Alaskan Way Viaduct REPLACEMENT PROGRAM

SEISMIC DESIGN OF SR 99 TUNNEL IN WASHINGTON STATE

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The Third International Bridge Seismic Workshop

Seattle, Washington, USA

October 1st to 4th, 2019

IABEE International Association Bridge Earthquake Engineering

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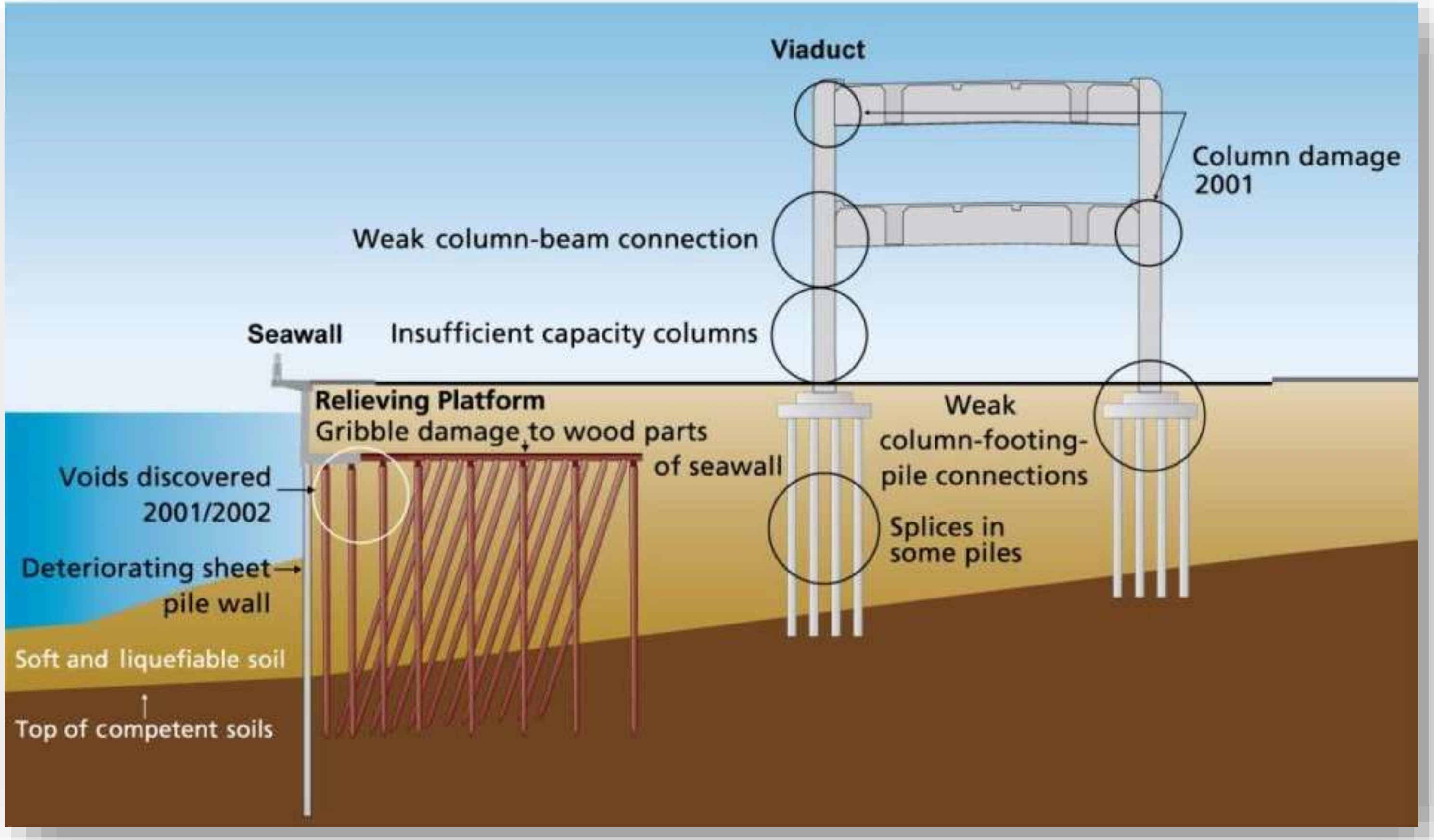
Presentation Outline

1. Project purpose
2. Tunnel configuration
3. Seismic performance design criteria
4. Basics of tunnel seismic response
5. Seismic design of SR 99 Tunnel
6. Concluding remarks

Purpose – Replacing Alaskan Way Viaduct in Seattle

Alaskan Way Viaduct (Looking North)

Replacing Alaskan Way Viaduct - A Safety Project



The viaduct and neighboring seawall are vulnerable to earthquakes

The viaduct

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Similarities with Cypress Street Viaduct in Oakland, California

Cypress Street Viaduct in Oakland, CA

Alaskan Way Viaduct in Seattle, WA

Collapsed Cypress Street Viaduct

After Loma Prieta earthquake on
October 17, 1989

Site visit on October 19, 1989

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SR 99 Tunnel in Seattle

Major Components:

- 1250 ft south approach
- 9270 ft bored tunnel
- 450 ft north approach
- 2 operations buildings

Challenges:

- Buoyancy resistance at the south end
- Tunnel deformation mitigation
- AWV remains open during construction
- Water tightness during seismic events

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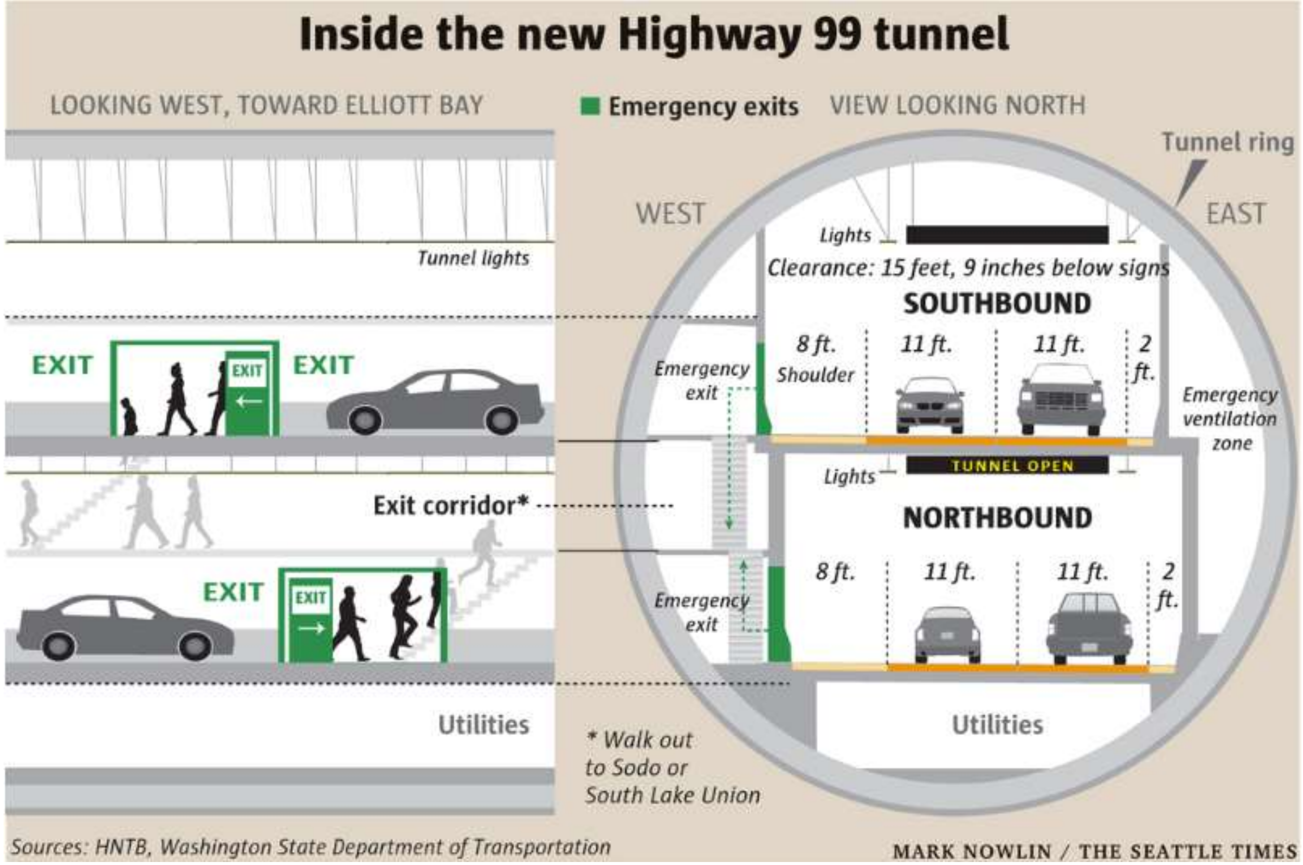
SR 99 Tunnel Configuration



Excavation diameter	57'- 4"
Internal diameter	52'
Exterior diameter	56'
Segment thickness	2'
Grouting thickness	8"
Average ring length	6'- 6"
Number of segments	7+2+1
Tunnel length	9270'

