Geology of Seattle

Downtown Seattle & the Alaskan Way Viaduct

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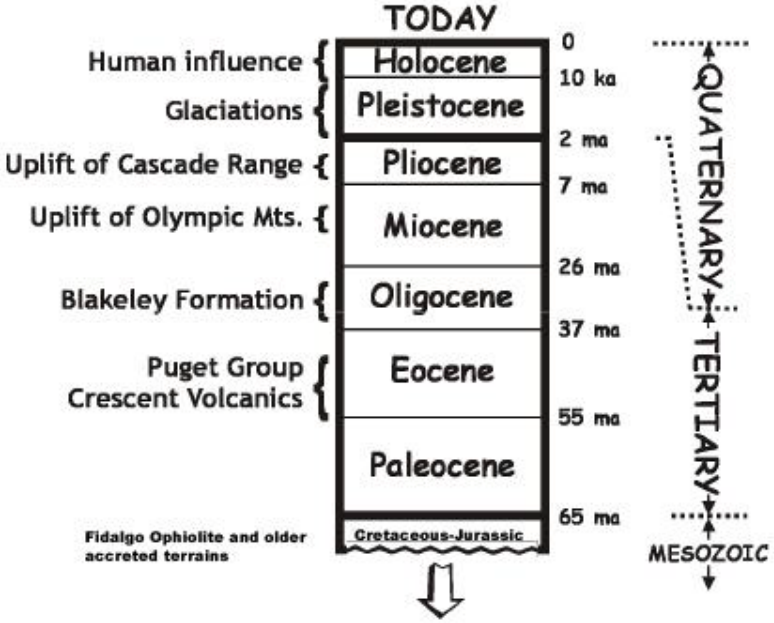
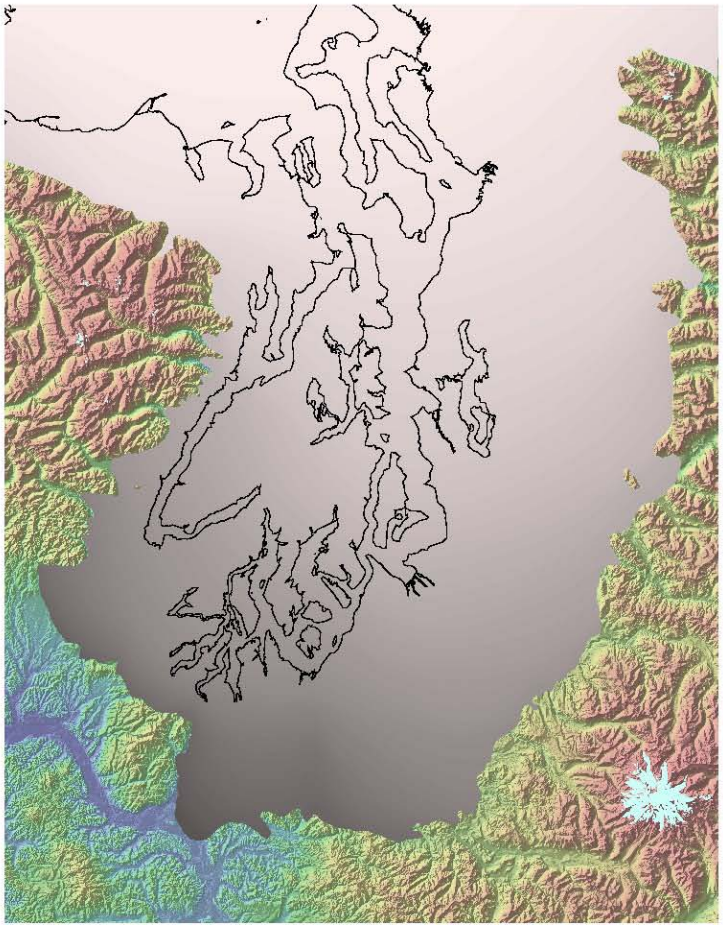
Geological Timescale



- Seattle has been impacted by repeated glaciations for the past 2.4m.y.
- The last glacier to override the area was the Vashon glacier (reached @ ~14,500 14C yr B.P & retreated by ~13,650 14C yr B.P). as part of the Fraser Glaciation (30-10 ka)
- Pre-Fraser, was the Olympia glaciation (65- 15ka)

