Chapter 9
Sequential Excavation Method

- Introduction
- Background and Concepts
- SEM Regular Cross Section
- Ground Classification and SEM Excavation and Support Classes
- Ground Support Elements
- Structural Design Issues
- Instrumentation and Monitoring
- Contractual Aspects
- Experienced Personnel in Design, Construction, and Construction Management

Sequential Excavation Method (SEM)

- SEM from philosophy through design, procurement, construction and construction management
- Based on the Understanding of
  - Interaction of Ground - Tunnel Excavation - Ground Support while mobilizing optimum ground self-support
  - Practical experience and Earth / Engineering Sciences Alike

Background and Concepts

- History
  - 1948 Patent – L. Von Rabcewicz
  - New Austrian Tunneling Method (NATM)

Background and Concepts

- Philosophy and Principles

Background and Concepts

- Range of Applications
- Economically Competitive

SEM Regular Cross Section

- Geometry
- Dual Lining
- Initial Shotcrete Lining
**SEM Regular Cross Section**
- Waterproofing
  - Smoothness Criteria

**SEM Regular Cross Section**
- Final Tunnel Lining
  - Cast-In-Place Concrete Final Lining
  - Water Impermeable Concrete Final Lining
  - Shotcrete Final Lining
  - Single Pass Linings

**Ground Classification**
- Rock Mass Classification Systems
- Ground Support Systems
  - Geological Model
  - Geotechnical Model
  - Tunnel Support Model

**Excavation and Support Classes**
- Excavation and support Classes (ESC) and initial support.

**Excavation and Support Classes**
- Longitudinal Tunnel Profile and Distribution of Excavation Support Classes
- Tunnel Excavation, Support, and Pre-Support Measures
  - Intact Rock
  - Stratified Rock
  - Moderately Jointed Rock
  - Blocky and Seamy Rock
  - Crushed, but Chemically Intact Rock
  - Squeezing Rock
  - Swelling Rock
Excavation and Support Classes
- Example in Rock

Excavation Methods
- Drill-and-Blast (hard rock)

Excavation Methods
- Road Header (Medium Hard, Jointed Rock)

Excavation Methods
- Backhoe (soft ground)

Ground Support Elements
- Shotcrete
- Rock Reinforcement
- Lattice Girders and Rolled Steel Sets
- Pre-Support Measurements and Ground Improvement
Effect of Shotcrete
- Flashcrete
- Shotcrete Face Support
- Initial Shotcrete Lining

Effect of Shotcrete
- Temporary Shotcrete Support

Types of Rock Reinforcement
- Rock Dowels
- Rock Bolts
- Rock Anchors

Practical Aspects
- Layout of Rock Mass Reinforcement Pattern
- Grouting
- Contact
- Testing and Monitoring

Immediate Support of the Ground
Control of Tunnel Geometry
Support of Welded Wire Fabric
Support for Fore Poling
Pre-Support Measures

Pre-Support Measures and Ground Improvement
- Pre-Support Measures
  - Pre-Support in Rock Tunneling
  - Pre-Support in Soft Ground (Soil) Tunneling
  - Pre-Support elements

Pre-Support Measures and Ground Improvement
- Pre-Support Measures
  - Grouted Pipe Arch Canopy
  - Face Doweling
Pre-Support Measures and Ground Improvement

- Ground Improvement
  - Groundwater Draw Down
  - Permeation Grouting
  - Ground Freezing

Portals

- General
- Pre-Support and Portal Collar
- Shotcrete Canopy

Structural Analysis

- Ground Structure Interaction: Stresses and Strains in Ground and Support
- Numerical Modeling
  - Two (2)-Dimensional and Three (3)-Dimensional Calculations
  - Material Models

Structural Analysis

- Material Models and Parameters for Rock, Soil, and All Structural Elements (Shotcrete, Concrete, Steel)
  - Ground Loads – Representation of the SEM Construction Sequence

Structural Analysis

- Ground Loads – Representation of the SEM Construction Sequence

- Ground Stresses and Deformations
- Lining Forces
- Ground Reinforcing Elements
- Considerations for Future Loads
Structural Analysis

Instrumentation and Monitoring

Structural Analysis

Instrumentation and Monitoring

SEM Contractual Aspects

- Contractor Pre-Qualifications
  - Russia Wharf, Boston
- Unit Prices
  - Excavation and Support
  - Local Support Measures
    - Shotcrete per cubic yard installed
    - Pre-support measures
    - Instrumentation and monitoring
    - Ground Improvement Measures
Experienced Personnel in Design, Construction, and Construction Management