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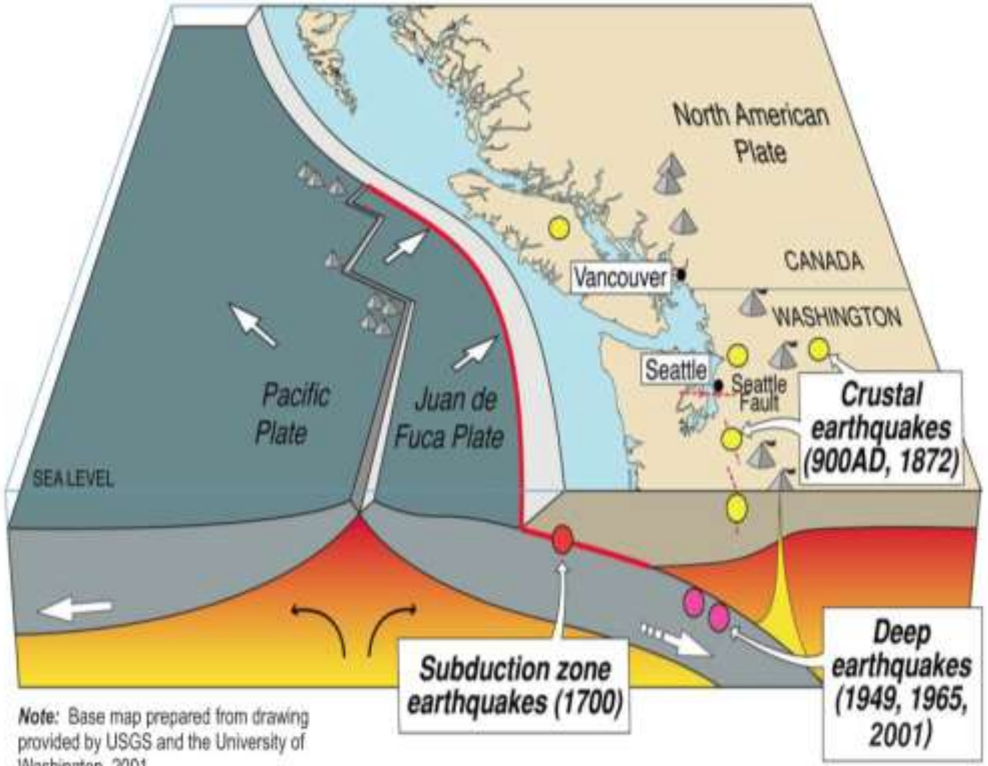
Seismic Hazards in Seattle

Magnitude 7.1
Olympia
Earthquake, 1949

Magnitude 6.5
Seattle-Tacoma
Earthquake, 1965

Magnitude 6.8
Nisqually
Earthquake, 2001



Note: Base map prepared from drawing provided by USGS and the University of Washington, 2001.

Source	Maximum Magnitude
Cascadia Subduction Zone - Interplate	9.0
Cascadia Subduction Zone - Intraplate	7.5
Crustal Faults	7.5

Seismic Design Criteria

Performance Objective

Expected Earthquake (108-Year Return) → **Operational**

- Minimal damage to liner, interior structures, and joints
- Minimal disruption to service
- Maintain water tightness
- Concrete strain < 0.003; Steel strain < 0.002

Rare Earthquake (2500-Year Return) → **Life safety**

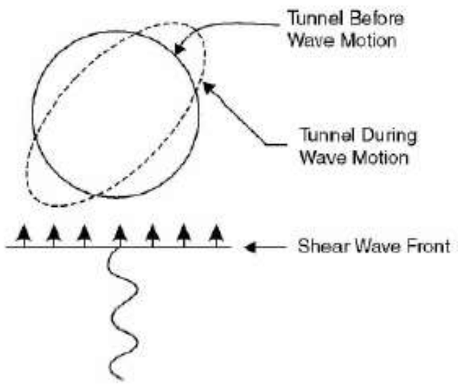
- No collapse
- Allow significant damage
- Allow significant disruption to service
- Water tightness shall allow for evacuation
- Concrete strain < 0.005
- Steel strain < 0.006 for rebar up to #10, 0.045 for #11 and larger

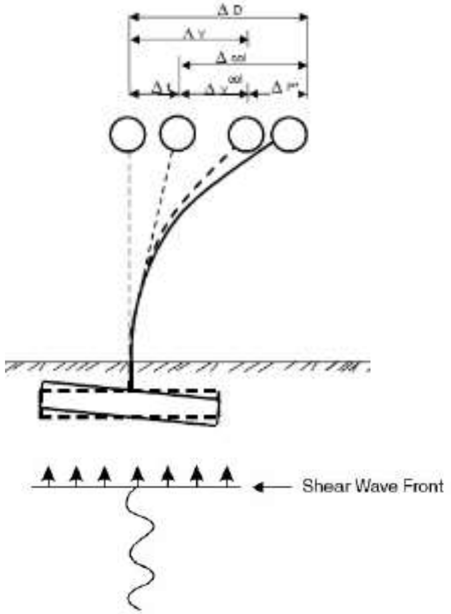
Seismic Performance of Underground Structures

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

* Magnitudes are M_w = moment magnitude, unless otherwise noted.

VS.





Source: Dean et al (2006)

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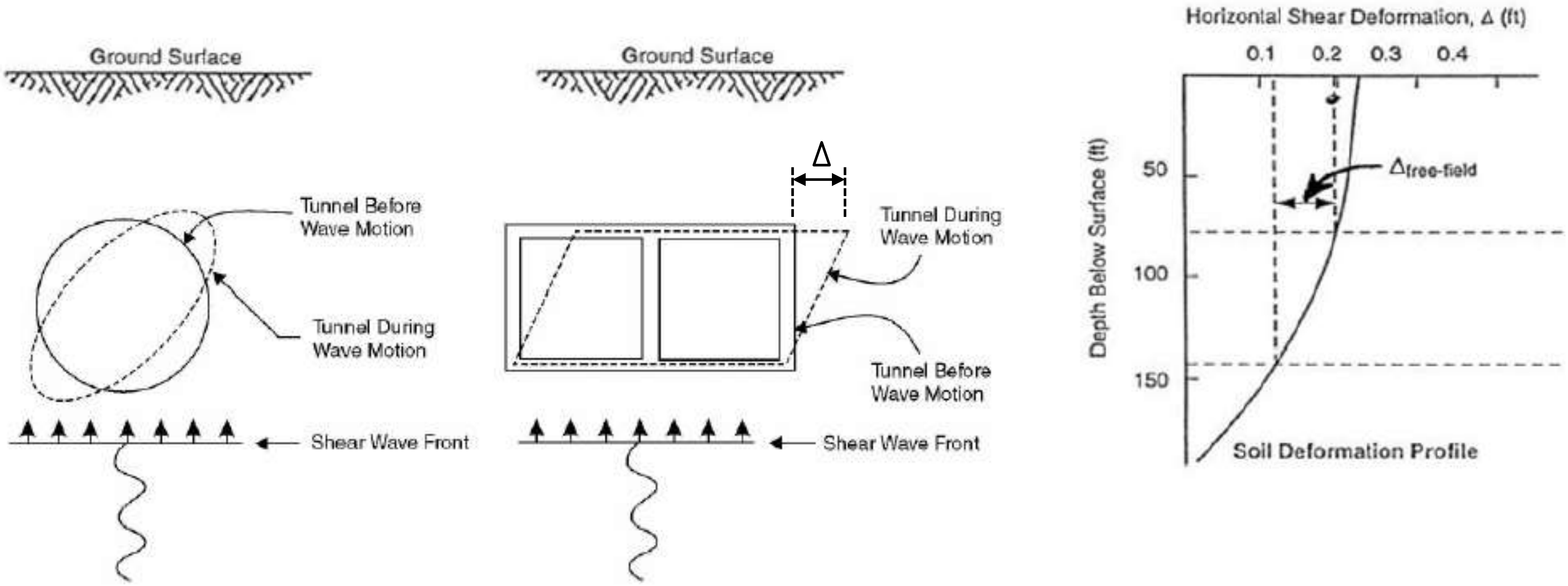
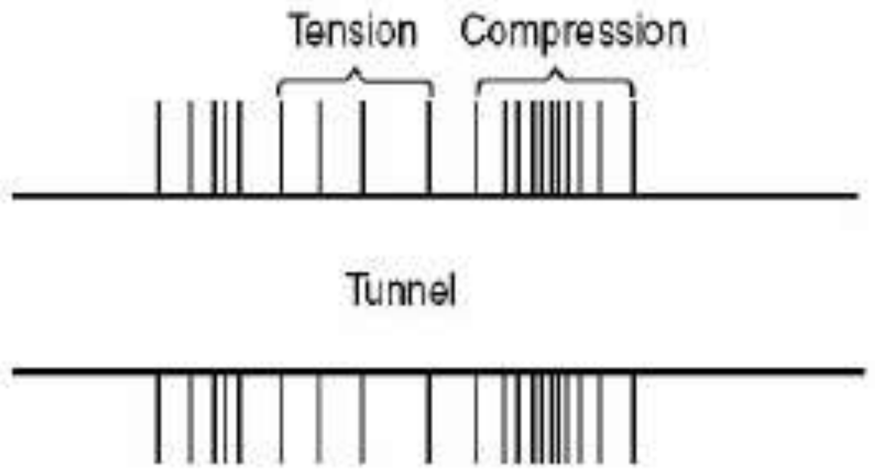
Tunnel Transverse Seismic Responses



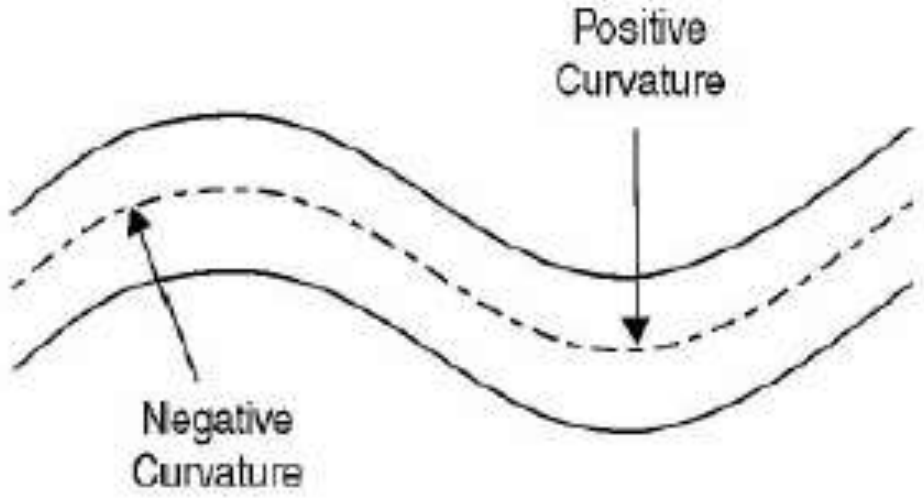
Tunnel Transverse Seismic Response (Ovaling or Racking)