Fraser Glaciation advancement and result



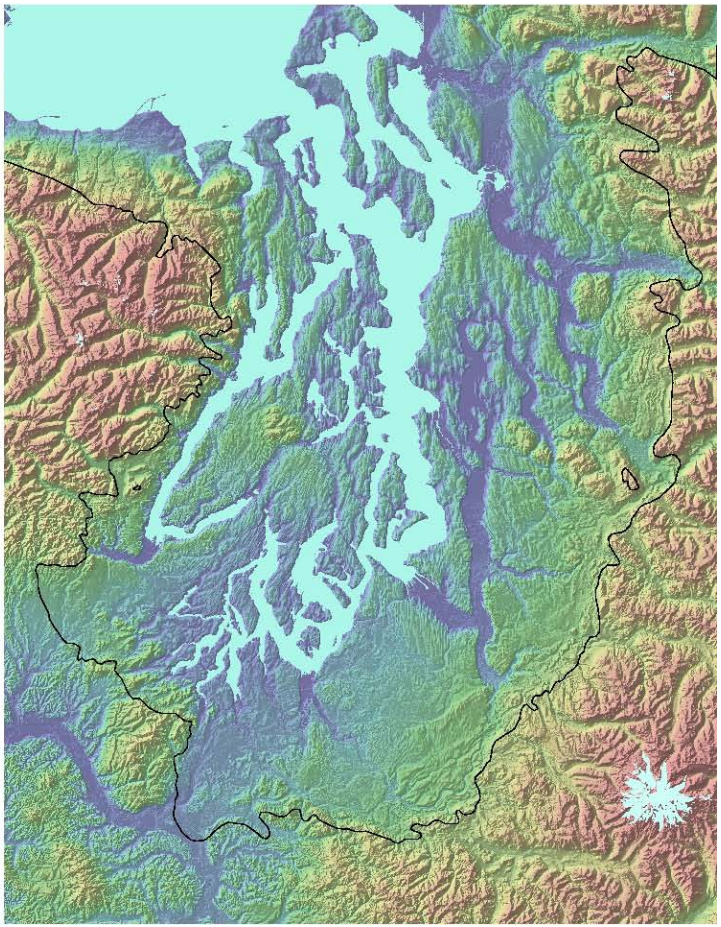
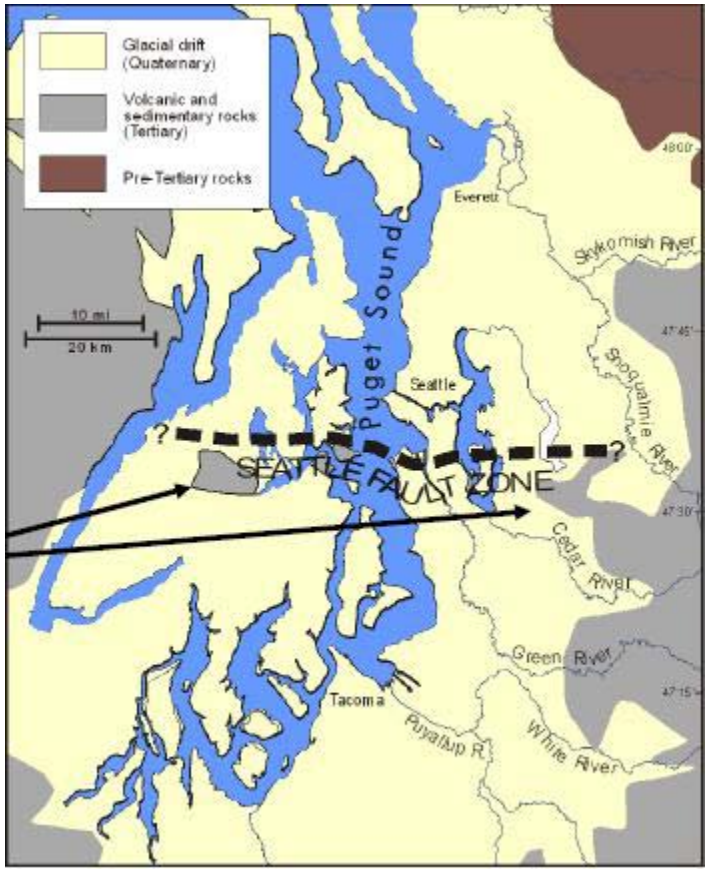
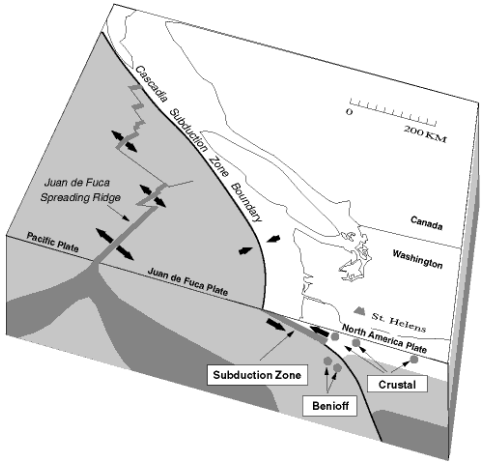


