Design and Construction of the SEM Cavern on LA Metro’s Regional Connector Transit Corridor Project

Carlos Herranz, PMP, PE, M.ASCE
Mott MacDonald Spain
1. Project Overview
2. SEM Cavern Design
3. SEM Cavern Seismic Analysis
4. SEM Cavern Construction
5. Conclusions
Project Overview

Regional Connector Transit Corridor Project (RCTC)

- 1.0 mi. twin bored tunnels
- 0.7 mi. cut-and-cover tunnels
- 3 cut-and-cover stations
- 0.2 mi. of at-grade alignment

Location map of RCTC twin bore alignment with stations and crossover cavern
Project Overview

BIM

Building Information Modeling (BIM)

* A digital representation of physical and functional characteristics of a facility ..... 

The US National Building Information Model Standard Project Committee

BIM is also a philosophy, with a central tenet being that all work is performed in a common data environment, which enhances workflows and coordination and allows for improved:

- Design
- Visualization
- Quality Control
SEM Cavern Design
Cavern Location and Ground Conditions

Site 3D view

Site cross section
SEM Cavern Design
Cavern shape and layout

Preliminary Engineering layout (By Others)

Detailed Design layout
SEM Cavern Design

Excavated Dimensions
56.1ft x 36.1ft x 289ft

Overburden
≈45ft

Temporary Lining
12 in 5000 psi SFRS

Waterproofing
HDPE (potent. gassy)

Permanent Lining
18 in 4000 psi CIP

Concrete

2nd / Broadway Station and SEM cavern HDPE placement
SEM Cavern Design
Displacements Limits and Surrounding Structures

a. Allowable Settlement/Heave for buildings, facilities, utilities, and other structures:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Action Level</th>
<th>Maximum Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Distortion*</td>
<td>1/1000</td>
<td>1/600</td>
</tr>
<tr>
<td>Total Settlement/Heave (in.)</td>
<td>0.25</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*Average settlement slope of slope between building walls or columns which ever less.

b. Allowable Settlement/Heave above each tunnel measured by MPBX

<table>
<thead>
<tr>
<th>Location</th>
<th>Action Level (in.)</th>
<th>Maximum Level (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 ft. above tunnel</td>
<td>0.5</td>
<td>0.75</td>
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Settlement Criteria

LAPD Headquarters (RC 434)  
Retail & Cityside FCU (RC-435)  
Higgins Building (RC-436)
SEM Cavern Design
Drift Configuration

Detailed design drift configuration - Base case

Detailed design drift configuration - Resequencing
SEM Cavern Design

Drift Configuration

Slide drift construction sequence – Longitudinal profile

Center drift construction sequence – Longitudinal profile
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Finite Element Analysis (FEA)

FEA settlement trough at Higgins building foundation level

2D numerical modeling - Sensitivity analysis

3D numerical modeling
SEM Cavern Seismic Analysis
Requirements and Seismic Loading

• **OPERATING DESIGN EARTHQUAKE (ODE)**
  • 50% / 100 years (150-year return period)
• **MAXIMUM DESIGN EARTHQUAKE (MDE)**
  • 4% / 100 years (2475-year return period)

Acceleration response spectra of spectrally-matched motions
SEM Cavern Seismic Analysis

Seismic Analysis Approach

1. Free-field 1D analysis
   - No soil-structure interaction.
   - Combine with elastic closed form solutions.

2. Pseudo-static 2D
   - 1D shear strain applied to boundaries.
   - Soil structure interaction.

3. 2D dynamic analysis
   - Ground motions applied to lower boundary.
   - Non linear response of soil and structure.

- Ground condition
- Geometry
- Soil-structure interaction
- Non-linear analysis
- Interior structures
- Seismic load
- Level of effort
SEM Cavern Seismic Analysis

2D Dynamic Analysis

Numerical model – Interior structure

Plenum slab support in corbel

DYNAMIC SHEAR STRESS

Horizontal velocity time history

$E_{Q_{vert}}$ Confining Pressure

FREE-FIELD BOUNDARY

QUIET BOUNDARY

Numerical model for dynamic analysis
SEM Cavern Seismic Analysis
2D Dynamic Analysis

1. Base Case (1a)
   Final lining only
   10° Soil / Structure Interface (waterproofing)

2. Alternate Base (1c)
   10° Soil / Structure Interface (waterproofing)
   No vertical seismic

3. Temporary + Final Lining (3a)
   10° Soil / Structure Interface (waterproofing)

4. Temporary + Final Lining (3b)
   45° Soil / Structure Interface
SEM Cavern Seismic Analysis
2D Dynamic Analysis

**STRENGTH I:**
\[ U = 1.25(\text{DC}+\text{DW}) + 1.35E + 1.25\text{WA} + 1.75\text{LL} \]

- **Strength Case**

**SERVICE:**
\[ U = 1.00(\text{DC}+\text{DW}+E+\text{WA}+\text{LL}) \]

- **Service Case**

**EXTREME EVENTS:**
\[ U = 1.00 (\text{DC}+\text{DW}+E+\text{WA}+\text{LL}+\text{EQ}) \]

**Dynamic max/min**
- Dynamic (1.0Su) Cape
- Dynamic (1.0Su) Kobe
- Dynamic (1.0Su) Loma

Internal loads in final lining – Load cases and type of analysis
SEM Cavern Seismic Analysis