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

Tunnel Longitudinal Seismic Responses



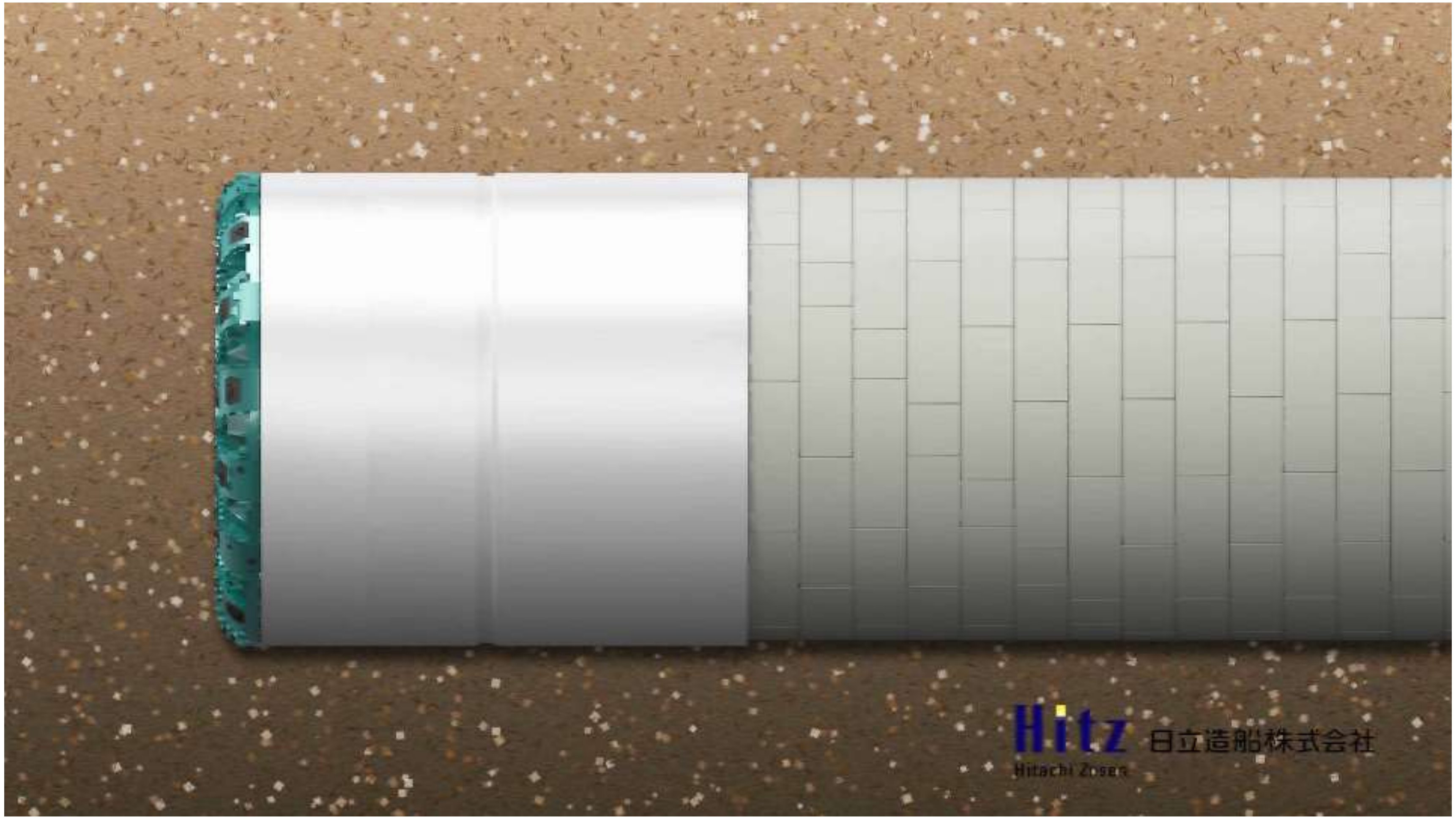
Axial deformation along tunnel



Curvature (bending) deformation along tunnel

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

Tunnel Boring Machine – Earth Pressure Balanced Machine



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Tunnel Construction – Liner Ring

Mockup Ring Assembly

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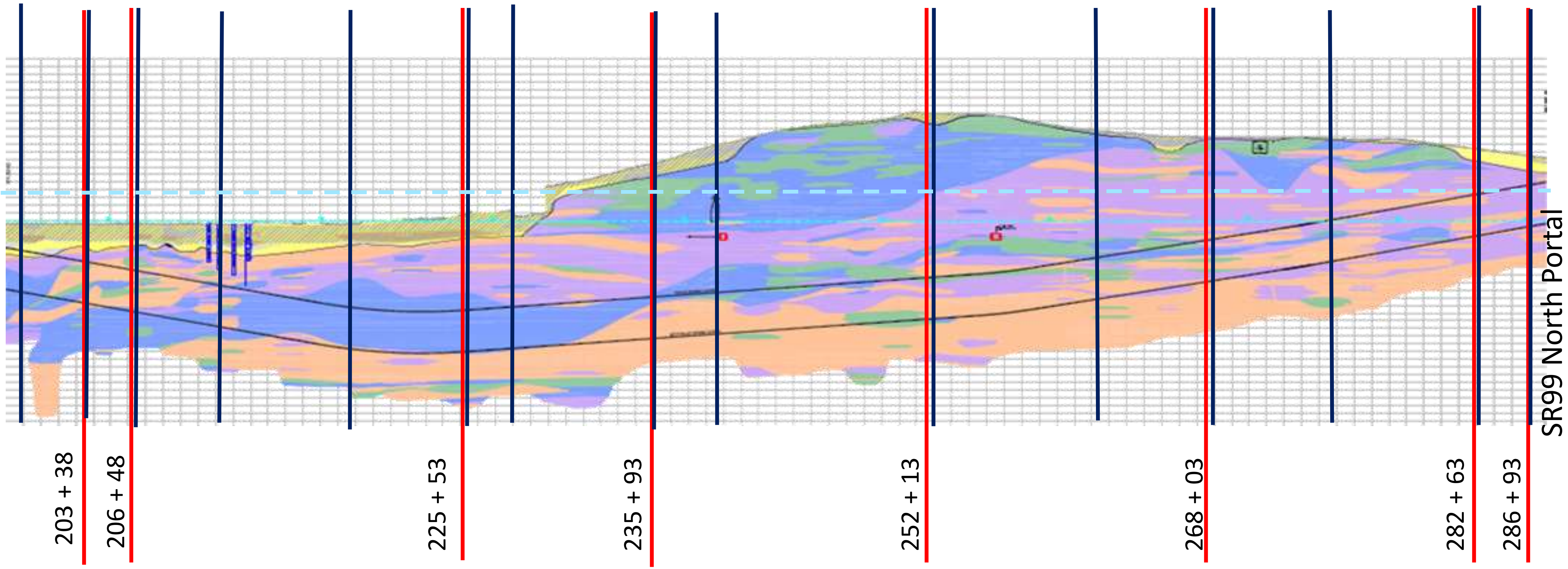
Transverse Design Sections

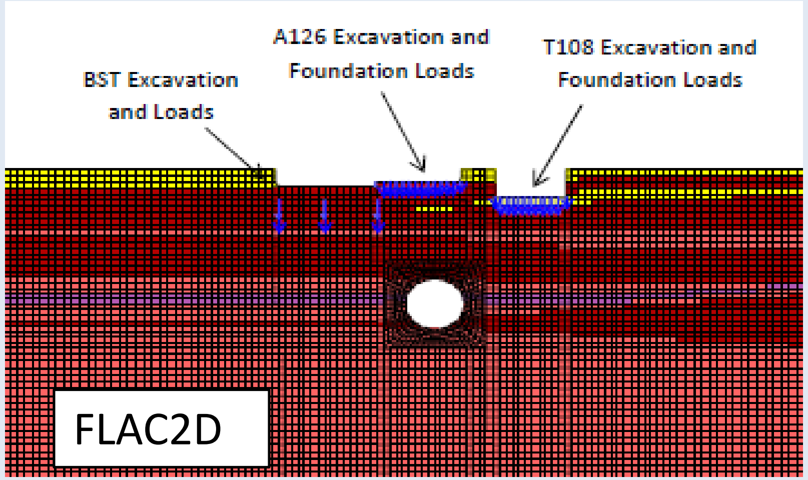


15 static design sections

8 seismic design sections

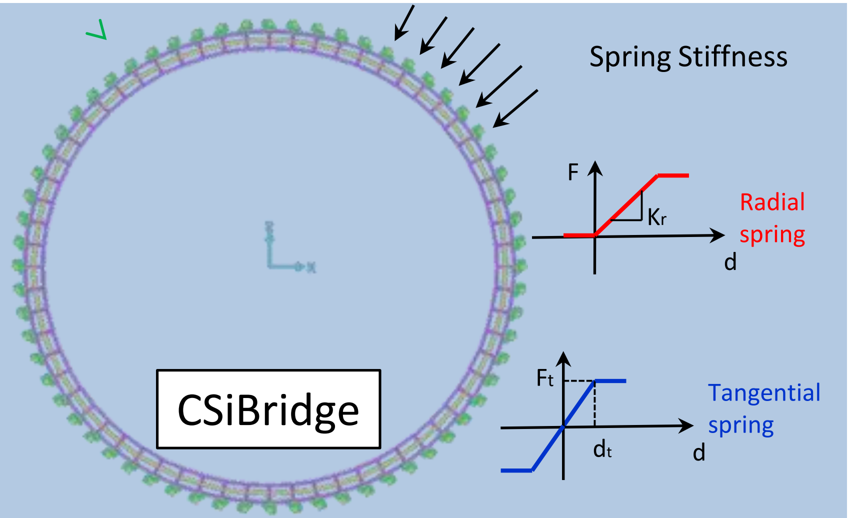
Transverse Design – Static Analysis – A Two-Step Approach

