Seismic Design of Tunnels

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Associate Vice President
National Tunnel Practice Lead – NW

Tuesday 9/10/2019, 3:30 p.m. – 4:15 p.m.
Seismic Environment

Seismic Performance of Above Ground Structures - Inertia Effects
## Seismic Performance of Underground Structures

<table>
<thead>
<tr>
<th>Date</th>
<th>Earthquake Location</th>
<th>Magnitude</th>
<th>Earthquake Tunnel Damage Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/23/80</td>
<td>Campania-Fasulcata,</td>
<td>7.0 (M)</td>
<td>No damage</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/19/85</td>
<td>Michoacan, Mexico</td>
<td>8.1</td>
<td>No damage to Underground Metro in</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mexico City</td>
</tr>
<tr>
<td>10/17/89</td>
<td>Loma Prieta, CA</td>
<td>6.9</td>
<td>No reports of damage to tunnels</td>
</tr>
<tr>
<td>4/25/92</td>
<td>Petrolia, CA</td>
<td>7.2</td>
<td>No PCTL tunnels existed in area,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>other tunnels were damaged</td>
</tr>
<tr>
<td>7/12/93</td>
<td>Hokkaido, Japan</td>
<td>7.7</td>
<td>No reports of damage to tunnels</td>
</tr>
<tr>
<td>1/17/94</td>
<td>Northridge, CA</td>
<td>6.7</td>
<td>No damage to PCTL tunnels</td>
</tr>
<tr>
<td>1/17/95</td>
<td>Kobe, Japan</td>
<td>6.9</td>
<td>No reports of damage to tunnels</td>
</tr>
<tr>
<td>8/17/99</td>
<td>İzmir (Kocaeli), Turkey</td>
<td>7.4</td>
<td>No reports of damage to tunnels</td>
</tr>
<tr>
<td>9/7/99</td>
<td>Athens, Greece</td>
<td>5.9</td>
<td>No reports of damage to tunnels</td>
</tr>
<tr>
<td>9/21/99</td>
<td>Chi Chi, Taiwan</td>
<td>7.5</td>
<td>No reports of damage to PCTL tunnels, other tunnels were damaged</td>
</tr>
<tr>
<td>2/28/01</td>
<td>Nisqually, Washington, USA</td>
<td>6.8</td>
<td>No reports of damage to tunnels</td>
</tr>
<tr>
<td>10/23/04</td>
<td>Niigata Prefecture, Japan</td>
<td>6.6</td>
<td>Several tunnels were damaged, final report not available</td>
</tr>
</tbody>
</table>

* Magnitudes are M<sub>s</sub> = moment magnitude, unless otherwise noted.
† Damage to a tunnels shed (which is a part of the portal to the Shimotani Tunnel) is reported in the EERI reconnaissance report (EERI, 1998b). The tunnel shed collapsed due to rockfall larger than that which the shed was designed for. This is scenario incorrectly referred to as a tunnel collapse.
‡ No damage to tunnels was described or noted in reconnaissance reports and other literature reviewed for this study.
§ Several tunnels were reportedly damaged in the Niigata Ken Chetto earthquake of October 23, 2004. A review of photographs in preliminary reports does not show any PCTL lined tunnels. However, these photographs are not comprehensive and the final reconnaissance report was not available at the time this paper was prepared.

Seismic Effects on Underground Structures – Imposed Deformation

Source: Shamsabadi et al (2001)

Source: JSCE (2008)
Seismic Effects on Underground Structures – Imposed Deformation

Source: JSCE (2008)
Work Flow for Seismic Design of Underground Structures

Determine Seismic Environment

- Design Criteria
  - Maximum Design Earthquake (MDE)
  - Operating Design Earthquake (ODE)
- Seismic Hazard Analysis
  - Deterministic SHA
  - Probabilistic SHA
- Ground Motion Parameters
  - Acceleration, velocity, displacement
  - Response spectra, motion time history
  - Spatial incoherence of ground motion

Evaluate Ground Response to Shaking

- Ground Failure
  - Liquefaction
  - Slope instability
  - Fault displacement
- Ground Shaking and Deformation
  - Longitudinal extension/compression
  - Longitudinal bending
  - Racking / Ovaling

