
- Downtown Charleston
- Harbor
- Plum Island WWTP

Mass of water to flush the carrier pipe

Hydraulic grade line
Tunnel Flushing Concept - Charleston SC

Charleston CPW, Sewer Flushing, 20-ft Shafts, Ashley Branch

20-foot diameter Terminus Shafts

> 2 fps ~20 min
Floating Debris Management

- Floatables are an important consideration
- If not flushed through the system, they can form a mat on the water surface
- This could interfere with real time control equipment (flow monitoring, etc.)
- Eventually sink during dewatering, and leaving deposits at the tunnel invert
- Mostly caught and removed at screening facilities

Often a seasonal problem due to large amount of leaves entering tunnel

Physical modeling can help to understand floating debris movement
Air Management

- Air entrainment at drop shafts
- Air entrapment during tunnel filling

Air vent shafts are incorporated into diversion works for controlled release.
Why Does Air Entrapment Matter?
Deaeration Chambers

- Connections above tunnel invert level to assist draining but protect vortex drops from geysering.
- Aerated zone confined to upstream end of chamber.

![Diagram](image)

- Inflow = 6.4m³/s (125% \( Q_{des} \))
- Water volume fraction: Dark blue = Water (non-aerated), Pink = highly aerated, Grey = Air
- 0.75mm bubbles
- 1.0 to 15mm bubbles

Plots show trajectory of bubble introduced directly beneath vortex tube.
H&H modeling (InfoWorks, SWMM5) and CFD simulation of City of Toronto, Coxwell Tunnel fill cycle for evaluation of transient flows and air entrainment (Black & Veatch, 2017)
Caution using below grade installations in areas prone to flooding

Carbon treatment is common for both passive and active odor control
Unique Tunnel Features – Live Connection to Existing Tunnel

- Optimized for hydraulics to manage large flows (30,000 cfs) and velocities (up to 35 fps)
- Live connection to TARP tunnel

Maximum velocity = 48 fps
Tunnel Connection Constructability Considerations

- Flat top maximizes the height of the profile across the connection section and flow from Mainstream Tunnel is forced downwards.
- Reducing height, but increasing width results in a flare for a smoother turning of flow into the Tunnel Connection.
Tunnel Gates Design – CFD Modeling + Structural Modeling

• High head wheel gates for tunnels are unique to Chicago (three gate systems are installed and in operation, fourth is under construction)

• McCook Gates - total of six (6) 29-ft high x 14.5-ft wide wheel gates inside 88-ft dia. shaft and bifurcated tunnel

• Operates under up to 300 feet of pressure head
Complex Tunnel Lining - High Strength Concrete and Steel Liners

Applicable to areas of high flow velocities and cavitation concerns

Chicago – McCook Main Tunnel System Steel Lined Bifurcation
CFD to Structural (ANSYS) Modeling

CFD 3D models are transported directly into 3D CAD and ANSYS for structural analysis and design of gate components.
High Head Wheel Gates for Tunnels

Factory Acceptance Tests for McCook Gates

Large gates allow for hydraulic controls in tunnels, systems operations and storage optimization, and maintenance of reservoirs and tunnels.
Screening Facilities
Other Lessons-Learned in Deep Water Tunnels in Operation

- Community relations and public’s perception, e.g., new tunnels do not equal no CSOs
- Comprehensive geotechnical investigations to mitigate risks
- Tunnel access is a necessity for future inspections and maintenance
- Corrosion protection for tunnel liners, mechanical components, etc. are important but inspections required due to damage/failures
- Optimize energy use with deep tunnel pump stations
- Transient flows and surges in deep tunnels can cause damage
- Odor management and ventilation - shafts in public places can cause major community concerns
- Startup and commissioning period, onboarding and training O&M staff
- Strategy for floatables and debris management
- Deep tunnel systems operational objectives maybe revised and changed to serve as both conveyance and storage tunnels

* Based on feedback from five major deep tunnel system owners/operators
Any Questions?