Step 1
Geotechnical Modeling



1. 2D continuum model
2. Geotechnical modeling
3. Soil and hydrostatic loads
4. Static SSI springs

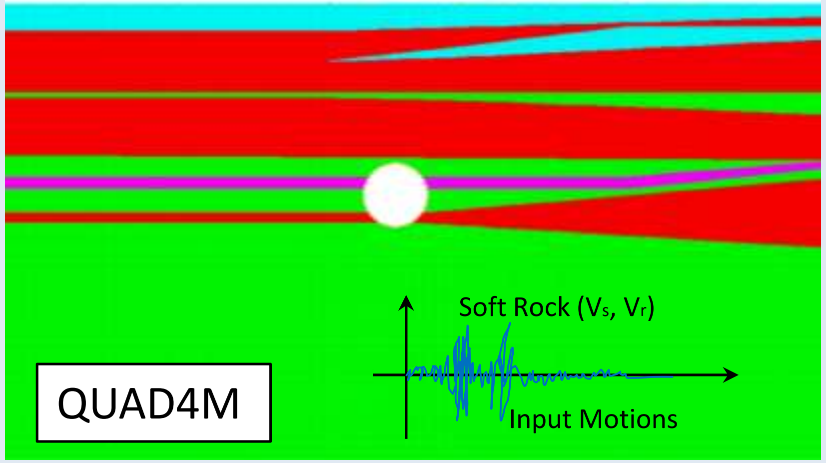
Step 2
Structural Modeling



1. 2D beam on spring model
2. Static analysis
3. LRFD load combinations
4. Structural design

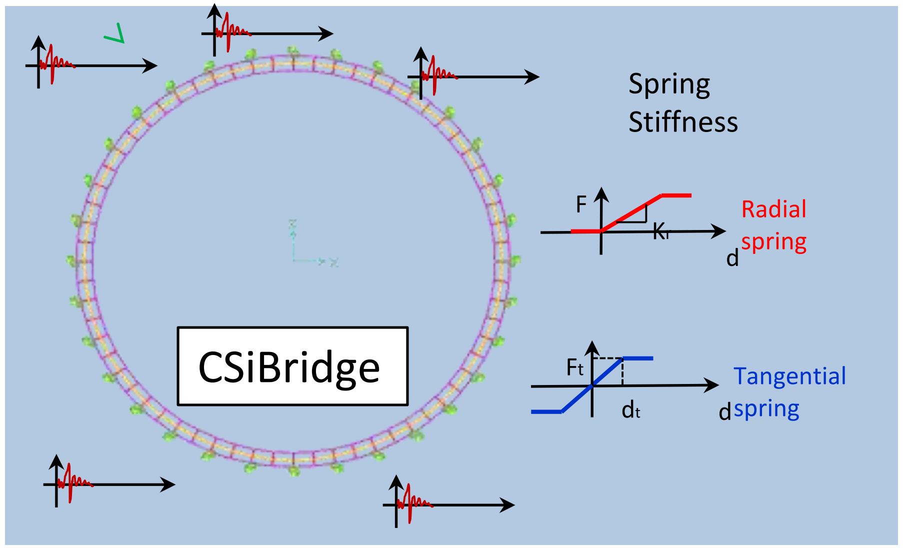
Transverse Design – Seismic Analysis – A Two-Step Approach

Step 1
Geotechnical Modeling



1. 2D continuum model
2. Displacement time histories
3. Dynamic SSI springs

Step 2
Structural Modeling



1. 2D beam on spring model
2. Dynamic time history analysis
3. Deformed shapes during seismic events

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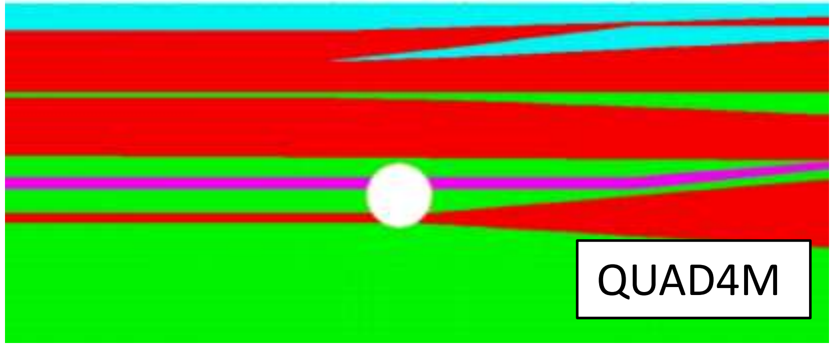
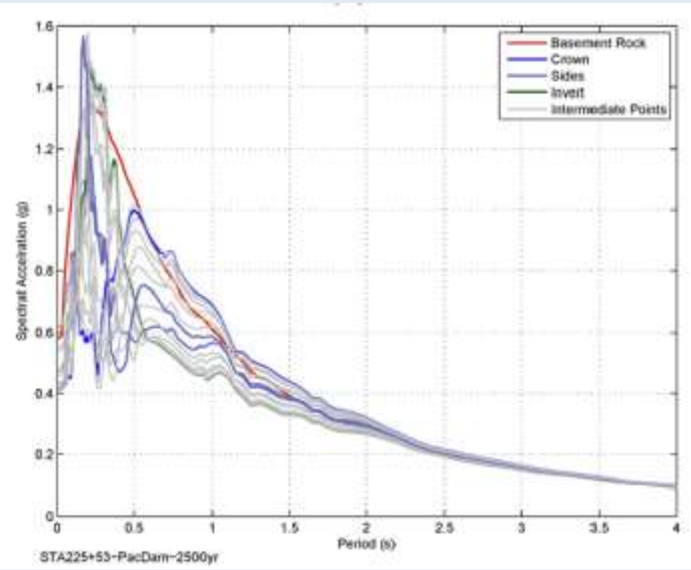
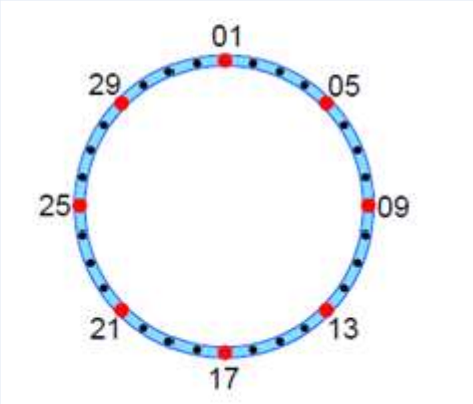
Geotechnical Modeling - 2D Wave Scattering Analysis



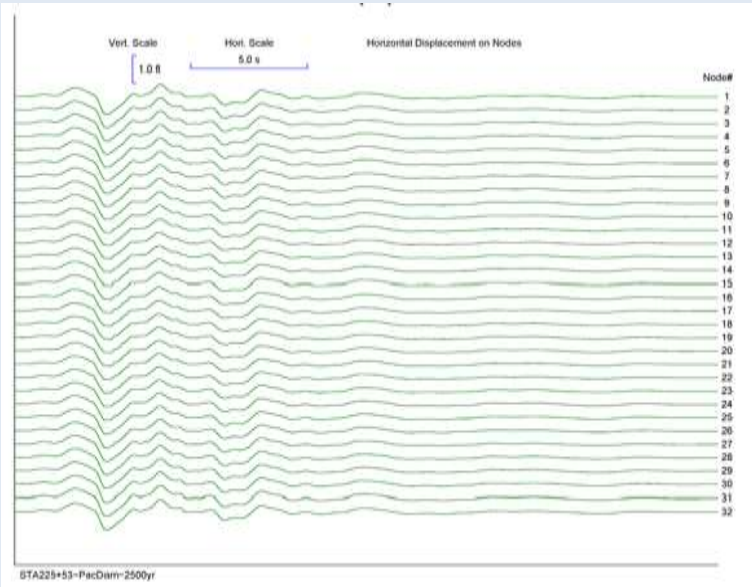
1. Strain-dependency properties (G/G_{max}, damping ratio)
2. Transmitting boundaries to mimic the infinite soil media
3. Generate free-field ground deformations at notes surrounding the ring



