GLOBAL DEEP TUNNEL CONVEYANCE & STORAGE SYSTEMS

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BUILDING A WORLD OF DIFFERENCE®
SCIENCE & TECHNOLOGY OF DEEP TUNNELS

- Innovations on methods and tools for design, construction, and operations of tunnels and integrated facilities
- Ways to improve level of service, efficiency, and resilience
- Advancements in technology for engineering, tunnels excavation and lining, and other mechanical, electrical, instrumentation, control and automation (MEICA) components
- Other unique ideas & concepts for future considerations
- Lessons-learned on deep tunnels in:

CHICAGO - SINGAPORE - MILWAUKEE - LONDON - CLEVELAND
Global Deep Tunnels + many others

- **Chicago Tunnel and Reservoir Plan (TARP)** *
- **Milwaukee Deep Tunnel** *
- **Singapore PUB Deep Tunnel Systems (DTSS) Phases I & II** *
- **Lee Tunnel (part of Thames Tideway, London)** *
- **Cleveland Deep Tunnel** *
- **Hong Kong Harbour Area Treatment System (HATS)**
- **New York City DEP Deep Tunnels for Water**

- **Paris TIMA**
- **Atlanta Deep Tunnel**
- **St. Louis Deep Tunnel**
- **Charleston, SC Deep Tunnel**
- **Seattle Deep Tunnel**
- **Portland Deep Tunnel**
- **Pittsburgh Alcosan Dry Weather Flow Tunnel (program underway)**
- **Toronto Deep Tunnel (program underway)**

*Deep tunnel systems that were represented at the WRF April 12, 2018 Deep Tunnel Workshop*
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 significant, and surely the most reliable and sustainable fabric of urban living today… and into the future

Tunnels are integral part of water, sewer, storm/flood management, transportation, utility and physics infrastructure for now and into the future - i.e., Hyperloop
Tunnels are Integrated Infrastructure Systems

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

Tunnels must be planned out holistically, but can be built out in multiple phases
BEST PRACTICES - PLANNING & DESIGN

System Components & Operations
Design Approach
Risk Management / Cost Estimating
Construction
Unique Features
Key Performance Indicators (KPIs)

- Safe, Constructible and Operable Systems
- Risks are Well Managed
- Meet Owner’s Primary Delivery Expectations:
  - Quality
  - Cost effective and within budget
  - On time
  - Regulatory compliant
  - Neighborhood friendly
- Cost Savings Through:
  - Innovative ideas
  - Flexibilities in means and methods (early contractor involvement)
  - Accelerated Delivery
- Smooth Startup & Commissioning
- Systems Reliability and Redundancy
- Transfer of Warrantees & Guarantees

KPI’s apply to all projects, not just deep tunnels.
Tunnels Program Development / Design Process

Planning & Preliminary Engineering Approach

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

Tech Memos & Feasibility Studies → OPTIMIZED OPERATIONS

Component Level Multi-Criteria Analyses → TRIPLE BOTTOM LINE WORKSHOPS

Communications & Consensus With Stakeholders → Contract Documents

Cost Savings & Value Creation Opportunities

Refinements → Provide Detailed Reliable Cost Estimates/Schedules

Risk Management & Consensus Building, Stakeholder Interactions
Key Operations & Maintenance Provisions for Tunnels

- System Sizing
- Flow Management and Equalization
- Screening and Pump Station Facilities
- Sediment, floatables and scum build up management
- Surges, air management, odor control
- Corrosion prevention
- Instrumentation, monitoring and inspections

Use of Asset Management Practices for Long Term Maintenance is Innovative
Deep Tunnel System Overview - CSO System