- Contract Document Requirements
  - Observation of the Ground
  - Evaluation of ground behavior
  - Implementation of "right" initial support
- CM and Inspection team SEM Experience
Chapter 10
Tunnel Lining

- Introduction
- Design Considerations
- Structural Design
- Cast-in-Place Concrete
- Precast Segmental Lining
- Steel Plate Lining
- Shotcrete Lining
- Selecting a Lining System

Design Considerations

- Lining Behavior
- Soil Structure Interaction
- Flexibility
- Ductility
- Materials
  - Cast-in-Place Concrete
  - Precast Concrete
  - Steel
- Structural Systems
  - Cast-in-Place Concrete
  - One Pass System
  - Steel
  - Precast Concrete
  - Two Pass System
- Durability
- Loads and Load Combinations
- Structural Analysis and Design

Types of Permanent Tunnel Lining

- Cast-in-Place Concrete Lining
- Precase Segmental Lining
- Steel Plate Lining
- Shotcrete Lining

Cast-in-Place Concrete Lining

- Accommodates any Tunnel Shape
- Accommodates and Excavation Method
- Durable and Low Maintenance
- Provides a Stable Substrate for Finishes and Appurtenances
- Reinforcing Should be Kept to a Minimum
- Practical Minimum Thickness is 10"
- Crown Void Requires Post Grouting
- Strength Gain Sets Production Limits
- Curing is Required
Cast-in-Place Concrete Lining

- Lining is Completed Simultaneously with Mining
- Waterproofing is Part of the Lining
- Lining is Fabricated During Start-up of Mining
- Segments are Manufactured to Tight Tolerances
- Mining must be to Tight Tolerance
- Provides a Stable Substrate for Finishes and Appurtenances
- Bolt Recesses May Require Filling
One Pass Precast Tunnel Lining
- Reinforcing Steel Placement

One Pass Precast Tunnel Lining
- Casting Plant

One Pass Precast Tunnel Lining
- Storage Yard

One Pass Precast Tunnel Lining
- Mock-Up
One Pass Precast Tunnel Lining
■ Tunnel Boring Machine

Two Pass Precast Segmental Lining
■ Requires Larger Opening
■ Requires Waterproofing Membrane
■ Segments are Lightly Reinforced
■ Segments are Fabricated to Lesser Tolerances
■ Requires Final Cast-in-Place Lining

Two Pass Precast Segmental Lining
■ Precast Initial Lining
■ Final Cast-in-Place Lining

Steel Tunnel Lining
■ Highly Flexible
■ Requires Additional Work to Create Substrate for Finishes and Appurtenances
■ High Thrust from TBM may make Segments More Complex
■ Susceptible to Corrosion
■ Fire can Cause Buckling
Steel Tunnel Lining

Design Considerations

- Lining Stiffness and Deformation
  - Lining and Ground Act together.
  - Lining is flexible relative to the surrounding soil.
  - Ground will deform to re-distribute internal stresses and to reach equilibrium
  - Ductility in lining allows redistribution of stresses without failure
  - Deformation of lining allows redistribution of soil stresses and maintains the earth face behind the lining.

Constructability Issues

- Each tunnel is unique due to the many variations in ground conditions.
- Details should facilitate construction and account for underground conditions.
- Use of reinforcing steel in cast-in-place concrete should be minimized.
- Segmental linings should be detailed to be handled in small space.
- Waterproofing should match the construction method.

Durability

- Corrosion Protection
- High Density Concrete
- Chemical Attack
- Fire Protection
- Waterproofing
- Groundwater Systems
### Loads
- Dead Load
- Lining
- Roadway Slab
- Ventilation Ducts
- Earth Pressures
- Ground Water
- Live Loads
- Surchage Loads
- Creep and Shrinkage
- Appurtenances
  - Signs, Signals, Communications, Monitoring, Utilities, Drainage
- Extreme Events
  - Earthquake, Fire, Blast

### Structural Design
- Load Factors and Combinations
- Ductility Factor = 1.0
- Redundancy Factor = 1.0
- Importance Factor = 1.05
- Resistance Factors as per AASHTO