Spectral acceleration of soil nodes



Liner node numbering



Horizontal displacement Histories of Soil Nodes

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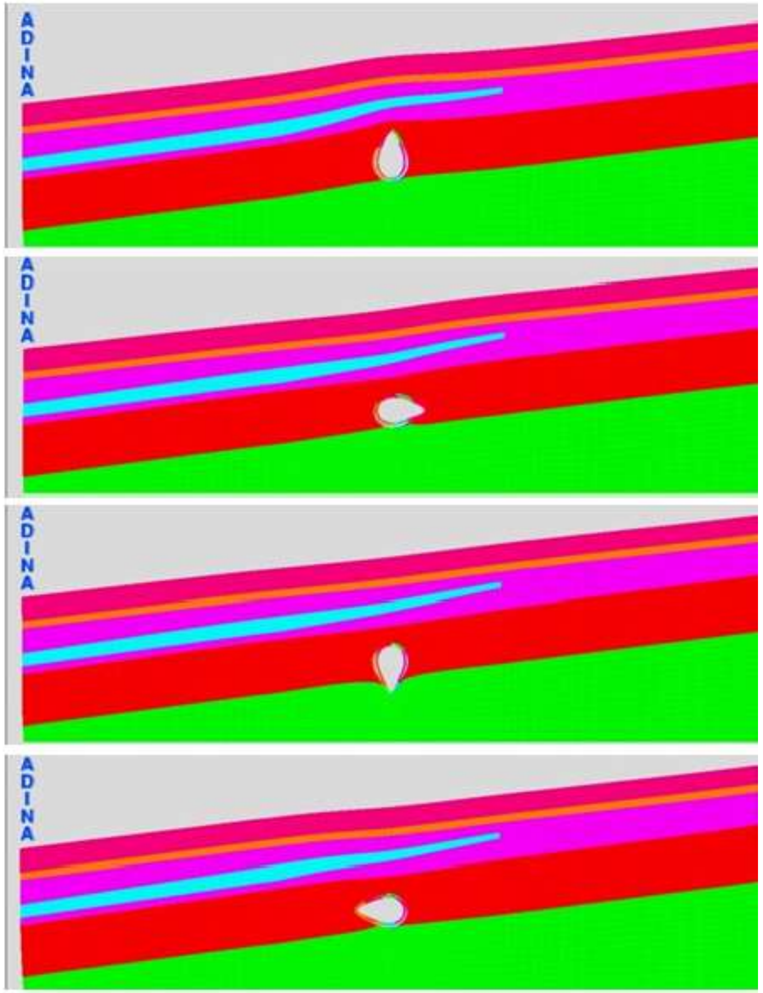
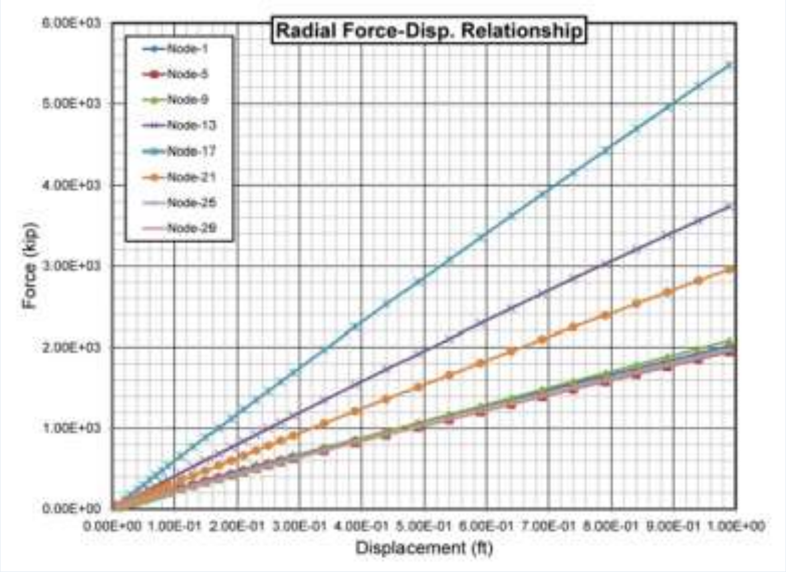
Geotechnical Modeling – Development of Spring Supports

1. Displacement-controlled push-over analysis for radial springs
2. Contact surfaces between liner and soil elements to allow slippage and separation
3. Tangential springs calculated based on maximum shear force between the liner and soils



Magnified deformed shapes at end of push-over analysis (Nodes 1, 19, 25)



Force-displacement relationship for radial springs

For cohesive soil

$$F_{max} = \alpha C$$

$$\begin{cases} \alpha = 0.5\psi^{-0.50} & \psi \leq 1.0 \\ \alpha = 0.5\psi^{-0.25} & \psi > 1.0 \end{cases}$$

$$\psi = {C_i}/{P_0}$$

For cohesionless soil

$$F_{max} = \mu\sigma_n$$

$$\mu = tan\left({2\phi}/{3}\right)$$

Max forces for tangential springs

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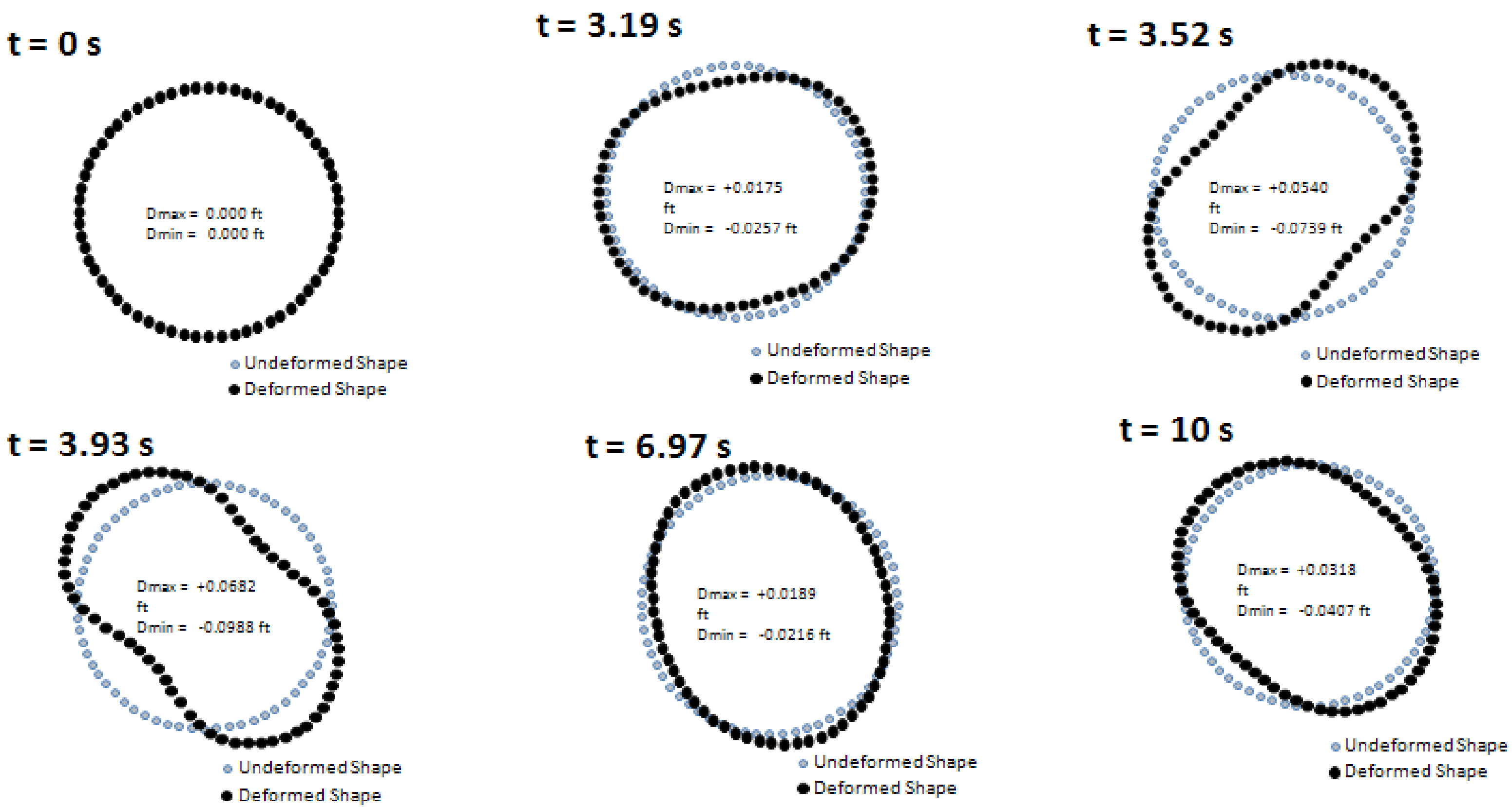
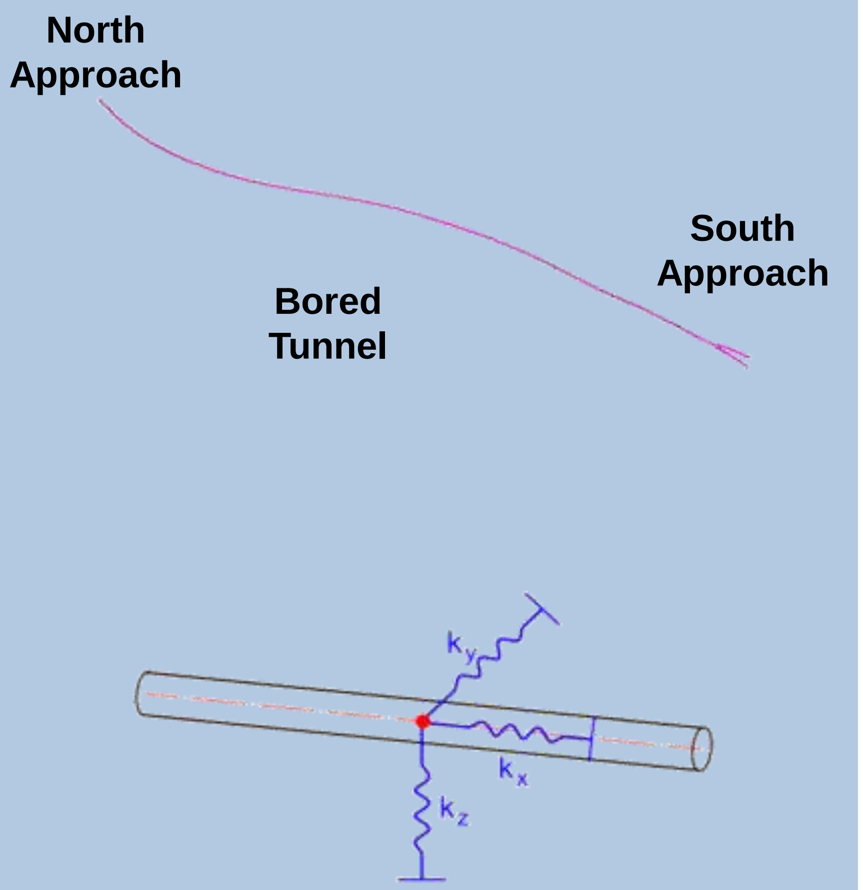
Transverse Seismic Results - Ovaling