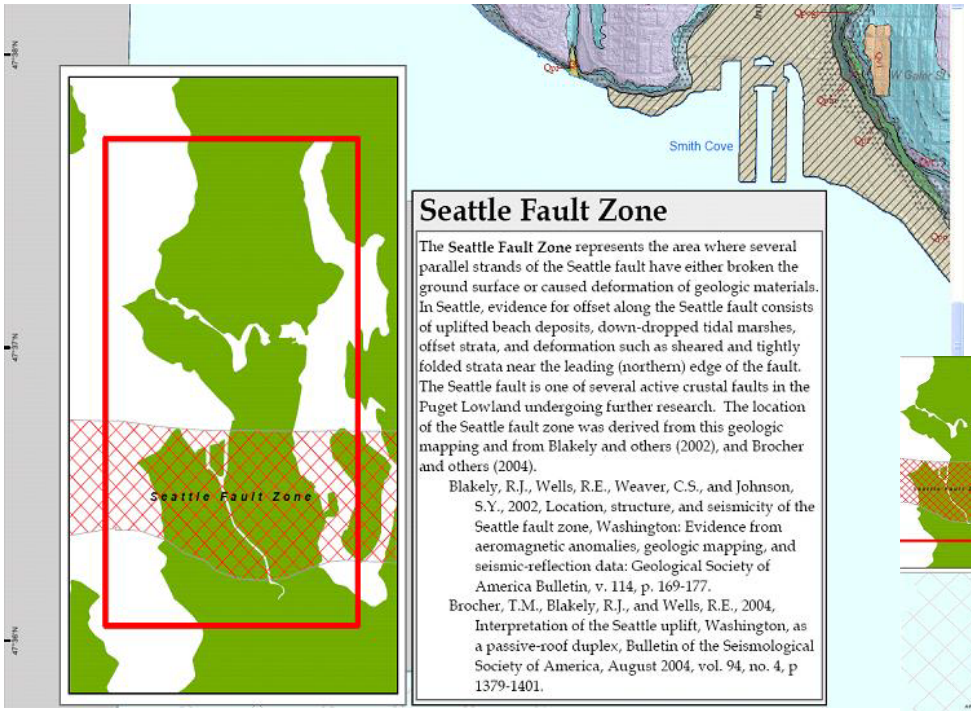
Plate Tectonics & Faults

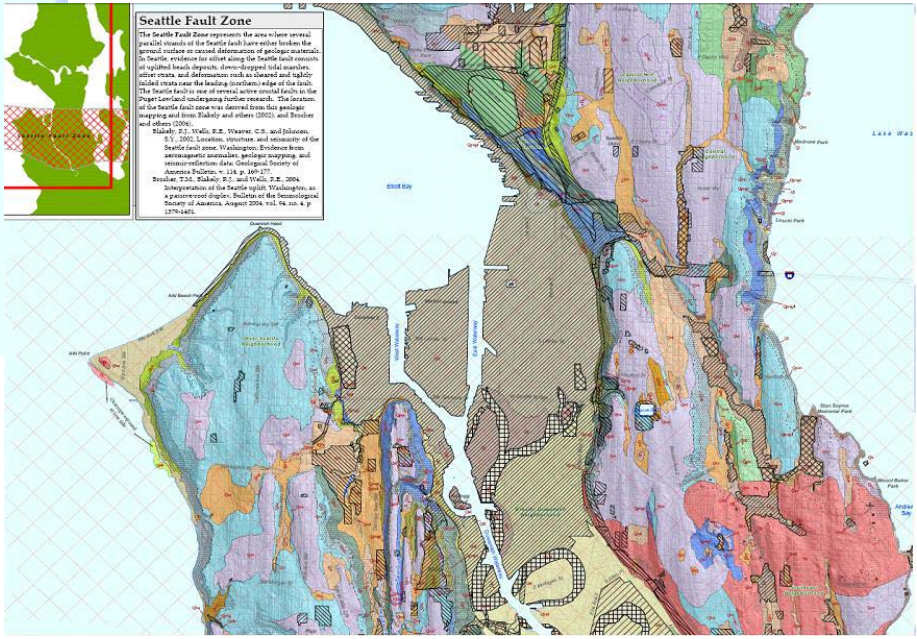