### Load Combinations

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### Resistance Factors

#### Plain Concrete
- Flexure = 0.55
- Compression = 0.55
- Tension = 0.55
- Shear = 0.55

#### Reinforced Concrete:
- Flexure = 0.9
- Shear = 0.9
- Bearing = 0.7
- Compression = 0.75

#### Structural Steel
- Flexure = 1.0
- Shear = 1.0
- Compression = 0.9
- Minimum Wall Area & Buckling = 1.0
- Minimum Longitudinal Seem Strength = 1.0

### Design of Plain Concrete
- Compression Capacity:
  \[ \phi P_C = 0.6 f'_c A \]
- Tension Capacity
  \[ \phi P_T = 5 f'_t^{1/2} \]
- Moment Capacity on Tension Face
  \[ \phi M_{T1} = 0.5 f'_t^{1/2} S \]
- Moment Capacity on Compression Face
  \[ \phi M_{C1} = 0.85 f'_c S \]
Design of Plain Concrete

- Compression Face Check
  \[ \frac{Q_a}{\phi P_c} + \frac{Q_m}{\phi M_{nc}} \leq 1 \]

- Tension Face Check
  \[ \frac{Q_m}{S} - \frac{Q_a}{A} \leq \phi P_T \]

Structural Analysis

- Ground Structure Interaction
- Lining Stiffness
- Empirical Method
- Beam Spring Method
- Numerical Method

Structural Analysis

- Empirical Method (Soft Ground Tunnels)
  \[ T = wR \]
  \[ M = 3EI/R \times \Delta R/R \]
  \[ I_e = I_j + I(4/n)^2 \]

Example Problem

Beam Spring Model

- Calculate Joint Coordinates
- Calculate Member Properties
- Lining Stiffness Calculated by:
  \[ I_e = I_j + I(4/n)^2 \]
- Spring Constants Calculated from Modulus of Subgrade Reaction
- External (Ground and Groundwater) Loadings Provided by Geotechnical Engineer
- Non-Linear Analysis
- Include Secondary Effects
Results – Selfweight Moments

Results – Jet Fan Moments

Results – Hydrostatic Pressure Moments

Questions?

Structural Analysis

- Beam Spring Model
  - 2D or 3D
  - Used for Rock and Soft Ground Tunnels
  - Applicable to any Tunnel Shape
  - Applicable to Intersecting Caverns and Cross Passage Locations
  - For Two-Pass System use Hinges Between Segments
  - For One-Pass System use Equivalent I
  - For CIP use Full Section I
  - Cracked Analysis can be Used for CIP Section
Chapter 11
Immersed Tunnels

- Introduction
- Construction Methodology
- Loadings
- Structural Design
- Watertightness And Joints Between Elements

Immersed Tunnels
Large Pre-cast Concrete or Concrete-filled Steel Tunnel Elements
Fabricated In the Dry and Installed under Water

Applications

- Crossing Water Body
- All Soils
- Transportation (Road and Rail)
- Utilities

Immersed Tunnels

- Over 100 Immersed Tube Tunnels in the world
- Ted William Tunnel, Boston
- Ft McHenry Tunnel, Baltimore
- Chesapeake Bay Tunnel, Virginia
- 1st and 2nd Hampton Road Tunnels, Hampton Road
- 1st and 2nd Downtown Tunnels, Norfolk
- Norfolk Midtown Tunnel

Long Crossing – Bridge -Tunnel

- 4Km Tunnel and 7.9 Km Bridge
- 4 Lanes 2 Tracks
- 38.8 m wide

Oresund Crossing
Denmark / Sweden
Widest Immersed Tunnel
**Typical Cross Section**

- Underwater Trench
- Foundation Course
- Tube Placement
- Locking Fill
- Backfill and Armor

**Immersed Tunnels Types**

- Steel
  - Single Shell
  - Double Shell
  - Sandwich
- Concrete

**Single Shell Tube**

- Composite Action of the Steel Shell and Interior Concrete
- No External Concrete
- Cathodic Protection
- Generally circular in shape

**Double Shell Tube**

- Composite Action Between the Interior Concrete and The Inner Shell Plate
- External Plate and Concrete Protect to the Interior Plate
- Diaphragms Stiffen the Plate
- Exterior Concrete Ballast
- Fabricated in Shipyards then Launched
- Generally Octagonal (with circular Interior)

**Sandwich Construction**

- Rectangular in Shape
- Cast in Basin near the Site
- Deep Draft (Small Freeboard)
- Minimize Thru Cracks
- Steel Membrane Waterproofing
- Heat of Hydration