- Determine the shape corresponding to maximum curvature
- Maximum ovaling is 1.5 inches from Rare Earthquake

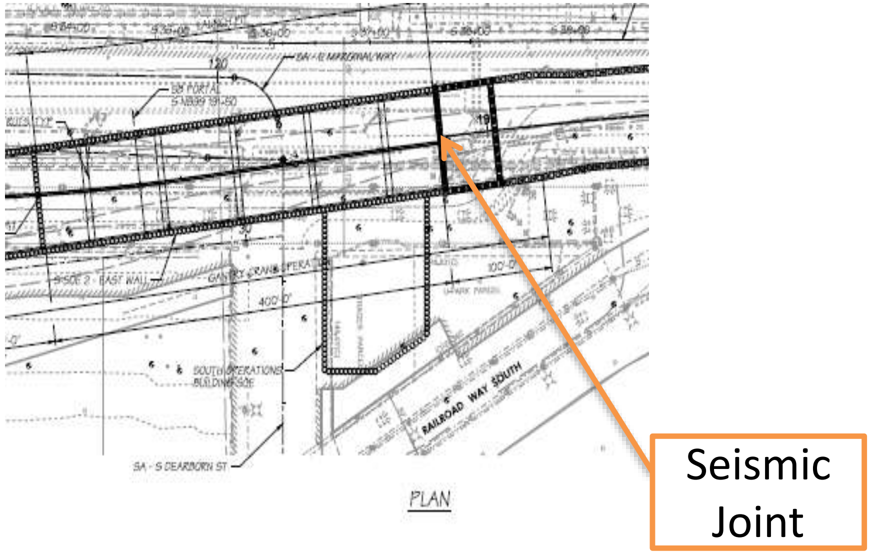
Longitudinal Analysis – Axial and Bending Deformations

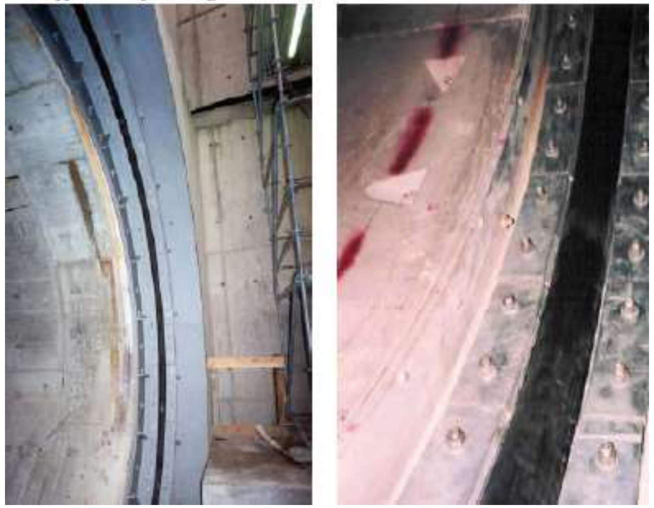
3D Spine Model



1. Study longitudinal behavior
2. Determine the forces at the transverse joints
3. Determine longitudinal deformation and curvature
4. Determine displacements at interfaces between liner and headwalls

Longitudinal Design – Joint Opening/Closing



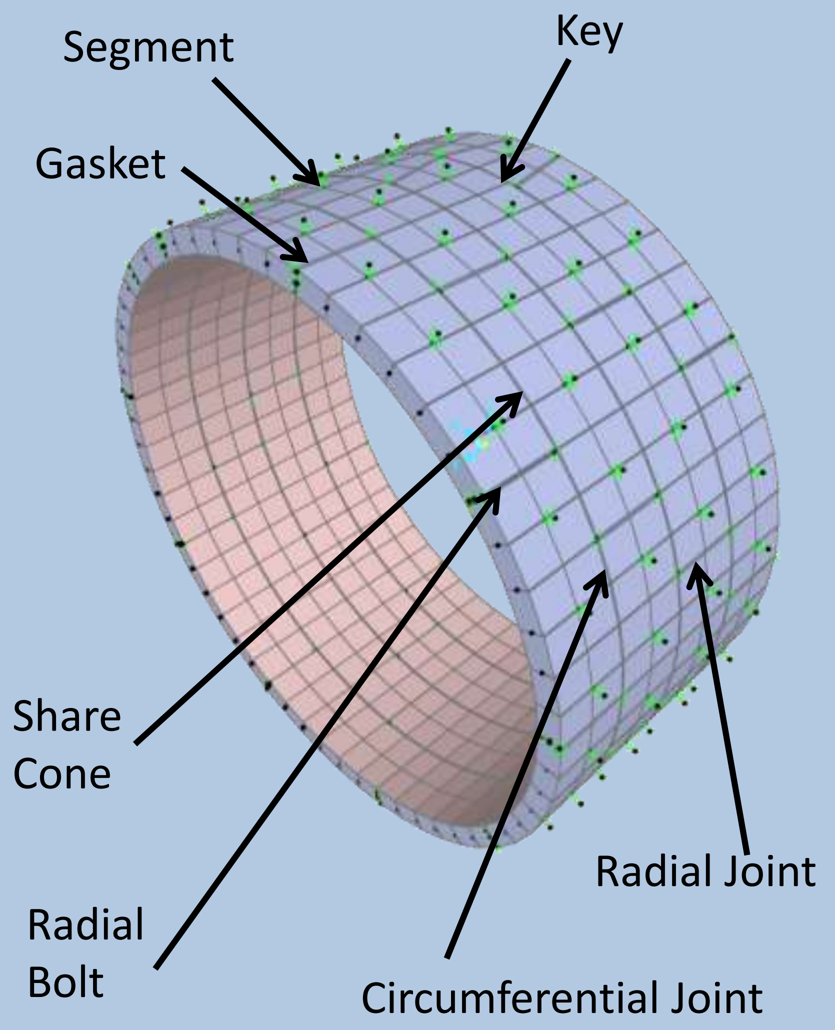


Results from the longitudinal analysis

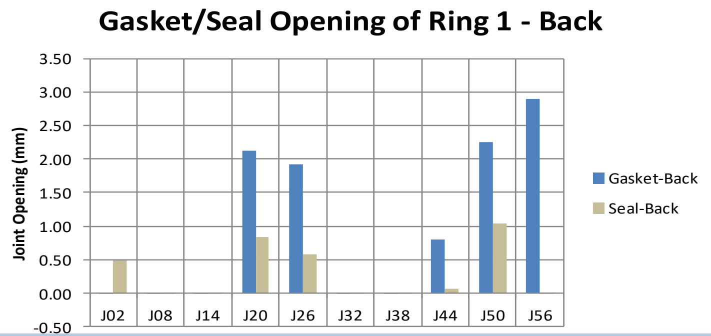
Gap	Expected EQ	Rare EQ
Opening	0.1”	6.6”
Closing	0.2”	8.6”

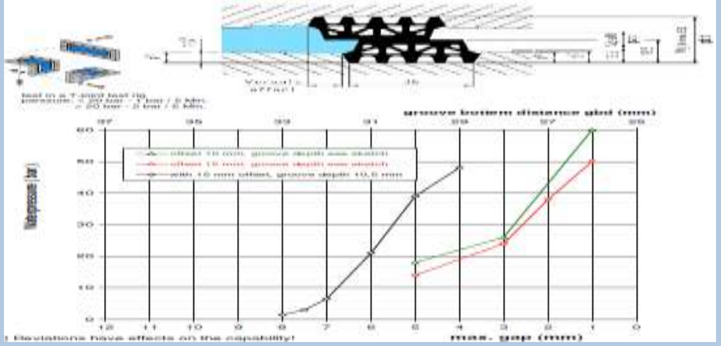
Seismic Performance – Gasket Design

3D Finite Element Model



1. Imposing transverse and longitudinal deformations on the 3D model
2. Determine the gap opening at the radial and circumferential joints





Tunnel Construction – Bertha in Launching Pit

Bertha on its public opening – July 2013

Tunnel Construction

Leaving the launch pit behind – October 2013

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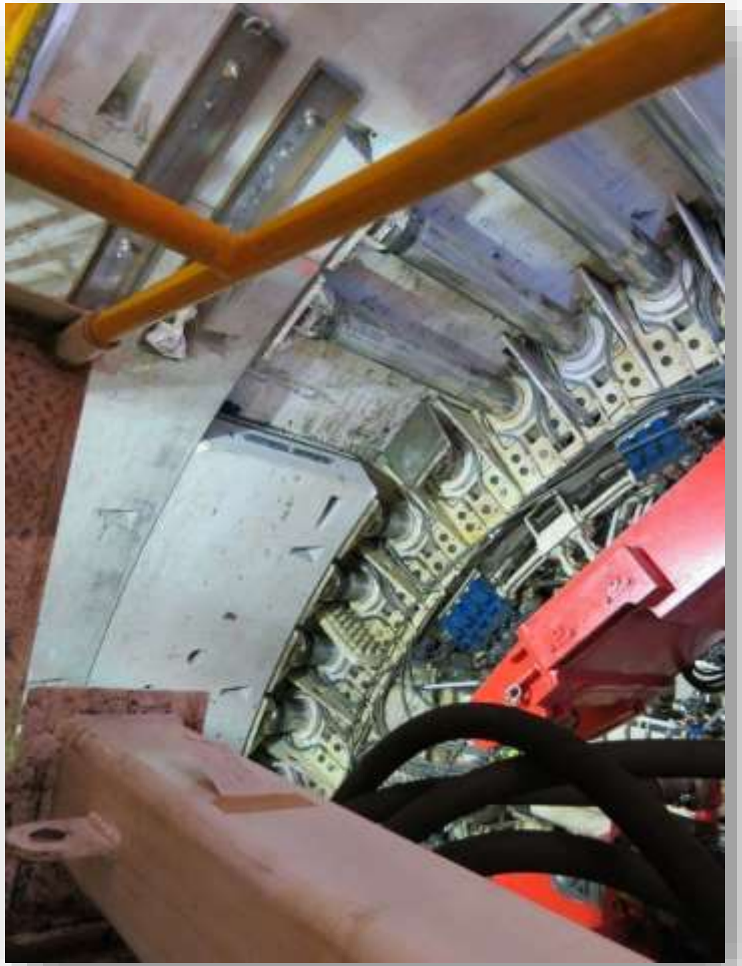
Tunnel Construction – TBM