Evaluate Underground Structure Response to Seismic Shaking

- Seismic design loading criteria
  - Loading criteria for MDE
  - Loading criteria for ODE
- Underground Structure Response to Ground Deformation
  - Free-Field Deformation Approach
  - Soil-Structure Interaction Approach
- Special Seismic Design Issues
Determine Seismic Environment

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- Design return periods for recent major mass transit projects:
  - MDE = 2,500 years (4% in 100 years)
  - ODE = 150 years (50% in 100 years)

Fig. 8. Probabilistic seismic hazard analysis procedure (after Reiter, 1990).
Determine Surface Ground Motion Parameters - Acceleration

Two-percent probability of exceedance in 50 years map of peak ground acceleration

Determine Surface Ground Motion Parameters – Velocity & Displ.

Table 2
<table>
<thead>
<tr>
<th>Moment magnitude (M_l)</th>
<th>Ratio of peak ground velocity (cm/s) to peak ground acceleration (g)</th>
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<tbody>
<tr>
<td></td>
<td>Source-to-site distance (km)</td>
</tr>
<tr>
<td><strong>Rock</strong></td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
</tr>
<tr>
<td><strong>Stiff soil</strong></td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
</tr>
<tr>
<td><strong>Soft soil</strong></td>
<td>6.5</td>
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<tr>
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<td>7.5</td>
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<td></td>
<td>8.5</td>
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*In this table, the sediment types represent the following shear wave velocity ranges: rock ≥ 750 m/s; stiff soil is 200–750 m/s; and soft soil < 200 m/s. The relationship between peak ground velocity and peak ground acceleration is less certain in soft soils.

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Source: FHWA-NHI-09-010 Road Tunnel Manual (2009)

\[
PGV = 0.394 \times 10^{0.434C}
\]

Where:

PGV is in in/sec

\[
C = 4.82 + 2.16 \log_{10} S_1 + 0.013 \ [2.30 \log_{10} S_1 + 2.93]^2
\]
Evaluate Ground Response to Shaking

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Evaluate Ground Response to Shaking
- Ground Failure
  - Liquefaction
  - Slope instability
  - Fault displacement
- Ground Shaking and Deformation
  - Longitudinal extension/compression
  - Longitudinal bending
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Geotechnical Earthquake Engineering

Tunnel Structural Engineering

Source: Kawashima
Directions of Seismic Wave Propagation – Design Implications

Fig. 6. Deformation modes of tunnels due to seismic waves (after Owen and Scholl, 1981).

Fig. 9. Simple harmonic wave and tunnel (after Wang, 1993).
Free-field Strains and Curvatures - Simplified Harmonic Waves

Table 5
Strain and curvature due to body and surface waves (after St. John and Zahrah, 1987)

<table>
<thead>
<tr>
<th>Wave type</th>
<th>Longitudinal strain</th>
<th>Normal strain</th>
<th>Shear strain</th>
<th>Curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-wave</td>
<td>$e_l = \frac{V_p}{C_p} \cos^2 \phi$</td>
<td>$e_n = \frac{V_p}{C_p} \sin^2 \phi$</td>
<td>$\gamma = \frac{V_p}{2C_p} \sin \phi \cos \phi$</td>
<td>$\frac{1}{p} = \frac{\sigma_p}{C_p} \sin \phi \cos \phi$</td>
</tr>
<tr>
<td></td>
<td>$e_{lm} = \frac{V_p}{C_p} \cos \phi$ for $\phi = 0^\circ$</td>
<td>$e_{nm} = \frac{V_p}{C_p} \cos \phi$ for $\phi = 90^\circ$</td>
<td>$\gamma_{lm} = \frac{V_p}{2C_p} \cos \phi$ for $\phi = 45^\circ$</td>
<td>$\frac{1}{p_{\max}} = 0.385 \frac{\sigma_p}{C_p}$ for $\phi = 35.16^\circ$</td>
</tr>
<tr>
<td>S-wave</td>
<td>$e_s = \frac{V_s}{C_s} \sin \phi \cos \phi$</td>
<td>$e_n = \frac{V_s}{2C_s} \cos \phi$ for $\phi = 45^\circ$</td>
<td>$\gamma = \frac{V_s}{C_s} \sin \phi \cos \phi$</td>
<td>$K = \frac{\sigma_s}{C_s} \cos \phi$</td>
</tr>
<tr>
<td></td>
<td>$e_{sm} = \frac{V_s}{2C_s}$ for $\phi = 45^\circ$</td>
<td>$\gamma_{nm} = \frac{V_s}{2C_s} \cos \phi$ for $\phi = 0^\circ$</td>
<td>$\gamma_{sm} = \frac{V_s}{2C_s} \cos \phi$ for $\phi = 0^\circ$</td>
<td>$K_n = \frac{\sigma_s}{C_s}$ for $\phi = 0^\circ$</td>
</tr>
</tbody>
</table>