**Concrete Tube**

- Rectangular in Shape
- Cast in Basin near the Site
- Deep Draft (Small Freeboard)
- Minimize Thru Cracks
- Steel Membrane Waterproofing
- Heat of Hydration
Construction Methodology
- Element Fabrication
- Trench Excavation
- Foundation Preparation
- Element Launching and Outfitting
- Towing to Site and Placement
- Backfill and Restoration

Element Fabrication
- Steel – (Modules)

Steel Fabrication

Fabrication - Casting
- Concrete
  - Casting horizontally
  - Vertically
  - Modules

Launching

Floating Concrete Tunnels
- Oresund Crossing Denmark
- Oresund Crossing, Hong Kong
- Western Harbour Tunnel, Hong Kong
- Western Harbour Crossing, Hong Kong
Transporting
- Towing or Barges
- Freeboard
- Lateral Stability (F.S. 1.4; a positive metacentric height 200 mm)

Outfitting

Dredging and Foundation Preparation
- Continuous Bedding Foundation (0.5 to 1.2 m Screeded Gravel) placed prior to element placement
- Jetted Sand and Floated sand
- Individual Support (Piles)
- Special Grouted Foundation

Trench Excavation and Foundation Preparation
- Dredging
- Environmental Issues
- Slope Stability
- Disposal of Dredged Materials

Foundation Preparation
Element Placement

- Transportation and Handling
- Lowering and Placing

Catamaran Placement Barge
Waxelin Harbour Crossing, Hong Kong

Transporting to Placing Site

Western Harbour Crossing, Hong Kong

Immersion Rig

- Maintain stability
- Minimum factor of safety against flotation and overturning of 1.025
- Negative buoyancy increased to give a minimum factor of safety against flotation and overturning of 1.04 within a few hours of lowering and placing

Immersion Sequence

A tunnel element being placed

Lowering and Placing

Maintain stability
Minimum factor of safety against flotation and overturning of 1.025
Negative buoyancy increased to give a minimum factor of safety against flotation and overturning of 1.04 within a few hours of lowering and placing

Lowering of Tunnel Element

A tunnel element being placed
Lowering and Placing

Connection
- Element Placement and Connection
- Approach previous element, touch gaskets, remove water in joint
- Water pressure on far end closes joint
- Backfilling and Protection

Connection to Previous Element

Joints Between Elements
- Immersion Joint (Typical Joint)
- Closure or Final Joint
- Seismic Joint

Seal Compression

Immersion (Typical) Joint
- The immersed element is pulled against the previously installed one.
- Due to the rubber profile (GINA), a small reservoir is created between the two bellmouths.
- Water is pumped out of the reservoir. The water pressure on the other end of the element compresses the GINA profile which seals the joints.
- The bellmouths are removed and a second rubber profile (OMEGA) completes the joint.
Element Joint

Immersion Joint (Typical Joint)

Closure Joints

Wedge-Type Final Joint - Japan

Backfill

- Selected locking fill to secure the elements laterally;
- General backfill to the sides and top of the tunnel structure, also providing an impact-absorbing / load-spreading layer above the tunnel;
- Rock protection blanket generally above and adjacent to the tunnel to provide scour protection;
- Rock-fill anchor-release bands at both sides of the tunnel are sometimes provided

Completing the Installation
Backfilling and Restoration

Fort Point Channel, Boston
Bosporus Crossing, Istanbul

Land Side Interface

- Ventilation buildings
- Earthquake joints
- Cut-and-cover tunnel
- Open approaches

Land Side Interface

Ft McHenry Tunnel, Baltimore

Loadings

- Same as Cut and Cover Tunnels
- Hydrostatic Loads
- Ship Sinking
- Ship Anchor Dropping and/or Dragging

Hydrostatic Loads

- Maximum and minimum hydrostatic loads should be used
- Specific gravity of water may vary according to depth, prevailing weather conditions and season
- For flotation (during launching or floating of the elements), the minimum relevant specific gravity of water should be used, and to prevent flotation (after placement of the element) the maximum should be used.
- Two water levels should be considered: normal (observed maximum water level) and extreme, 1 m (3 ft) above the design flood level (200-year flood level)
- The buoyancy force should be resisted by dead loads

Special Loads

- Ship Anchors
  - Penetration depth should not exceed 90% of the total thickness of the protection layer
- Ship Sinking
    - Uniform 50 kN/m² (1 ksf) over the full width and
    - Concentrated 1,000 kN (225 kips) over a 1x2 m (3.3x6.6 ft)
Anchor Penetration

CEB Bulletin d’Information No 187, August 1988

\[ x = 10N_p \cdot d_p \]

\[ N_p = \frac{m_{A}}{F_{d}} \cdot d_p \]

\[ d_p = \sqrt{\frac{4Ad}{\pi}} \]

\[ A = 0.6 \cdot 0.2 \frac{m_{A}}{1000} \]

The calculated maximum penetration depth should not exceed 90% of the total thickness of the protection layer covering the tunnel.

