Design of Concrete Lined Tunnels in Rock

CUP McCook Reservoir – Distribution Tunnels Contract

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Outline of Presentation

- General Project overview – McCook Reservoir Project
- Overview of Distribution Tunnels Contract
- Design of Circular Tunnel Lining on Distribution Tunnels Contract
- Design of Concrete Bifurcations on Distribution Tunnels Contract
- Overview of Steel Liner Design on Distribution Tunnels Contract
McCook Reservoir Project
Overall Goal – Control Flooding and Keep CSO Out of Lakes and Rivers!
McCook Reservoir

- Estimated cost $520 million
- Provides flood control between Des Plaines River and Chicago Sanitary and Ship Canal
- Excavation of reservoir will be by Drill and Blast (Quarrying)
- Captures CSO’s from Chicago and 37 suburbs
- Provides > 10 billion gallons of storage
- Scheduled Project Completion - FY 2012
Reservoir Project

Location of Distribution Tunnels
Distribution Tunnels
Contract
Distribution Tunnels Contract

- **LS:** Metropolitan Water Reclamation District of Chicago (MWRD)

- **Designer:** Montgomery Watson Harza

- **Construction Contractor:** Kenny Construction

- **Gate Designer:** INCA (sub to Kenny)

- **Steel Liner Fabricator:** CBI (sub to Kenny)
Purpose of Distribution Tunnels

- Convey and Distribute CSO’s between the new Reservoir and the existing TARP Pump Stations and Tunnels
Plan – Distribution Tunnels

- **Tunnel “C”**: 1500 ft, 11.5’ DIA
- **Tunnel “E”**: 600 ft, 8.5’ DIA
- **Tunnel “F”**: 200 ft, 8.5’ DIA
- **Tunnel “D”**: 1600 ft, 11.5’ DIA

- **Distribution Chamber**: 100’x60’
- **Access Shaft**: 26’ DIA
- **25’ Long Rock Plug**

**Bifurcations**

- **TO INFLOW/OUTFLOW STRUCTURE AND FUTURE RESERVOIR**
Distribution Chamber
Bonneted Slide Gates – 5’ x 5’
Total contract $60 million
Completed 85%
Anticipated Completion Date: Jan 2006
Design of Circular Tunnel Lining
Tunnels and Shafts in Rock
Tunnels General

- 3100 Lineal Feet of 11.5’ DIA. Tunnel
- 800 Lineal Feet of 8.5’ DIA. Tunnel

- Approximately 310’ below grade

- Excavation by Drill and Blast - Creating a horseshoe shaped excavation
Rock Dowels

Tunnel Excavation – Drill and Blast
Final Tunnel cross sections are Circular except at bifurcations.

- At bifurcations cross sections are oblong or vary between circular and oblong.
Reinforced and Concrete Lined

Typical Tunnel Cross Section

B - B
TUNNEL CROSS SECTION
SCALE: 1/4" = 1'-0"
Why Reinforced?

- Most of the Chicago TARP tunnels are not reinforced because;

  - Exfiltration is not a concern since external pressures from ground water exceed internal pressures.
On Distribution tunnels reinforcement is provided because:

- The proximity of the reservoir draws groundwater down allowing exfiltration
Hydraulic Design Considerations

- Velocities > 100 fps can occur around gates and valves in tunnels – those areas are steel lined and backed with 6000 psi concrete

- Tunnel C and D are low velocity gravity – 4000 psi concrete
Design Loads
Circular Tunnel Liners

- **Internal Pressures**
  
  Max Hydraulic Dynamic Pressure of 160 psi

- **External Pressure**
  
  Hydrostatic Load from Ground Water
  
  head = 310 ft or 132 to 134 psi
Key Design Assumptions

- All rock loads are assumed to be fully supported by permanent rock dowels. No rock loads to the liner.