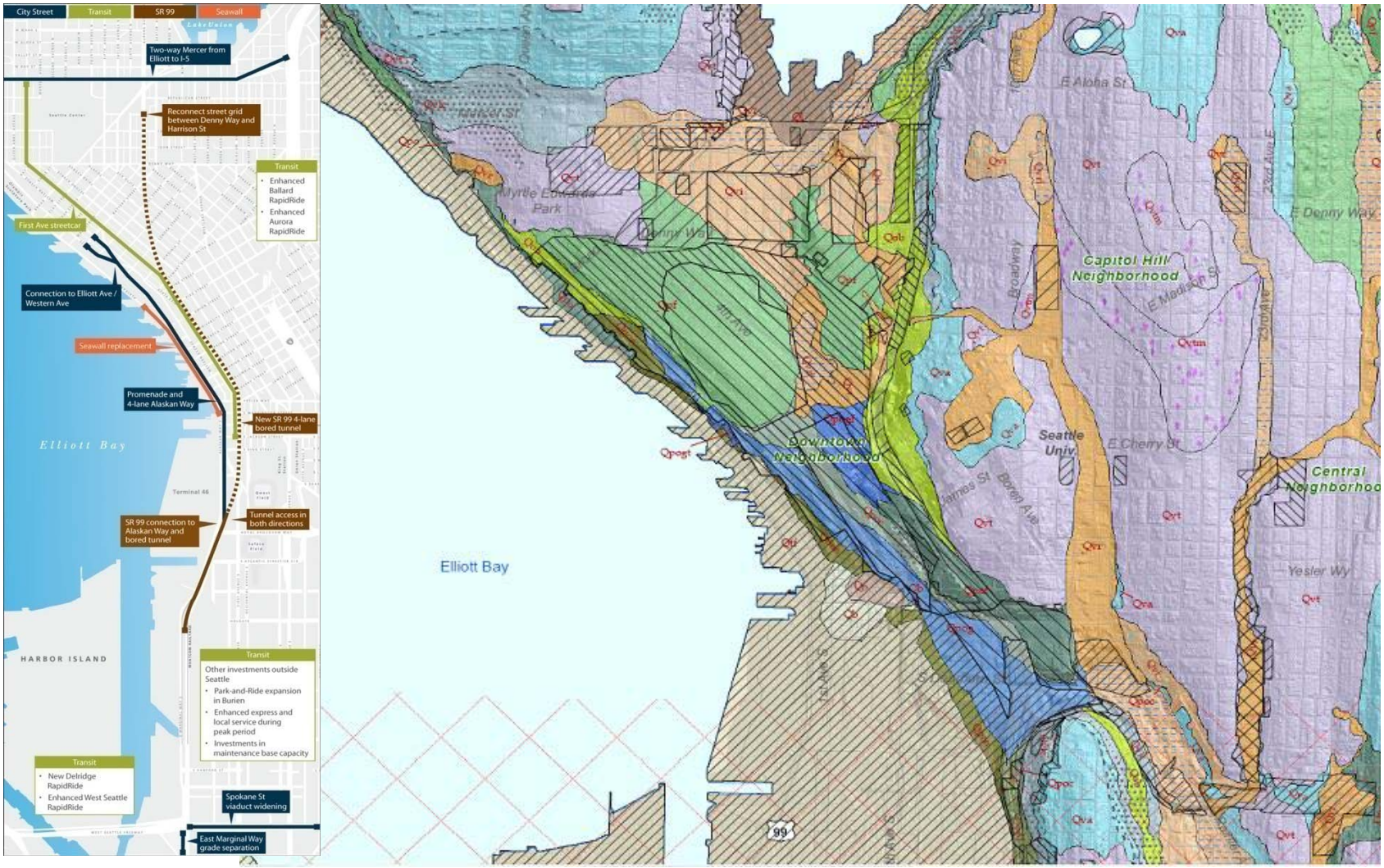
- Cascadia subduction zone
- Seattle Fault
- Seattle Fault Zone

What and where is the Seattle Fault Zone?