Tunneling Boring Machine control room and hydraulic jacks

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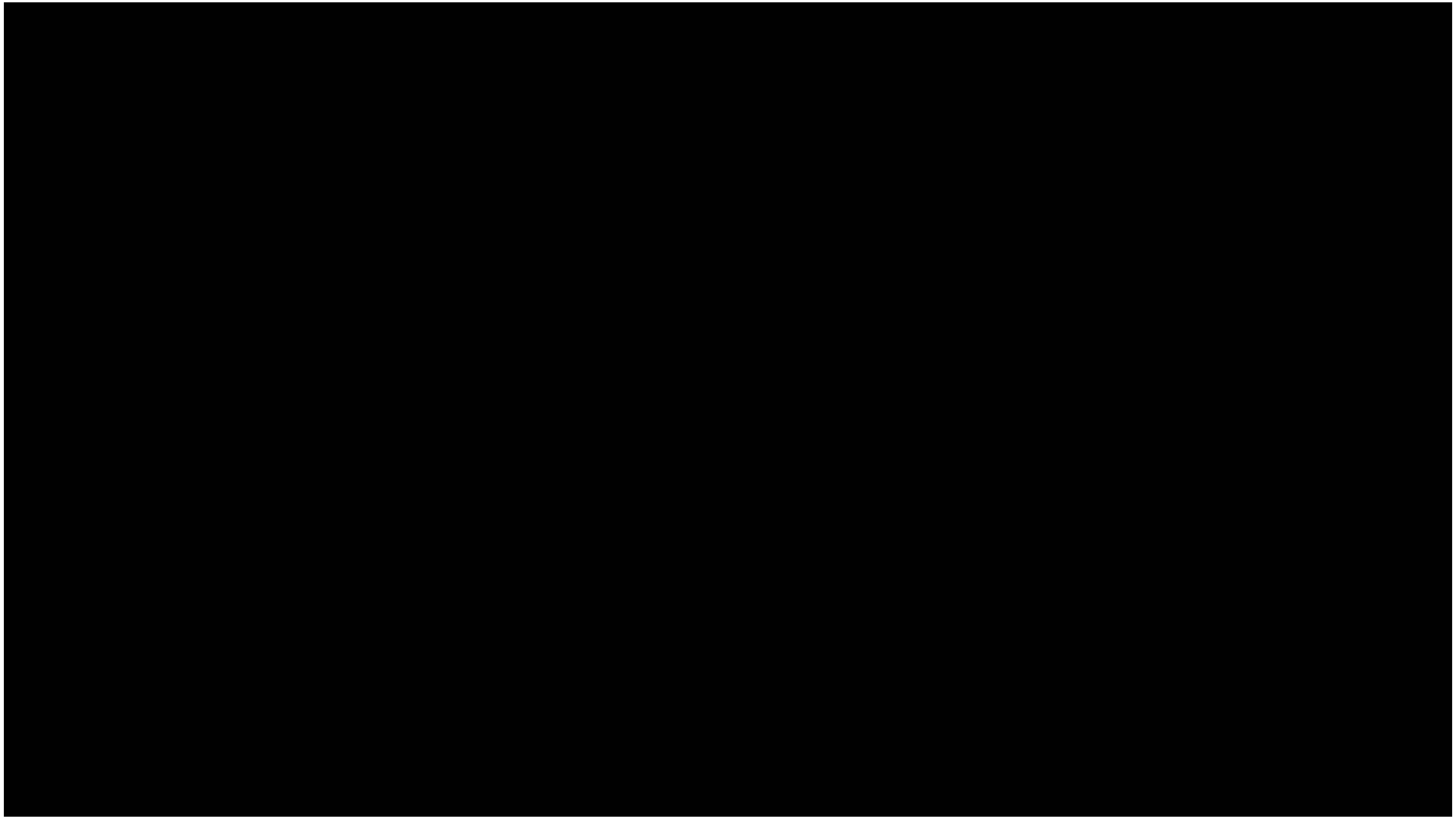
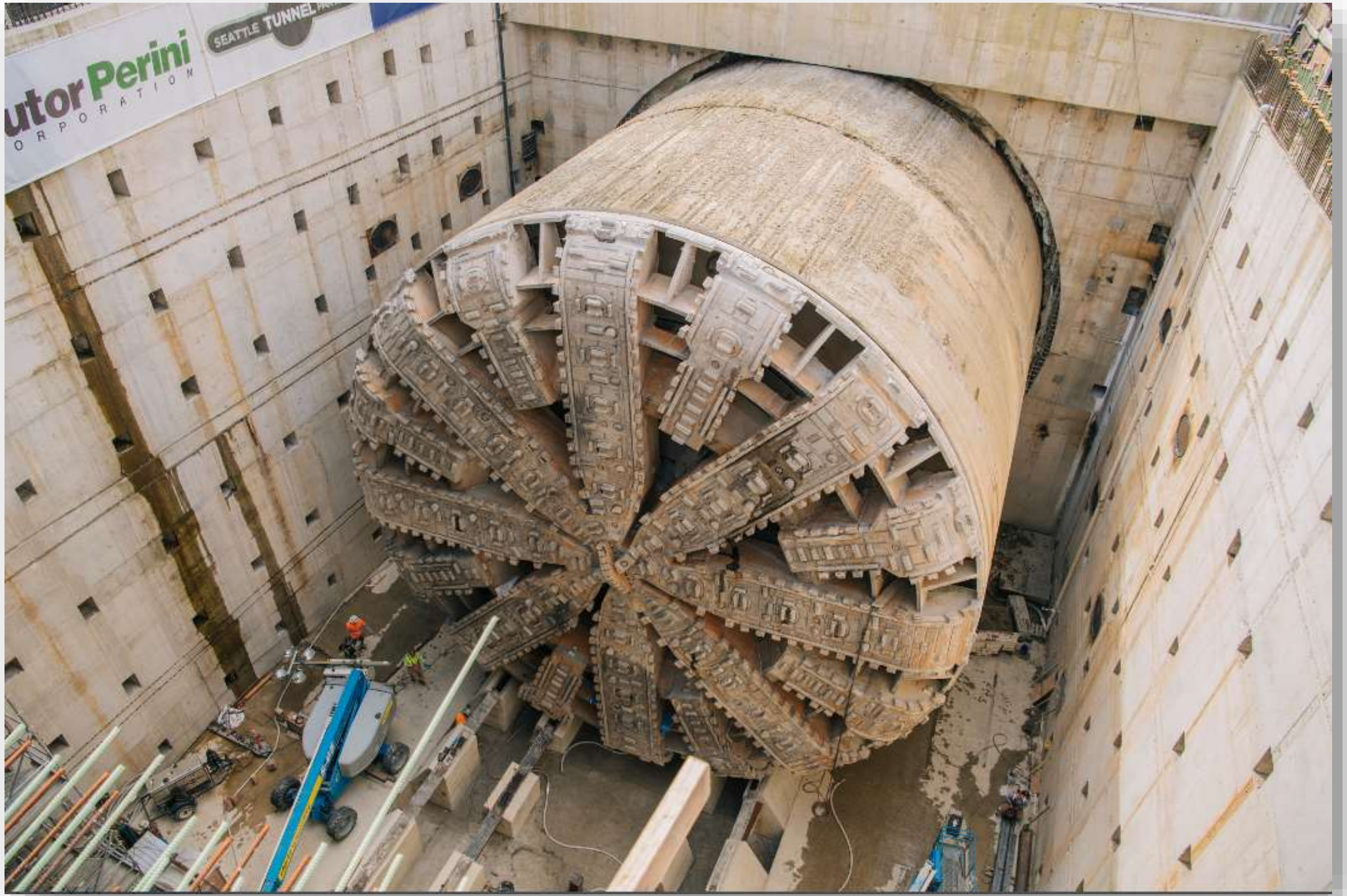
TBM Breakthrough – Drone Footage



TBM Breakthrough



Breakthrough - April 2017

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Completed Tunnel without Interior Structures