The Poisson’s ratio and dynamic modulus of a soil deposit can be computed from measured P- and S-wave propagation velocities in an elastic medium: $\nu = \frac{(C_p/C_s)^2 - 2}{(C_p/C_s)^2 - 4}$ and $C_n = \rho C_s^2$, respectively.

Source: Hashash et al (2001) and St John and Zahrah (1987)
Site Response Analysis (e.g. SHAKE, Opensees, DeepSoil)
Evaluate Underground Structure Response to Seismic Shaking

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Policy
Seismology
Geotechnical Earthquake Engineering
Tunnel Structural Engineering
Underground Structure’s Response to Ground Deformation

Evaluate Underground Structure Response to Seismic Shaking

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Rectangular Section

Ratio of Underground Structure Deformation vs Free Field

- Tunnel deformation could be up to 2.4x free field deformation
- Dependent on stiffness ratio
- Additional reference for circular and rectangular sections:
  - Penzien, 2000, Seismically Induced Racking of Tunnel Linings
- Closed form approximation for longitudinal (snaking) deformation
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**Evaluate Underground Structure Response to Seismic Shaking**
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Policy
Seismology
Geotechnical Earthquake Engineering
Tunnel Structural Engineering
Example #1 – Cut and Cover Subway Station (Los Angeles)
Example #1 – Seismic Soil-Structure Interaction Analysis

Table 3-1: Estimated Free-Field Relative Displacement Between Top and Bottom of Structure

<table>
<thead>
<tr>
<th>Location</th>
<th>Top, bottom of station box (ft, bgs)*</th>
<th>Earthquake Motion</th>
<th>Estimated Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MDE</td>
<td>ODE</td>
</tr>
<tr>
<td>1st/Control</td>
<td>0, 45</td>
<td>Motion 1</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motion 2</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motion 3</td>
<td>1.38</td>
</tr>
</tbody>
</table>


Table 8: Results of Racking Analysis (All Maximum Values)

<table>
<thead>
<tr>
<th>Racking - Maximum (inches)</th>
<th>Left Wall (top corner - bottom corner)</th>
<th>Right Wall (top corner - bottom corner)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loma Prieta ODE</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Cape Mendocino ODE</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Kobe ODE</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Loma Prieta MDE</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Cape Mendocino MDE</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Kobe MDE</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Example #2 – Pump Station (Portland, OR)

- 220 MGD pump station
- 135 ft dia. X 162 ft deep
- Subsurface:
  - Fill 25 ft
  - Alluvium 115 ft
  - Troutdale formation 185 ft
  - Mudstone
- Avg. shear wave velocity = 550 ft/s
- PGA = 0.34 g
Example #2 – Seismic Soil Structure Interaction Analysis

- **FEA model**
- **Solid elements for soils, 9x shaft diameter wide**
- **Shell elements for shaft walls and slabs**
- **Free field deformation applied to the side boundaries**
Example #2 – Seismic Soil Structure Interaction Analysis

- 1.2” differential displacement (top vs bottom of shaft)
- Principal stresses in shaft walls (psi) well within concrete capacity

- Use of simple 3D model helped us understand seismic performance (and reduce wall thickness & cost)

Source: Wongkaew and Owyang, 2004
Example #3 – SEM Tunnel Adjacent to Building Basement (Wash.)

- Soil-tunnel-building FEA model
- Free field displacement applied at left and right boundaries
- Evaluated seismic deformation and interaction of basement and tunnel

Source: Yang and Penrice (2014)
Key Takeaways

- “Ground Displacement Problem”
- NOT “Inertial Problem”
- Consider Soil-structure Interaction
- Design underground structures to accommodate displacement demand

Determine Seismic Environment ➔ Evaluate Ground Response to Shaking ➔ Evaluate Underground Structure Response to Seismic Shaking