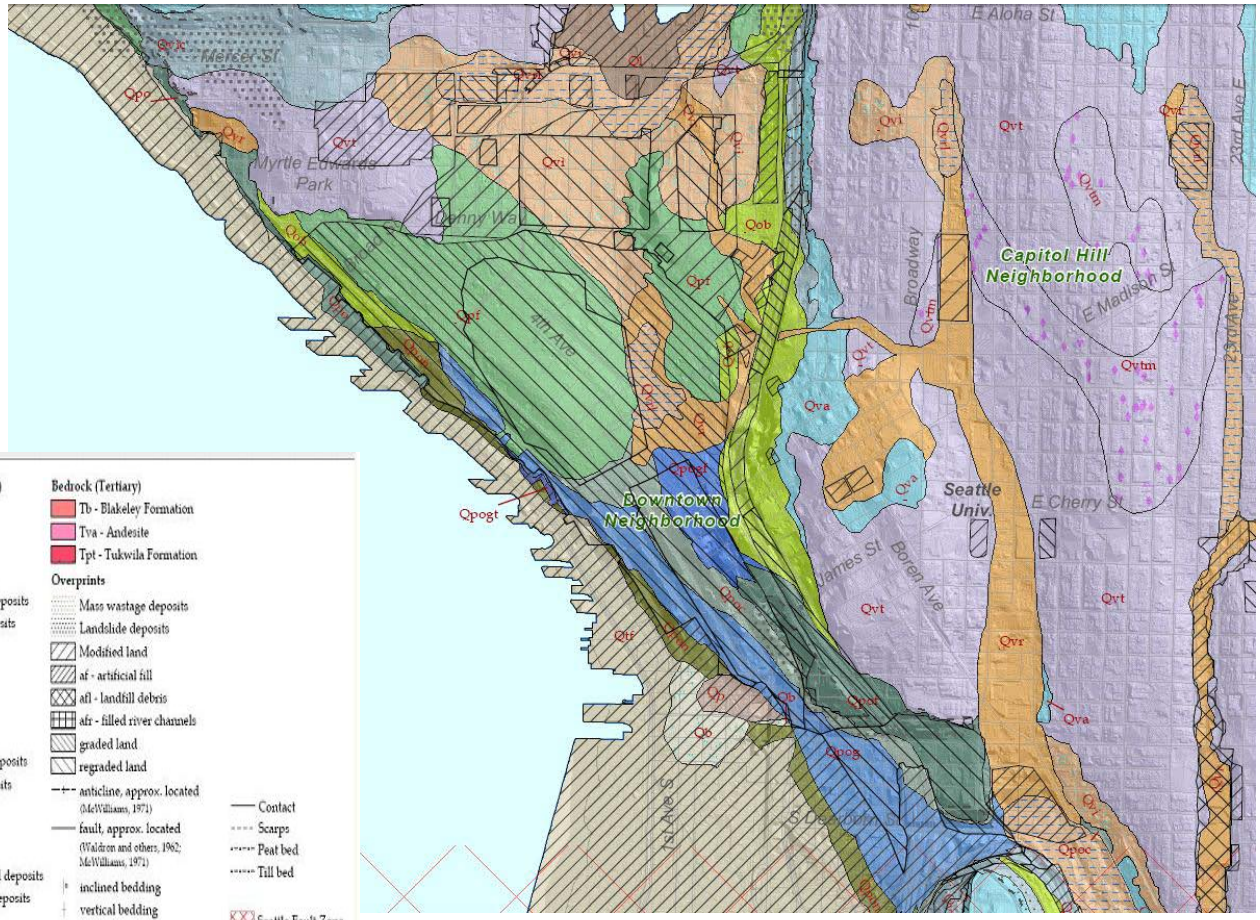




Downtown Seattle Geological Map



Map Units



Map Units

Nonglacial Deposits (Holocene)

- water
- Qw - Wetland deposits
- Qp - Peat
- Qb - Beach deposits
- Qbu - Uplifted beach deposits
- Qtf - Tideflat deposits
- Qal - Alluvium
- Qyal - Younger alluvium
- Ql - Lake deposits
- Qf - Fan deposits
- Qt - Terrace deposits