Tunnel interior with ventilation ducts – 2017

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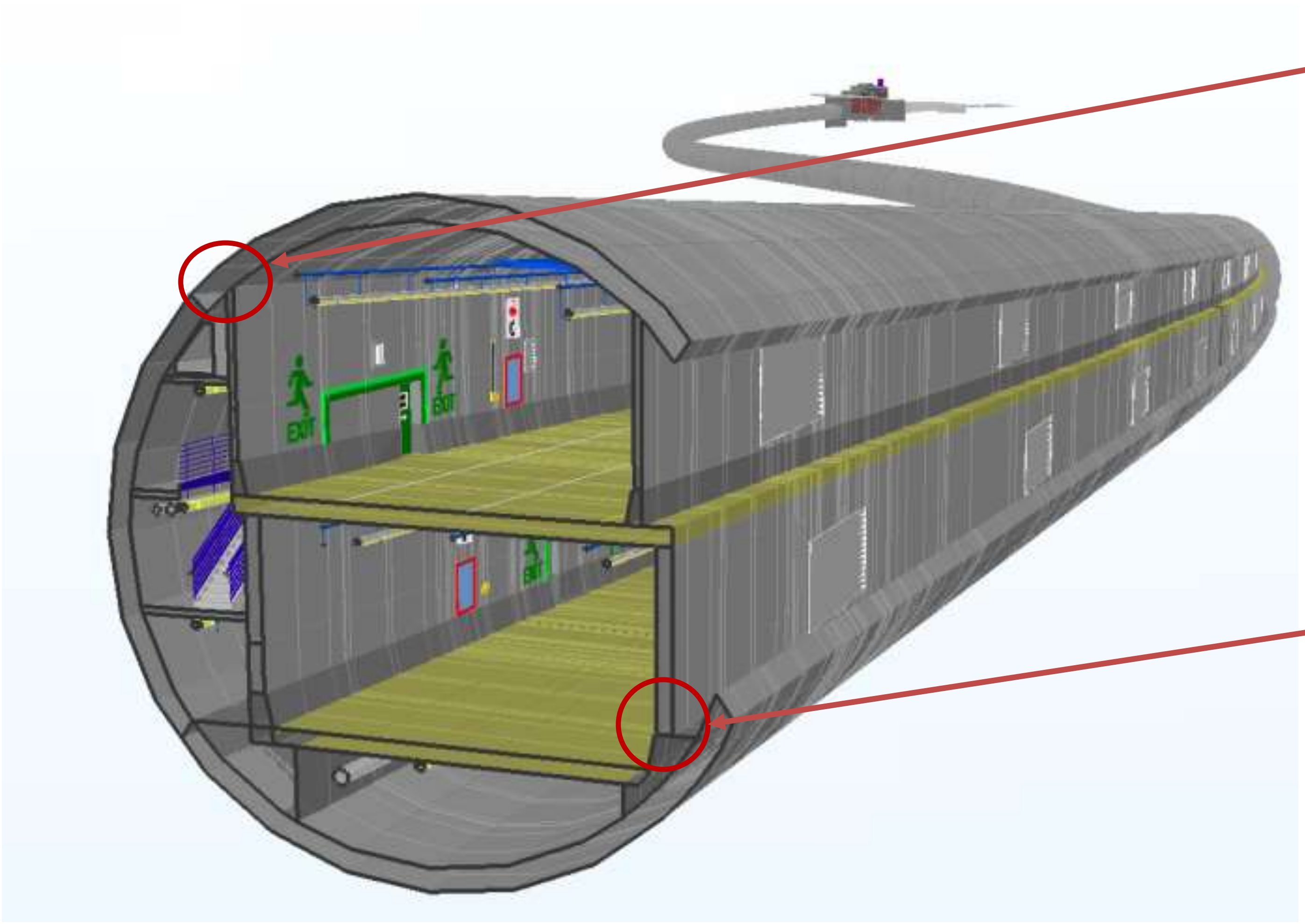
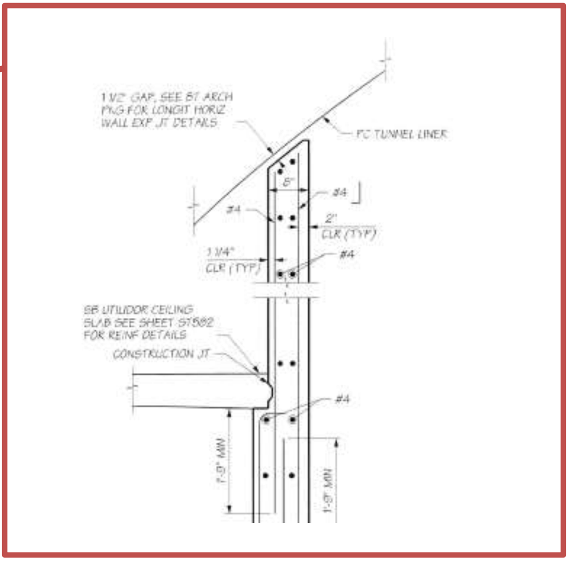
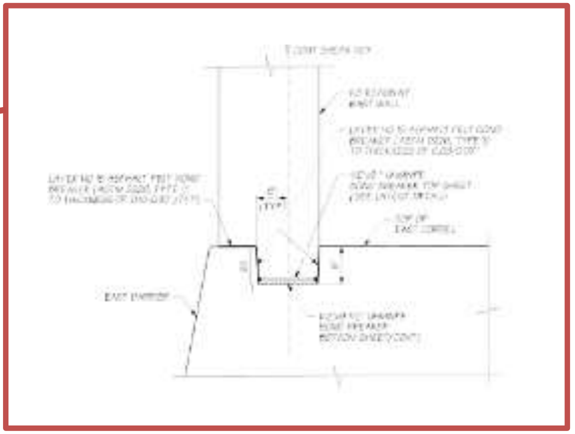
Tunnel Construction – Interior Structures



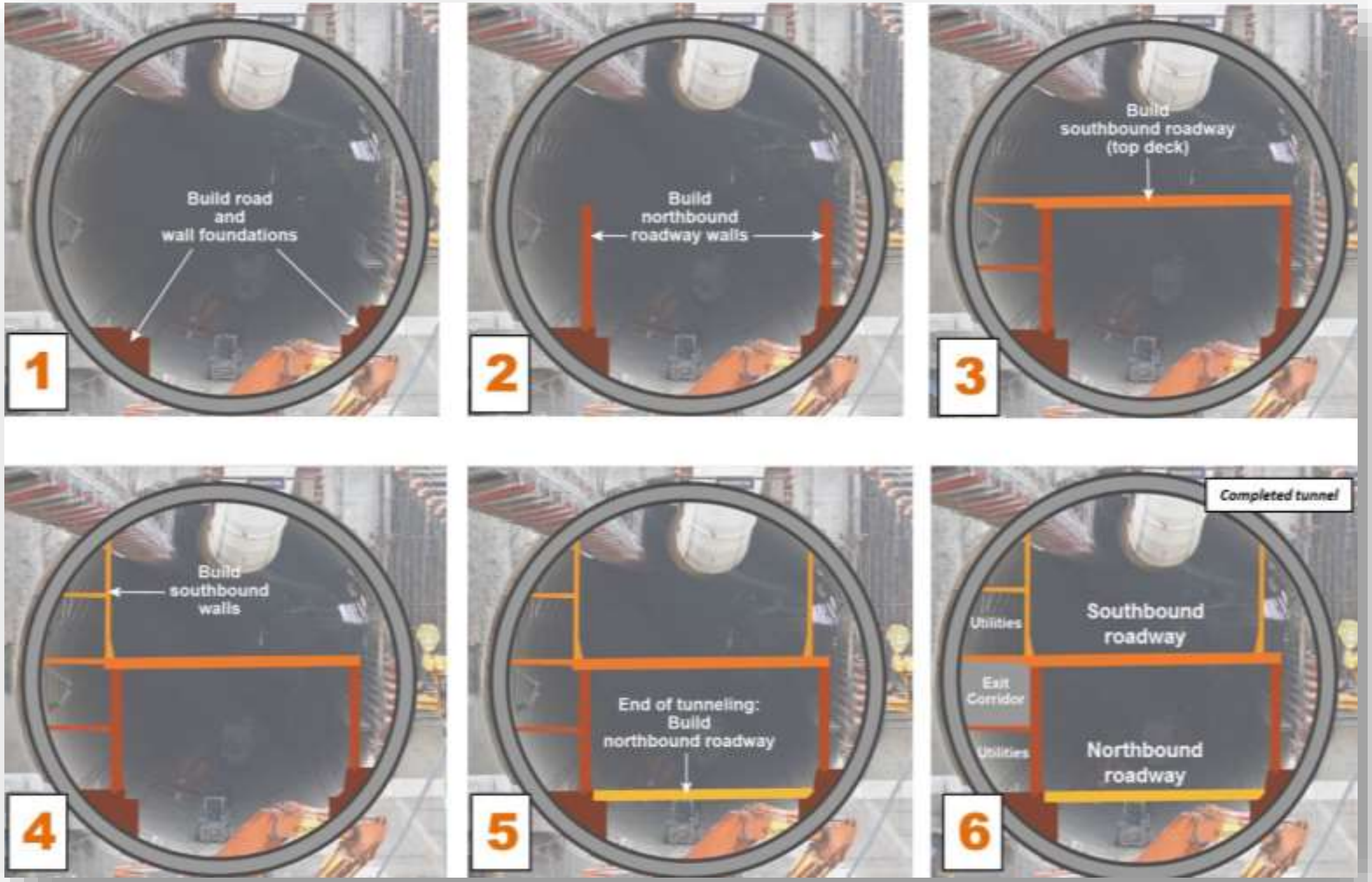
Freestanding Concrete Frame with 650’ Units





Sample Liner -Structure Compatibility Details

Constructing Interior Structures



Construction sequence of the interior structures

Source: WSDOT

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Inside the Tunnel

Inside completed tunnel - April 2019

Future Look of Seattle Waterfront

Waterfront with Alaskan Way Viaduct

Artist's Rendering of Future Seattle Waterfront

Concluding Remarks

1. Seismic loads and deformations did not govern the size and reinforcement of the liner, but the size of the shear cones and the size of the gasket
2. Non-linear dynamic time history analysis can help demonstrate that the liner meets stringent seismic performance criteria
3. The two-step approach is an efficient and sufficiently accurate method for liner design
4. Temporary stress conditions such as TBM jacking and gasket compression are more critical for large diameter liner segments
5. There is room to go larger for TBM bored tunnels

Team Members

Owner: Washington State Department of Transportation

DB Contractor: Seattle Tunnel Partners

Joint Venture: DRAGADOS USA; Tutor Perini Corporation

Designer: HNTB

Sub-Consultant: Intecsa-Inarsa; HartCrowser; Earth Mechanics Inc. Geotechnical and Earthquake Engineering