In-Service Load Combinations

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Structural Analysis and Design

- Structural Analysis
  - Frame Analysis
  - Finite Elements or Finite Differences
  - Large Deflection Theory

- For Cast-in-Place
  - \( \phi = 0.90 \) for flexure
  - \( \phi = 0.85 \) for shear
  - \( \phi = 0.75 \) for compression

- For Steel
  - \( \phi = 1.0 \) for flexure
  - \( \phi = 1.0 \) for shear
  - \( \phi = 0.85 \) for compression

Construction Load Combinations

- Fabrication, Transportation, and Placement

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</tr>
<tr>
<td>Service 2</td>
<td>1.25</td>
<td>1.00</td>
<td>0.00</td>
<td>1.5</td>
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<tr>
<td>Service 3</td>
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<td>1.00</td>
<td>0.00</td>
<td>1.5</td>
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<tr>
<td>Service 4</td>
<td>1.25</td>
<td>1.00</td>
<td>0.00</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Completed Tunnel

- Hampton Roads, Virginia
- Fort McHenry Tunnel - Baltimore

No different operationally than any other tunnel
Chapter 13
Seismic Considerations

- Introduction
- Determination of Seismic Environment
- Factors That Influence Tunnel Seismic Performance
- Seismic Performance and Screening Guidelines of Tunnels
- Seismic Evaluation Procedures – Ground Shaking Effects
- Seismic Evaluation Procedures – Ground Failure Effects

Introduction

- Tunnels Behave Better
  - Not Excited Independent of Ground
  - Amplitude Reduces with Depth
  - Can Produce Damage
- Design Based on Ground Deformation
  - Ignore stiffness of Structure
  - Structure Follows Ground
  - Rock or Very Stiff Soil
  - OK (Conservative)
  - Soil-Structure Interaction
  - Structure Stiff Relative to Ground
  - Intersections or Junctions

Seismic Environment

- Due to Earth Tectonic Plate Movement
- Principal Plate Boundary Along Western Coast
- In Central and Eastern US, Intraplate Source Zones

Types of Faults

- Strike Slip
- Dip Slip
- Oblique Slip
**Earthquake Magnitude**

- Measure of Energy Released
- Variety Exist
  - Short Period Body Wave Magnitude, $m_b$
  - Long Period Magnitude, $M_b$
  - Local (Richter) Magnitude, $M_L$
  - Surface Wave Magnitude, $M_S$
  - Moment Magnitude, $M_w$

  - Measure of Kinetic Energy Released (Hanks and Kanamori, 1986)

**Ground Motion Characteristics**

**East Coast vs. West Coast**

- Lower Recurrence Rate
- Lower Intensity but Lower Attenuation Rate
- Rich in High Frequency Content
- Potential Hazard due to Infrequent Event is Relatively High

**National Ground Motion Hazard Map**

**Hazard Analysis**

- Deterministic
  - Evaluate Worst-case Scenarios
  - Little Info on Likelihood, Frequency
- Probabilistic
  - Probability of Exceedence Corresponding to Levels of Ground Motion
  - Incorporates Uncertainty of Attenuation of Strong Ground Motions and the Randomness of Occurrences

**Impact Areas of Major Historical Earthquakes**

**Design Ground Motion Levels**

- Maximum Design Earthquake (MDE)
  - 2% probability of exceedance within a 50 year period
  - return period of 2500 years
  - Life safety
- Operating Design Earthquake (ODE)
  - 10% probability of exceedance within a 50 year period
  - return period of 500 year
  - no damage
Ground Motion Attenuation with Depth

<table>
<thead>
<tr>
<th>Tunnel Depth (m)</th>
<th>Ratio Of Ground Motion At Tunnel Depth To Motion At Ground Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 6</td>
<td>1.0</td>
</tr>
<tr>
<td>6-15</td>
<td>0.9</td>
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<tr>
<td>15-30</td>
<td>0.8</td>
</tr>
<tr>
<td>≥ 30</td>
<td>0.7</td>
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</tbody>
</table>