Younger Glacial Deposits (Fraser Glaciation, Pleistocene)

- Qvr - Vashon recessional outwash deposits
- Qvrl - Vashon recessional lacustrine deposits
- Qvrc - Vashon recessional coarse-grained deposits
- Qvi - Vashon ice-contact deposits
- Qvt - Vashon subglacial till
- Qvtm - Vashon subglacial meltout till
- Qva - Vashon advance outwash deposits
- Qvlc - Lawton Clay member of the Vashon Drift

Older Glacial and Nonglacial Deposits (Pleistocene)

- Qpf - Pre-Fraser glaciation age deposits
- Qpfc - Pre-Fraser coarse-grained deposits
- Qpff - Pre-Fraser fine-grained deposits
- Qpfn - Pre-Fraser nonglacial deposits
- Qpfnc - Pre-Fraser coarse-grained nonglacial deposits
- Qpfnf - Pre-Fraser fine-grained nonglacial deposits
- Qob - Olympia beds
- Qpo - Pre-Olympia deposits
- Qpoc - Pre-Olympia coarse-grained deposits
- Qpof - Pre-Olympia fine-grained deposits
- Qpog - Pre-Olympia glacial deposits
- Qpogc - Pre-Olympia coarse-grained glacial deposits
- Qpogf - Pre-Olympia fine-grained glacial deposits
- Qpogt - Pre-Olympia glacial till
- Qpogd - Pre-Olympia glacial diamict
- Qpon - Pre-Olympia nonglacial deposits
- Qponc - Pre-Olympia coarse-grained nonglacial deposits
- Qponf - Pre-Olympia fine-grained nonglacial deposits
- Qpdf - Possession drift fine-grained deposits
- Qhc - Hamm Creek formation
- Qpone - Pre-Olympia estuarine deposits

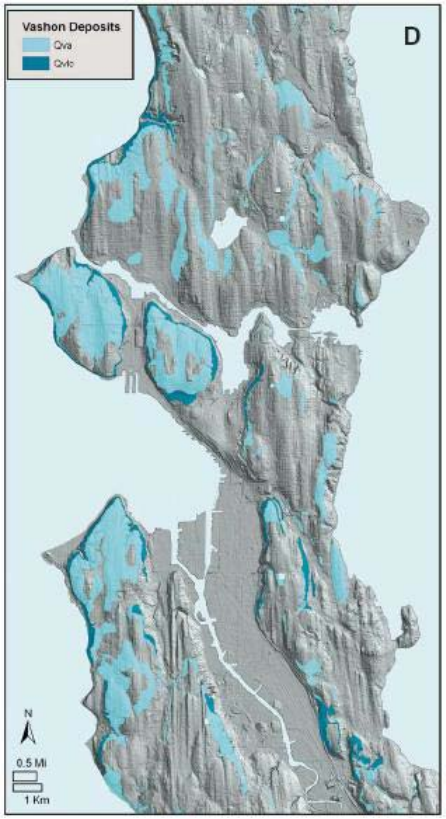
Bedrock (Tertiary)

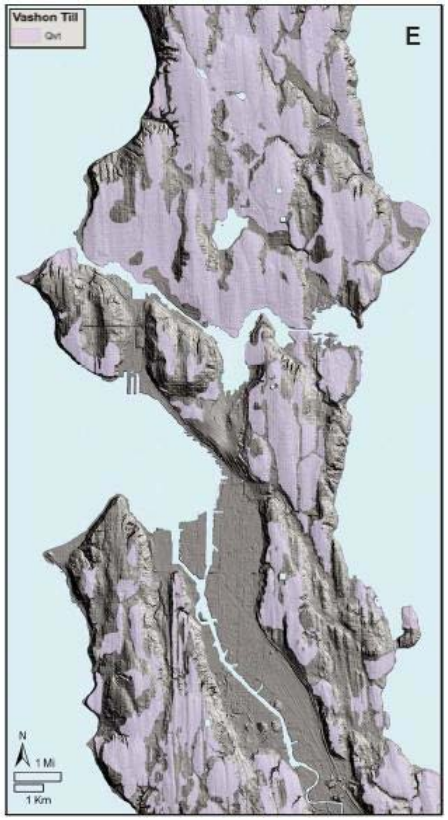
- Tb - Blakeley Formation
- Tva - Andesite
- Tpt - Tukwila Formation