- CSO to Tunnel
- Rivers / Lakes
- CSO Outfall
- Storage / Conveyance Tunnel
- Drop Shafts
- Consolidation
- Sewer
- Regulators
- Wet Weather
- Combined Sewer To WRP
- WRP
- Combined Flow to WRP and Tunnel
- Retrieval Shaft
- Deep Tunnel System Overview - CSO System
- CSO to Tunnel
- Working Shaft
- Deep Tunnel Pump Station to WRP
- Consolidation Sewer
- BEDROCK
- SOILS
- Rivers / Lakes
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
  - Tunneling under rivers, wetlands, etc.
  - 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
- Route Tunnel for High Productivity Excavation
- Minimize Public Disruption
- Provide Construction and Operational Flexibility

Evaluation and Optimization Plan
- Evaluated location and number of diversion structures/drop shafts
  - Consolidate sewers
  - Limit drop shafts
  - Limit public disruption
  - Route tunnel near sewer relief need
- Maximize straight runs
- Utilize curves for direction changes
- Site tunnel in high-quality rock
- Follow existing right-of-ways
- Avoid sensitive structures (hospitals, laser eye centers, etc.)
- Minimize property acquisition needs
- Site drop shafts in open/available land
- 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
Conveyance Tunnels – Detailed Design Elements

- Systems operations, instrumentation, and monitoring requirements
- Hydraulics and operational controls
- Geologic and geotechnical considerations
- Environmental and groundwater conditions
- Tunneling methods, TBMs, and tunnel permanent lining
- Initial ground support
- Community impacts mitigation, permits, etc.
- Risk, constructability, cost, schedule
- Diversion works and drop shafts
- Commissioning and startup

Blacksnake Tunnel, Columbus Ohio
Geology & Geotechnical Considerations

Geotechnical Investigations and Geotechnical Data & Baseline Reports
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
- Instrumentation and Control
- Future connection, alternative use/operating schemes
Hydraulics Modeling - “Lynchpin” for System Optimization

The model will guide size of investments and operations for maximum benefits.
Gravity vs. Siphon Flow Concepts

• Gravity Flow Tunnel
  • Mostly open channel (partial full) flow
  • Deep - high head pumping Required
  • Air space in tunnel leading corrosion
  • Sediment/grit moved to pump station
  • Not pressurized, minimal exfiltration
  • Inflow/infiltration possible

• Siphon Tunnel
  • Siphon (full-tunnel) flow
  • No pumping or Low Head Pumping
  • No air space – thus minimal or no corrosion
  • Possible sediment/grit handling at large diversions into tunnel
  • Some exfiltration, but no infiltration

Siphon tunnels may require larger diameter tunnels. Energy efficiency is through elimination or low head pumping and cutting off infiltration volume.
Diversion Works & Drop Shafts Designs Evolved Over Time

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.
CFD Modeling of Diversions & 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 up to 30 ft - 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 deaeration

A baffle drop CFD simulation compared to scaled physical model (above)
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)
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 0.15 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 due to energy required to convey sediment along the invert.

• 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)
  • Loss of flow section alone would cause less than 3% loss
  • Vast majority of effect is due to roughness of deposited bed

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

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

Inlet flow

Downtown Charleston

Mass of water to flush the carrier pipe

Hydraulic grade line

Harbor

Plum Island WWTP

WWTP
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 into tunnels.
Air Management

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

Air vent shafts are incorporated into diversion works for controlled release.
Deaeration Chambers

• Connections above tunnel invert level to assist draining but protect vortex drops from geysering.

• Aerated zone confined to upstream end of chamber.
Why Does Air Entrapment Matter?
Odor Control at Drop Shafts

Caution using below grade installations in areas prone to flooding

Carbon treatment is common for both passive and active odor control, Charleston, SC
Drop Structure & Air Jumper – Singapore DTTS Phase 2

- Negative pressure in tunnel may not be sufficient to pull incoming air from link sewers.
- Air Jumper forces air into tunnel
Tunnel Lining Design - UDEC (Universal Distinct Element Code)

• Two dimensional numerical program based on the distinct element method for discontinuum modeling.
• UDEC simulates the response of soils and discontinuous rock mass subjected to either static or dynamic loading
• Influence of water pressure
• Cohesion and friction of intact soil/rock and discontinuities.
• Shear strength of planar and rough surfaces, filled joints, faults, etc.