Ground Shaking Effects on Tunnels
- Ovaling/Racking
- Axial
- Curvature

Screening Guidelines for All Tunnels
- Ground Shaking Only
- Active Fault Intersecting Tunnel
- Landslide Intersecting Tunnel
- Liquefiable Soils
- History of Static Distress
- Other Unfavorable Geologic Conditions
- Type of Tunnel

Tunnel Damage Under Ground Shaking

Seismic Design for Ground Shaking Above ground vs. Underground
- Surface Structures (Bridges & Buildings)
  - Inertial Forces
  - Amplification
  - Force-governed Design Approach
- Underground Structures (Tunnels)
  - Surrounded by Ground
  - Seismic Displacement Approach

Tunnel Response
**Ovaling/Racking of Tunnels**

- Free-Field Shear Strain
  - Use Computer (Shake, Flush, Flac, Plaxis, et al.), or
  - Simplify to Horizontal Layered System, use 1-D wave Propagation (Schnabel, Lysmer, and Seed, 1972)

**Ovaling/Racking of Tunnels (cont’d)**

- Deep Tunnel in Homogenous Soil, Rock
  \[
  \gamma_{\text{max}} = \frac{V_s}{C_w}
  \]
  \(\gamma_{\text{max}}\) = Maximum free-field shear strain
  \(V_s\) = Peak particle velocity
  \(C_w\) = Effective shear wave propagation velocity

**Lining Stiffness**

- Compressibility and Flexibility Ratios
  \[
  C = \frac{E_m(1-\nu_m^2)R}{E_l(1+\nu_m)(1-2\nu_m)}
  \]
  \[
  F = \frac{E_m(1-\nu_m^2)R^3}{6E_l(1+\nu_m)}
  \]
  - \(E_m\) = Modulus of elasticity of the medium
  - \(\nu_m\) = Poisson’s Ratio of the medium
  - \(E_l\) = The modulus of elasticity of the tunnel lining
  - \(\nu_l\) = Poisson’s Ratio of the lining
  - \(R\) = Radius of the lining

**Circular Tunnel**

- Adjust for Relative Stiffness-Compressibility and Flexibility Ratios (C and F)
  \[
  K_1 = 1 + \frac{F[(1-2\nu_m)-(1-2\nu_a)C] \cdot \left(\frac{1}{2} - (1-2\nu_a)^2\right) C + 2}{F(3-2\nu_a)+(1-2\nu_a)C + C[\frac{1}{2} - 8\nu_u + 6\nu_u^2] + 6 - 8\nu_a}
  \]
  \[
  e_i = \pm K_1 \frac{E_m}{(1+\nu_m)} \frac{R^2}{2E_l} \frac{\gamma_{\text{max}}}{I_{\text{per unit width}}}
  \]
  \[
  e_f = \pm K_2 \frac{E_m}{(1+\nu_m)} \frac{R^2}{2I_{\text{per unit width}}} \frac{\gamma_{\text{max}}}{E_l}
  \]

**Ovaling/Racking of Tunnels (cont’d)**

- Shallow Tunnels
  \[
  \gamma_{\text{max}} = \frac{\tau_{\text{max}}}{G_m}
  \]
  \(G_m\) = Effective strain-compatible shear modulus of ground surrounding tunnel
  \(\tau_{\text{max}}\) = Maximum earthquake-induced shear stress

**Lining Deformation vs. “F”**

\[
F = \frac{\text{Soil Stiffness}}{\text{Lining Stiffness}}
\]
**Racking of Box Structure**

- Determine Racking Coefficient $R_r = \frac{\Delta_s}{\Delta_{free-field}}$

**Racking/Ovaling**

No Mechanisms!

**Racking of Structure**

$$\Delta_s = R_r \cdot \Delta_{free-field}$$

**Racking/Ovaling**

No Mechanisms!