- Relaxation of the rock and stress redistribution is assumed to occur prior to installation of the lining.
Crack Width Limitation
(Internal Pressure Design)

- Crack Width Limited to .008” for water tightness
- Tensile stresses in the reinforcing are limited to limit the crack width.
Materials

- **Concrete strength:**
  - 4000 psi in tunnels
  - 6000 psi around steel liners
  - 10,000 psi at concrete bifurcation

- **Reinforcing:**
  - ASTM A615, GR 60
Tunnel Lining is analyzed for Internal External pressure
External Pressure Design Procedure

1. Determine and apply external pressures:
   132 psi for 11.5’ diameter tunnels

2. Determine Load Case(s):
   1.1 D + 1.4 H (EM 2901, Table 9-1)

3. Model tunnel Lining using STAAD

4. Design Concrete for Hoop Compression
Tunnel Lining modeled with beam elements

STAAD FE Model

72 Beam Elements
Rock Modeled With truss elements

Analyses is iterative where any truss element developing tension is released until the liner is supported only by compression elements.

Radial spring Stiffness assigned Per Equation 9-18, EM 2901.

STAAD Model
STAAD Model

External Pressure Load 132 psi
Results – External Pressure Design

- Primary Load is hoop compression

\[ Pu = 164 \text{ K/FT} \quad \text{for 11.5’ Tunnels} \]

- Moments and Shears are negligible
Internal Pressure Design Procedure

1. Determine and apply internal pressures:
   160 psi ............. 11.5’ diameter tunnels

2. Determine Load Case(s):
   1.1 D + 1.4 H (EM 2901)

3. Model the tunnel using Program “TUNNEL” developed by MWH.

4. Design Reinf. to Limit crack width to .008”
1. Surrounding Rock Mass was modeled as a thick walled cylinder

2. Deformation properties of the concrete lining and sound and fissured rock were modeled.

3. Strain compatibility was performed to determine % of load carried by the rock and the lining.
Rock Properties (Internal Pressure Design)

- A 40” ring of fissured rock was modeled – due to drill and blast excavations.
- Then, sound rock was modeled beyond the fissured zone

Fissured Rock (grouted) ……Erock = 480,000 psi

Sound Rock ……………………Erock = 1,300,000 psi
Results

(Internal Pressure Design)

- Primary Load was tensile stress in the Concrete.

  Maximum Tensile Stress = 600 psi

- Reinforcement was sized to limit crack width to .008 inches

- Resulted in #6 @12 inches
Rock Dowels

Setting Forms
Window in Forms for Concrete Placement
Design of Concrete Bifurcations
Concrete Bifurcation
Plan of Concrete Bifurcation
Hydraulic Design Consideration

- Concrete Bifurcation is subjected to moderate turbulence - 10,000 psi concrete
External Pressure Design

- Designed for external pressure of 136 psi
- External Pressures are resisted by the use of rock anchors on all sides - necessary due to non-circular shape
- Concrete sections are designed per ACI 318.
Internal Pressure Design

- Designed for internal pressure of 160 psi
- SAP 2000 was used for the Analyses to include the effects of the surrounding rock mass. Similar to tunnel design.
- Concrete designed for watertightness and allowable crack width of .008 inches
Maximum Stresses – (Internal Pressure)

Maximum tension stress in x-direction

Maximum tension stress in y-direction
Overview of Steel Liner Design
Steel Liners Located at Distribution Chamber
Purpose of Steel Liners

- Provide erosion protection in areas around Distribution Chamber
  - Velocities > 100 fps
- Form the bifurcation geometry
Design of Steel Liners

- Designed for internal and external pressures
- Circular Section designed per EM 2901 Section 9-5d.
- ASME Pressure Vessel Code, Section VIII used for design of noncircular sections
- Stiffeners are provided on obround liner sections to resist buckling
- In areas of geometric discontinuities, 3-D STAAD Model used to design the cross sections.
Steel Nosing being lowered into 26’ dia. Access shaft
View From Inside Steel Liner
Positioning Steel Nosing
Thank You
Machine-bored Tunnel
(the new way)
Intersection of Machine-bored Tunnels

1/20/2000
TUNNEL BORING MACHINE
27-ft Diameter Machine-bored Tunnel – Before Lining
Placing Concrete for Tunnel Lining