Successfully used for many tunnel permanent support and lining systems.
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 while existing TARP tunnel is kept in service
- 16.5 ft radius sides allows smooth transition to cross-section of 33 ft diameter Mainstream Tunnel
- Flat top maximizes the height of the profile across the connection section and flow from Mainstream Tunnel is forced downwards
- Reducing the height, but increasing the width results in a flare for a smoother turning of the flow into the Main Tunnel and Reservoir
Mainstream Tunnel Connection - Elliptical Mitre

Maximum velocity = 48 fps
Minimum absolute pressure = 0.6 atm

Velocity on central plane

Region with sub-atmospheric pressure

Note separation of flow at 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 psi pressure

• Separate design, fabrication, and installation contracts
CFD 3D models are transported directly into 3D CAD and ANSYS for structural analysis and design of gate components.
3D & BIM Renderings

3D BIM is supplemented with 3D printing and physical models
Deep Tunnel Pump Station Examples

Submersible Pump Station
Cutaway from 3D Model

Outboard Wetwell
Cutaway from 3D Model

Cavern Pump Station
Cutaway from 3D Model

Horizontal Split Case

Vertical End Suction

Partial Cavern View
Screening Facilities
ADVANCEMENT IN CONSTRUCTION METHODS AND TUNNEL LINING MATERIALS
TUNNELING METHODS

<table>
<thead>
<tr>
<th>Early TBMs</th>
<th>Modern TBMs/EPBMss</th>
<th>Drill/Blast Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest Relief Tunnel MMSD, Milwaukee, WI</td>
<td>OARS Scioto River Tunnel Columbus, OH</td>
<td>McCook Main Tunnel, Chicago IL</td>
</tr>
</tbody>
</table>

**ADVANTAGES**

- Conventional, favorable ground conditions
- Soft/hard ground, high groundwater, gas, difficult formations
- Shorter tunnels

Tunnel Boring Machines (TBMs) and excavation and lining methods have significantly advanced over the past two decades.
Advancements in Tunnels Construction

- Accurate estimating of TBM/EPBM advance rates and costs - more history on state-of-the-art TBMs
- Advancement in slurry TBM technologies and tunnel lining systems (Columbus OARS Tunnel)
  - Open and closed mode operations to effectively manage variable (mixed) ground conditions
  - Composite segments and high pressure grouting behind segments (improvements to TBM brush seals)
- Variable drive and larger diameter TBM cutterheads with less frequent need for “interventions” to replace cutters
- Tighter turn radius

Fully shielded and pressurized slurry TBMs

Columbus OARS Tunnel MixShield EPBM - the most advanced slurry TBM and segment erection technology by Herrenknecht (2016)
TBM Technology Advancements

• 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
• The behavior of ground types is better understood
• The work force and technical support are experienced
• Owners and contractors aim for less risk and expect more out of TBMs.

TBMs are still benefiting from continuous technological advancements

Larger diameter TBMs are now much more reliable in handling difficult ground conditions
Shafts Construction Methods

Excavation and support methods must be compatible with site and ground conditions while controlling groundwater inflow, subsidence, environmental concerns, final support and finishes, etc.

Shaft support methods include:

- Caisson Sinking
- Ribs and lagging (with stiffners)
- Gasketed Sheet Pile
- Ground Freezing
- Secant Piles
- Drilled shafts (top down and bottom up)
- Drill-and-blast in lifts
- Pre-excision grouting
Shafts Construction Methods

TOP DOWN DRILLING – UP TO 15 FT DIAMETER

BOTTOM-UP DRILLING OR RAISE BORING
Tunnel Lining Systems

- **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
  - EPDM (ethylene polythene diene monomer) composite gaskets

- **Steel Lining with Corrosion Protection** - cathodic protection, metalizing, etc.