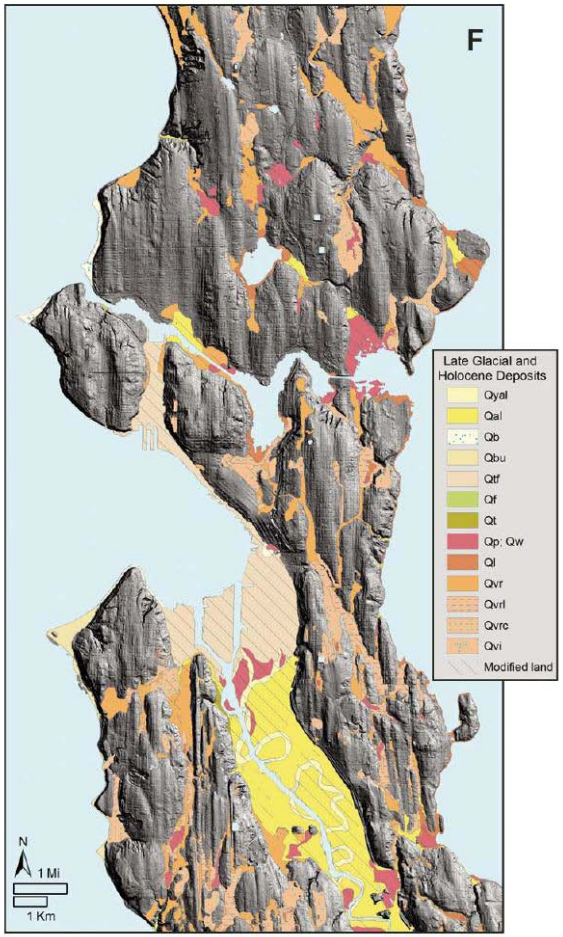
Overprints

- Mass wastage deposits
- Landslide deposits
- Modified land
- af - artificial fill
- afl - landfill debris
- afr - filled river channels
- graded land
- regraded land
- anticline, approx. located (McWilliams, 1971)
- fault, approx. located (Waldron and others, 1962; McWilliams, 1971)
- inclined bedding
- vertical bedding
- inclined jointing
- vertical joint
- Contact
- Scarps
- Peat bed
- Till bed
- Seattle Fault Zone
- Seattle City Limit

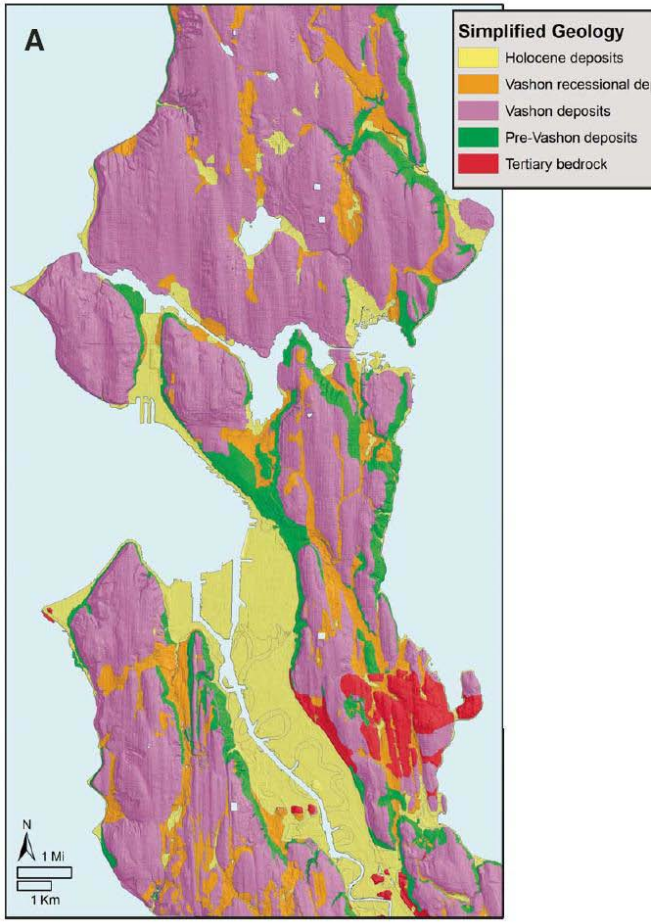
Vashon Deposits/Till vs Late Glacial & Holocene Deposits