**Racking of Structure**

- Racking/Ovaling Work for Simple Geometry, Simple Geology
- Computer Analysis Needed for More Complicated Situations
Seismic Numerical Modeling

Above:
- Shows Principles, But Simplified
- Completely Circular or Rectangular
- Material Uniform and Isotropic
- Deep Tunnel (No Surface Effects)
- Deep Tunnel, No Other Structure in Proximity

Seismic Numerical Modeling

Better:
- Computer Modeling
- More Complicated Structure and Geology

Seismic Numerical Modeling

Evaluation For Fault Displacement
Ground Failure – Fault Crossing

Design of LA Metro Tunnel Across Hollywood Fault Zone

Design Strategy Against Faulting (Soft Backfill)

Landslide (Portal Stability)

Enlarged Tunnel at Fault Crossing

Liquefaction
Step-by-Step Seismic Evaluation Procedures

- Ground Shaking Affect
- Ground Failure
  - Fault Rupture
  - Soil Liquefaction
  - Landslide

Closure – Seismic Considerations

- Earthquakes not limited to California
- Underground structures behave differently
- Shaking is usually major concern
- Analysis
  - Simple
  - More Complicated
  - May require computer
- ODE and MDE
Chapter 14
Construction Engineering

- Introduction
- Constructability
- Construction Staging and Sequencing
- Mucking and Disposal
- Health & Safety
- Cost Drivers and Elements
- Schedule
- Claims Avoidance and Disputes Resolution
- Risk Management

Constructibility

- Constructibility starts at the planning stage
  - Realistic schedule
  - Defendable cost estimate
  - Linear structure
  - Repetitive
  - Geotechnical conditions
  - Ground water
  - Environmental issues (contamination, gas, petroleum, etc...)
  - Health and safety of workers and the public
  - External constraints (location, available laydown areas, hours of operations, noise regulations, community impact, etc...)
- Risks

Construction Staging

- Construction staging area
  - Equipment
  - Material storage
  - Muck storage and handling
  - Shops
  - Electrical substation
  - Contractor/CM offices
  - Labor change rooms, showers, access, etc...
- Important to balance availability of space vs efficiency of construction

Site Constraints
**Construction Sequencing**

- Series of individual repetitive steps
  - Drill and Blast (drill, load, detonate, ventilate, scale, muck, bolt, repeat)
  - NATM
  - TBM
  - Final Liner
  - Efficiency is critical to meet the schedule and budget

**Health and Safety**

- "Everyone goes home safely at the end of the shift"
- Work is in noisy, closed area, with moving heavy equipment, and limited lighting
- Openings must be supported
- Gasses (hydrogen sulfide or methane)
- Ground Water

**Muck Removal**

- Conveyors (horizontal and vertical)
  - Uniform size
  - Crushers
  - Muck train
  - Lift
  - Hopper
  - Vertical conveyor
  - Pumped (slurry)
  - Swell volume (70% - 100% in rock, 25% - 40% soil)
  - Muck removal is critical for tunnel production – muck bound
  - Disposal (contaminated soils)

**Construction Cost Issues**

- Physical Costs
  - Materials, labor, construction equipment, ground & water control, waterproofing, finishes, ventilation, lighting, traffic control, etc...
- Economic costs
  - Labor (direct, support crews, indirect)
  - Insurance, bond, soft costs
  - Scrutiny of insurance and surety companies
  - Volatility of material costs (cement, steel cooper, etc...)
  - Fuel cost
  - Muck disposal cost
- Political costs
  - Communities
  - Restrictions (hours of operations, noise level, limited staging area, shaft location, etc...)
  - Concessions
  - “No damage for delay” clause

**Health and Safety**

- Fire
  - single point entry
  - Rescue Chamber
  - Multi-point entry
  - Prevention measures
- OSHA Requirements
  - Lighting
  - Ventilation (200 cfm/person)
  - Construction Equipment
  - Enclosed spaces
  - Safety Gears
  - Fall protection
  - Etc...
  - Safety requirements shall be specified

---

Parsons Brinckerhoff
Schedule Issues
- Road map (include planning, EIS, design, ROW, bidding, construction, equipping, testing and commissioning)
- Construction schedule
  - Linear structure and repetitive operations
  - Restrictions or unrealistic expectations
  - External influences (upcoming event or election)
  - Risk

Dispute Resolution
  - Different Site Condition Clause
  - Dispute Review Board
  - Escrow Bid Documents
  - Mediation and Arbitration
  - Full Geotechnical Disclosure
  - Contractors Pre-Qualification
  - Constructibility Analyses – Contractors input
  - Value Engineering
  - Partnering
  - Owner Controlled Insurance Program (OCIP)
  - Unit Prices and Contingent Bid items
  - Incentives (Early Completion, Safety, Quality) vs Liquidated Damages

Construction Schedule
- Divide the work into discrete activities
- Production rates
- Ties with other activities
- Basis of construction cost estimate
  - Size of the crews
  - Productivity
  - Equipment needed
  - Materials
  - Consumables
  - Direct cost
  - Indirect cost