- **CombiSegments**

- **Other common (and past) solutions**
  - Cast-in-place concrete (reinforced/unreinforced)
  - Corrosion Protection Liners (CPLs) (or corrosion resistant internal lining)
    - HDPE & PVC liners, resistant liner plates
    - Sacrificial concrete (mortar lining)
    - Sprayed on membranes (not good experience)

- **Pipe in Tunnels (mostly pressure flow)**
  - FRP Pipe (Hobas, Flowtite)
  - Polymer concrete pipe
  - T-Lock lined RCP
  - PCCP

Pre Cast segments are becoming cost-competitive vs. cast-in-place liners
Polymer Fiber Reinforced Precast Segments

Cost of segmental lining has become more competitive over the past 5 years.
Advanced Tunnel Lining - CombiSegments

- **Inliner**: pDCPD (poly-dicyclopentadiene)
- **Gasket**: EPDM, mechanical integrated in the inliner (overmoulded)

**Inliner quality**
- Compared to GRP, easier handling during segment production
- pDCPD inliners are not brittle, high resistance against abrasion
- Durability: Withstands very aggressive media
- Chemical resistance is already proofed by various material test
- Fast, because coating is done during lining (no welding, etc.)

Singapore PUB DTSS II
Complex Tunnel Lining - High Strength Concrete and Steel Liners

Applicable to areas of high flow velocities and cavitation concerns
Large gates allow for hydraulic controls in tunnels, systems operations and storage optimization, and maintenance of reservoirs and tunnels.
Roller Gates

- Modular Gate System
- Working Platform
- Link Sewer
- Gate System (Assembled & Lowered)
- Tunnel

Gate Module

ISOMETRIC VIEW

GATE PANEL ASSEMBLY

SHAFT STRUCTURE (BASE)

Gate System

Singapore PUB DTSS II
RISK & COST MANAGEMENT APPROACH

Risk Register
Stochastic (probabilistic) Cost Estimating
Alternative Project Delivery
Approach to Risk Identification and Mitigation

- Industry/Region’s (owners, designers, and contractors) Perspective on Risk Management
- Risk Register
- Geotechnical Baseline Report
- Contract Documents (plans and specifications)
- Escrow Documents
- Disputes Review Board
- Construction Management Support

BALANCE RISK AND VALUE

- Tunneling and ground conditions risks
- Contractual, technical, community concerns, political, operations, third-party, funding, etc.
- Begins at planning
- Has the right leadership and experts

Iterative Risk Analysis Process at Every Step of Project

STEPS
- Risk Registry
- Ranking and Probabilities
- Mitigation When Possible
- Cost Evaluation
- Risk Apportionment
- Develop Contract Contingencies
Risk Management Strategy

- Safety
- Design
- Environmental
- Construction
- Operation
- Third-Party

**RISKS**

- Establish the Context and Risk Register
- Identify Risks
- Analyze & Quantify Risks and Consequences
- Identify Mitigation Options
- Monitor, Review, Report
- Avoid & Mitigate Risks

**Flowchart**

1. Start
2. Identify Risks
3. Assess Risks
   - Quantify
   - Rank
4. Identify Control Measures
   - Mitigation
   - Management
   - Control
5. Implement Control Measures
6. Monitor
7. Review Option
   - Is Residual Risk Acceptable?
     - No
     - Yes
     - Update risk register
Tunnels Baseline - Risk Management
**Sample Risk Register**

### AREA 4 TUNNEL - PHASE I DESIGN - SAMPLE RISK REGISTER

(Risk Management Plan and Risk Register will continuously be updated and shared with CDWM)