Liner Yielding

1. Identify Nodes Yielding
2. Min and Max Curvatures (φ)
3. M-T pairs corresponding to φ dynamic times for Min and Max curvatures
4. M-φ diagram:
   - Max Curvature (φu)
   - Yield curvature (φyield)
   - Max Moment Ductile Capacity μc = φu/φyield
5. εSR, εc

MRDC 3B.8.5.4 and MRDC 3B.7.4

Yielding of Temporary Linning

Yielding of Permanent Linning

Structural yielding

Ductility check

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SEM Cavern Seismic Analysis
Gap at corbel

Summary of Change of Width of Cavern at Corbel-Level

Cavern Widening/Shorting at Corbel

Plenum slab support in corbel

Local X-axis corbel Gap Closure
### SEM Cavern Seismic Analysis
#### 2D Dynamic Analysis Conclusions

1. **Type of analysis**
   - 1D SHAKE
   - 2D Pseudo-Static
   - 2D Dynamic

2. **Dynamic model set up**
   - Ground damping
   - Cracking
   - Elasto-plastic liner
   - Interfaces
   - Structural Links

3. **Peripheral Lining Response**
   - Ovaling
   - Internal loads
   - Plastic Hinges
   - Curvature analysis

4. **Interior Structure Response**
   - Internal loads
   - Relative displacements at supports

5. **Model sensitivity**
   - Temporary + Permanent Lining
   - Strength case, pseudo-static, dynamic
   - Interface properties
SEM Cavern Construction
RESS Meetings

Build
Selects means and methods
Performs monitoring, data, strength testing and final geometry

Design
Value engineering
Reviews and interprets monitoring data, compares with expected trends

 Own
Oversees
Communicates with stakeholders

Control
Monitors compliance with design
Provides independent verification
Suggestions and recommendations

RCC
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CM

LA Metro

• Topics for discussion
• Ground condition (incl. water and gas)
• Shotcrete strength results
• Required excavation and support
• Monitoring data
  • Bored tunnels
  • Cavern
  • MPBXs
  • Storm Drain
  • Surface
• Sign RESS

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SEM Cavern Construction
Other SEM Structures in Regional Connector

Tieback Removal Shaft and Adit
SEM Cavern Construction
Other SEM Structures in Regional Connector

Tieback Removal Shaft and Adit
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Other SEM Structures in Regional Connector

Crosspassages
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Construction Sequence - Side Drifts

Top heading excavation
Invert support
Wire mesh in temporary sidewall

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SEM Cavern Construction
Construction Sequence - Side Drifts

Steel pile
Styrofoam and wire mesh placement
Steel pile
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Construction Sequence - Side Drifts

SEM round length detailed sequence around PCTL

Excavation face around PCTL
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Construction Sequence - Center Drift

Center drift. Access ramp.

Center drift bench and invert excavation.
SEM Cavern Construction
Construction Sequence – Temporary Sidewall Demolition

Temporary sidewall demolition
Access ramp to top heading.
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Monitoring

Monitoring data visualization – Site plan and Ground Surface Settlement Point data
SEM Cavern Construction Monitoring

Settlement contours plan

Longitudinal settlement along right drift

Surface settlement profile
SEM Cavern Construction
Permanent structure

Permanent structure and trackwork – View from station side
Design and Construction of the SEM Cavern on LA Metro’s Regional Connector Transit Corridor Project

**56.1ft x 36.1ft x 289ft**
Largest Mined Excavation in Los Angeles

**Design-Build scheme**
Designer, Contractor, CM, Owner collaboration
SEM optimization, streamline decisions (RESS meetings)

**Settlement assessment**
0.5” maximum allowable in surrounding buildings
Pipe canopy limitations for settlement control
3D Finite Element Analysis and extensive 2D sensitivity analysis
Actual values very close to predictions (volume losses 0.2-0.3%)

**Seismic design**
MDE and ODE design levels – Performance requirements
Approaches to seismic design of underground structures
Sensitivity analysis
Initial + Final lining scenario
Final lining - Ductility under MDE
Interior structures – Gap

**Construction**
Other SEM structures – Learning curve
Design modifications
✓ Steel piles
✓ Flashcreting invert
✓ Increase round length
✓ Center drift cast-in-place concrete invert
✓ Center wall demolition staggered

**Instrumentation and Monitoring**
Automatization and postprocessing
Compare with predicted values and validate design modifications
Thank you

Carlos Herranz, PMP, PE, M.ASCE
Mott MacDonald Spain
Carlos.HerranzCalvo@mottmac.com