Risk Management
- Simply – Managing Surprises
  - Identify potential risks
  - Assess the consequences
  - Plan to make them harmless
- Risk management is
  - Evaluation of alternatives
  - Making choices
  - Understanding consequences

Claim Avoidance and Dispute Resolution
- Change site conditions
- Delay claims
- Differing Site Condition Clause
  - Predicted or anticipated
  - Contractor contingency
  - Risk sharing

Definitions
- Hazard: An event having a consequence to cost, schedule, operations, environment, quality, public
- Risk: Combination of consequences or severity of impact and probability of occurrence. Can be quantified such that decisions can be made on how to deal with the project-specific risk.
- Risk probability: is the frequency with which any particular hazard may occur.
- Risk Consequence: is the impact or outcome of the hazard manifestation.
- Risk Register: Management tool to track mitigation actions and manage risk throughout project.
**Major Risk Categories**
- Technical (design/construction issues)
- Geotechnical/Geological (surprises due to unforeseen conditions)
- Technological (equipment not suitable for the type of construction)
- Regulatory/Approvals (obtaining permits on time)
- Public impact (complaints)
- Construction (means and methods)
- Environmental issues (contamination, air quality, noise, etc.)
- Schedule (potential delays)
- Financial and funding (cost too much)
- Operation and maintenance (accessibilities, inspection, etc.)
- Security (natural and man-made hazards)
- Others (political, market conditions, other projects, etc.)

**Third Party Risks**
- Environmental Approvals (EA, EIS, etc.)
- Approvals of Funding Agencies
- Public Participation and Approvals
- Stakeholders Input (Adjacent Property Owners, Operating agencies, etc.)
- Easement and Right of Way
- Permitting Agencies

**Construction Risks**
- Subsurface and geotechnical issues
- Utilities and buried structures
- Third party approvals and permits
- Differing site condition
- Contractor’s contingency
- Risk sharing and risk management

**Risk Assessment Process**
- Identification of potential risks
- Identifying appropriate mitigation measures for each risk
- Providing qualitative and quantitative assessment of risks
- Making an assessment of risk allocation and potential risk
- Design measures to reduce consequences of risks
- Develop and implement monitoring measures
- Assign financial contingencies to deal with risks
- Establish and maintain risk register

**Geotechnical/Underground Issues**
- Difficult ground conditions
- Unanticipated/different site conditions
- Contaminated soil and ground water
- Boulders and buried objects
- Extent (limit) of geotechnical investigation
- Interpretation of geotechnical data
- Anticipated ground behavior
- Abandoned or un-chartered utilities
- Buried footings and structures
- Rubble and uncontrolled fill
- Archeological finds

**Risk Management Process**

Risk Register

- The risk register is the primary tool used to record identified risks, track risk exposure and monitor risk management throughout the project.
- Formalized record of risks that are identified throughout the risk management process.
- The risk register is a living document that can be passed on to the contractor for its use.

Risks Classes

- **Tolerable**: The level of risk is tolerable, but further risk reduction should be considered.
- **ALARP (As Low as Reasonably Possible)**: The level of risk is undesirable. Considerable efforts should be made to reduce the risk.
- **Intolerable**: The level of risk is intolerable and work or operational activities should not be started or continued until the risk has been reduced.

Risk Rating and Quantification

\[ R = F \times C \]

- **R** = Risk Rating
- **F** = Frequency of occurrence; and
- **C** = Magnitude of consequences

<table>
<thead>
<tr>
<th>Category</th>
<th>Risk Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerable</td>
<td>R = 1-6</td>
</tr>
<tr>
<td>ALARP</td>
<td>R = 8-12</td>
</tr>
<tr>
<td>Intolerable</td>
<td>R = 15-25</td>
</tr>
</tbody>
</table>

| Matrix 3x3 or 5x5 |
Risk Management
Design – Construction – O&M

- Risk Mitigations Incorporated - Designing Risk Carried Forward
- Final Owner's Risk Register Risk Allocations
- Risk Management Actions During Construction

Design Team - Owner
- Final Designer - Owner
- Contractor - Owner
- Final Designer - Construction Manager
Owner

Project Entities Required For Beginning-To-End Risk Management

Timing and Effectiveness

Risk management: the sooner the better

Greater Risk Reduction

Most Effective

Planning

Concept

Prelim Design

Final Design

Construction

Time