<table>
<thead>
<tr>
<th>Entered By</th>
<th>Hazard ID</th>
<th>Hazard</th>
<th>Cause of Hazard</th>
<th>Potential Consequences</th>
<th>Risk Consequence*</th>
<th>Control Measures Implemented</th>
<th>Action Item for Risk Mitigation</th>
<th>Risk Owner (Entity or Name)</th>
<th>Action Item Completion (Target Date)</th>
<th>Residual Likelihood</th>
<th>Mitigation Strategies and Actions</th>
<th>Residual Consequence - Once Implemented</th>
<th>Residual Consequence - Once Effective</th>
<th>Residual Risk Score - Once Effective</th>
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<td>Safety and Security</td>
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<td>Compliance with safety and public safety hazards</td>
<td>Unexpected, no safety plans in place</td>
<td>Accidents, damage to facilities</td>
<td>2 3 3 4 5</td>
<td>Mandate safety plans, hazard analysis, job safety plans</td>
<td>Management commitment, prepare safety plans, train, monitoring, and safety actions</td>
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<td>Violate local or city by-law</td>
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### Consequence Rating

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### Probability Rating

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### Risk Consequence Table

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<td>High</td>
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<tr>
<td>5</td>
<td>Very High</td>
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### Example

- **Risk Consequence**: 1 (Very Low)
- **Probability Rating**: 1 (Probable)
- **Consequence Rating**: Low (2)

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### Additional Information

- **Risk Mitigation Strategies** include detailed actions and responsibilities.
- **Risk Register** is continuously updated and shared with CDWM.
Tunnel Cost Analysis

Benchmarking to Other Projects:

- References to cost curves developed with more than 200 tunnel projects bid and completed over the past 20 years
- Adjusted for local conditions – urban setting, cost of labor, materials, delivery, tunnel rock/spoil disposal, access, working hours, etc.
- Cost of unusual diversion works, shafts, gates, pump stations, etc. can skew per foot/dia. estimates.
Stochastic Cost Estimating Verification Approach (Black & Veatch)

1. **Deterministic Estimate**

2. **Identify Assumptions to Apply Distributions**

3. **Develop Distributions**

4. **Define Cost Correlations**

5. **Perform Monte Carlo Simulation**

6. **Generate & Review Results**

### Summary

- **General Requirements**: $1,500,000
- **Main Tunnel**: $47,900,000
- **Working Shaft**: $10,500,000
- **Retrieval Shaft**: $5,000,000
- **Deep Pump Station at Zorn Avenue**: $15,300,000
- **Near-Surface Transmission Mains**: $800,000
- **Collector Wells**: $42,100,000
- **Land Acquisition, Easements, and Maintenance of Traffic**: $2,100,000

**Subtotal Probable Construction Cost**: $125,200,000

- **Contingencies (20%)**: $25,100,000

**TOTAL Probable Construction Cost**: $150,300,000

- **Professional Services (20%)**: $30,100,000

**TOTAL Probable Project Cost**: $180,400,000

**150 MGD Deep Tunnel Zorn Avenue Alternative**
Tunnel Stochastic Estimating Results

Mean Capital Cost of $172 Million with +/- $10 Million (P10 to P90 range, 80% of results)

Linear Section of ‘S-Curve’ (80% of Results)
Tunnels Project Delivery Options

- Design-Build (lowest lump sum bid) and Progressive Design-Build
- Third Party Program Management and Construction Management (PM/CM)
- Construction Management at Risk (CMAR)
- Design-Build-Operate-Finance (DBOF)
- Design-Build-Operate/Maintain-Transfer (DBOT)
- Public Private Partnership (PPP)
- Alliance Contracting
- Others

Owners want flexibility - custom variations such as best value selection, are also used as alternative procurement though projects are delivered using traditional design-bid-build delivery.

Alternative delivery is intended to bridge gap between the Owner and Contractor during procurement.

McCook Tunnel Project above was awarded based on “best-value” selection.
Primary delivery mode is “traditional” in the U.S., “design-build” elsewhere.

Progressive design-build is catching on.

O/E, PrM, PM/CM options are being widely implemented.
Project Delivery Approach and Gateways – Decision for Alternative Delivery

**Stage 1 – Initiation**
- Program Objectives
- Program Organization
- Program Controls (budget, schedule, documentation, information technology, communications)
- Safety
- Stakeholders
- Risk Management
- Quality
- Environmental Management
- Sustainability
- Regulatory
- Technical Integrity Panel
- Legal
- Financial
- Operations
- Contract Packaging Strategy
- Delivery Options

**Stage 2 – Feasibility**
- Facilities Layout
- Investigations
- P&I D
- Alternatives Definition
- Alternatives Selection
- FEED
- Performance Specs
- Cost Estimates
- Schedule
- Value Analysis, Constructability Review
- Preliminary Engineering
- Guidance Documents and SOPs for Engineering and Construction
- Market Conditions

**Stage 3 – Execution**
- Design
- Design and Design-Build Contracts
- Construction
- CM and RE Roles
- Contractor VE Proposals
- Chartering
- Award / Penalty Criteria
- Performance Management

**Stage 4 – Operations**
- Substantial Completion
- Testing and Startups
- Commissioning
- O&M Manuals
- Training
- Warranty Transfers
- Facilities Acceptance and Turnover
- Project Records
- Project Awards

**Gateway 1** – Program Management Strategy and Implementation

**Gateway 2** – Program Components, Delivery, Design Liability, Procurement and Execution Strategy, Safety, Budget, Schedule, Operations, and Quality Criteria and Performance Metrics are Established.

**Gateway 3** – Compliant Facilities Construction Using Various Procurement Methods, Assurances to Meet Design and Operations Intent and Criteria, Implement Project Controls and Documentation

Owner Determines Gateways - Critical Project Milestone Accomplishments

1. Gateway 1 – Program Management Strategy and Implementation
Innovation in Deep Tunnel Systems – Fiber Optic Monitoring

• Fiber Optics for Tunnel Monitoring & Communications
  • Distributed fiber optic sensing (strain and temperature) and monitoring of liner integrity, in response to movements (settlement & earthquakes) and leakages, etc.
  • Transmitting operations & communications data (flow, velocity, metering, gated controls, security, etc.) - widely used in oil & gas industry

Fiber optics can be successfully are embedded in tunnel liners or installed in a conduit
Tunnel Inspections Using Remotely Operating Vehicles (ROVs)

- Floating and crawling ROVs with tethering - chosen based on water depth, flow velocity, data needs and accuracy, distance, etc.

- Inspections done remotely through shaft access/hatches without need to dewater tunnel

- Up to 10,000 ft tunnel length is within tethered ROV capabilities (and it is increasing)

- Good for periodic inspections, especially hydraulic capacity is diminishing after flushing

- Collects HD CCTV, sonar (acoustic), and 2D/3D laser scanned data

- Safer than personnel entry

- Drones are being introduced gradually

ROV technology continues to advance rapidly - Autonomous Underwater Vehicles or AUVs are gaining wider applications in long and pressurized water transmission tunnels

Photos: Courtesy of Redzone Robotics, ASI Marine
Life-cycle Analysis and O&M Strategies

- Risk-based Asset Management and O&M Strategies
  - Predictive
  - Economic-based
  - Condition monitoring
  - Run to failure
- Prioritization to maximize benefits of scheduled O&M activities
- Proper allocation of funds and cost savings
- Avoiding emergencies

Vulnerability & risk-based asset assessment can reveal O&M best management practices
Other Lessons-Learned* in Deep Tunnels in Operation

• Community relations and public’s perception, e.g., new tunnels do not equal no CSOs
• Comprehensive geotechnical investigations to mitigate risks
• Asset management and record keeping practices are crucial for reliability and redundancy
• Tunnel access is a necessity for future inspections and maintenance
• Corrosion protection for tunnel liners, mechanical components, etc. are important but tunnel liners will fail due to aging, loading, pressures, or other factors
• 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
KEY TAKE AWAYS

• Deep Tunnels = Integrated Infrastructure
• Hydraulics, geotechnical, operations, community
• Significant technology & materials advancements in TBMs and tunnel lining systems
• Innovative practices in Design, Construction, Instrumentation, Monitoring, Inspections
• Tunnels are significant, and surely the most reliable and sustainable fabric of urban living today and tomorrow
Thank You – Questions & Answers