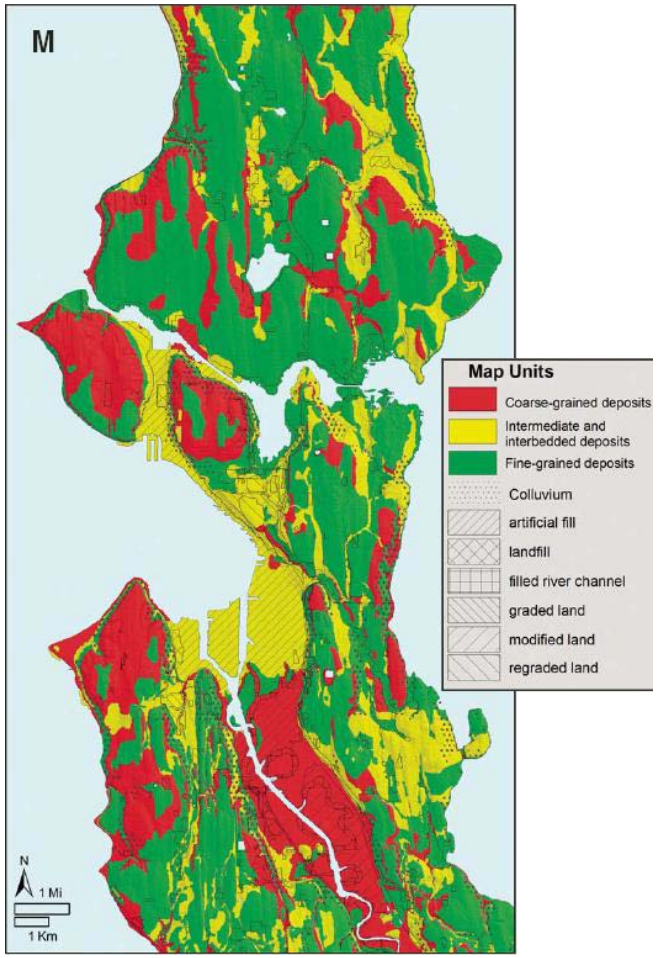




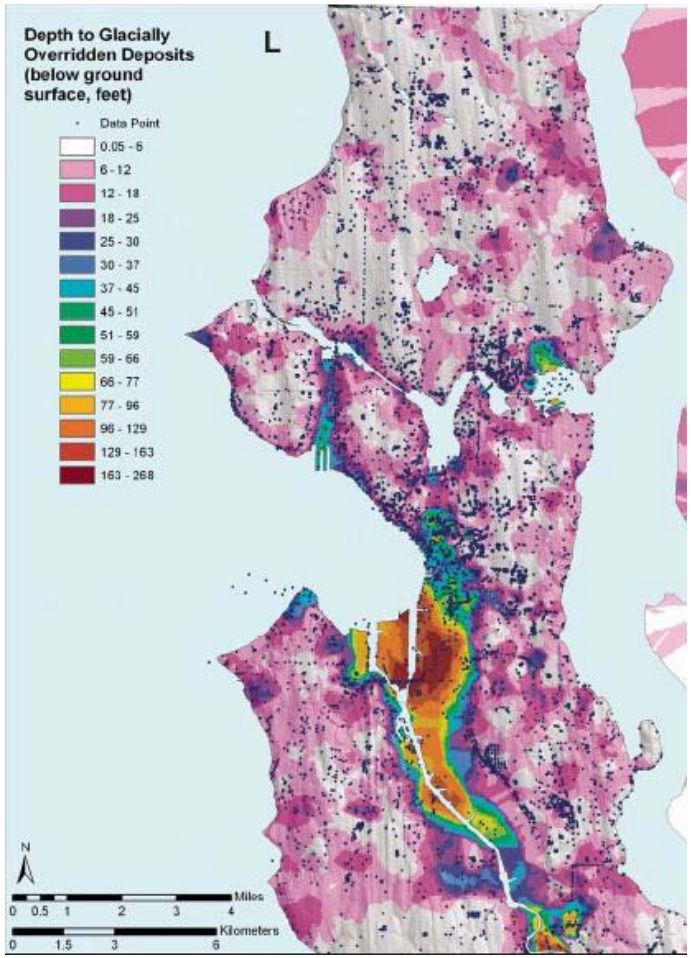


Maps: Simplified Geology & Grain Sizes



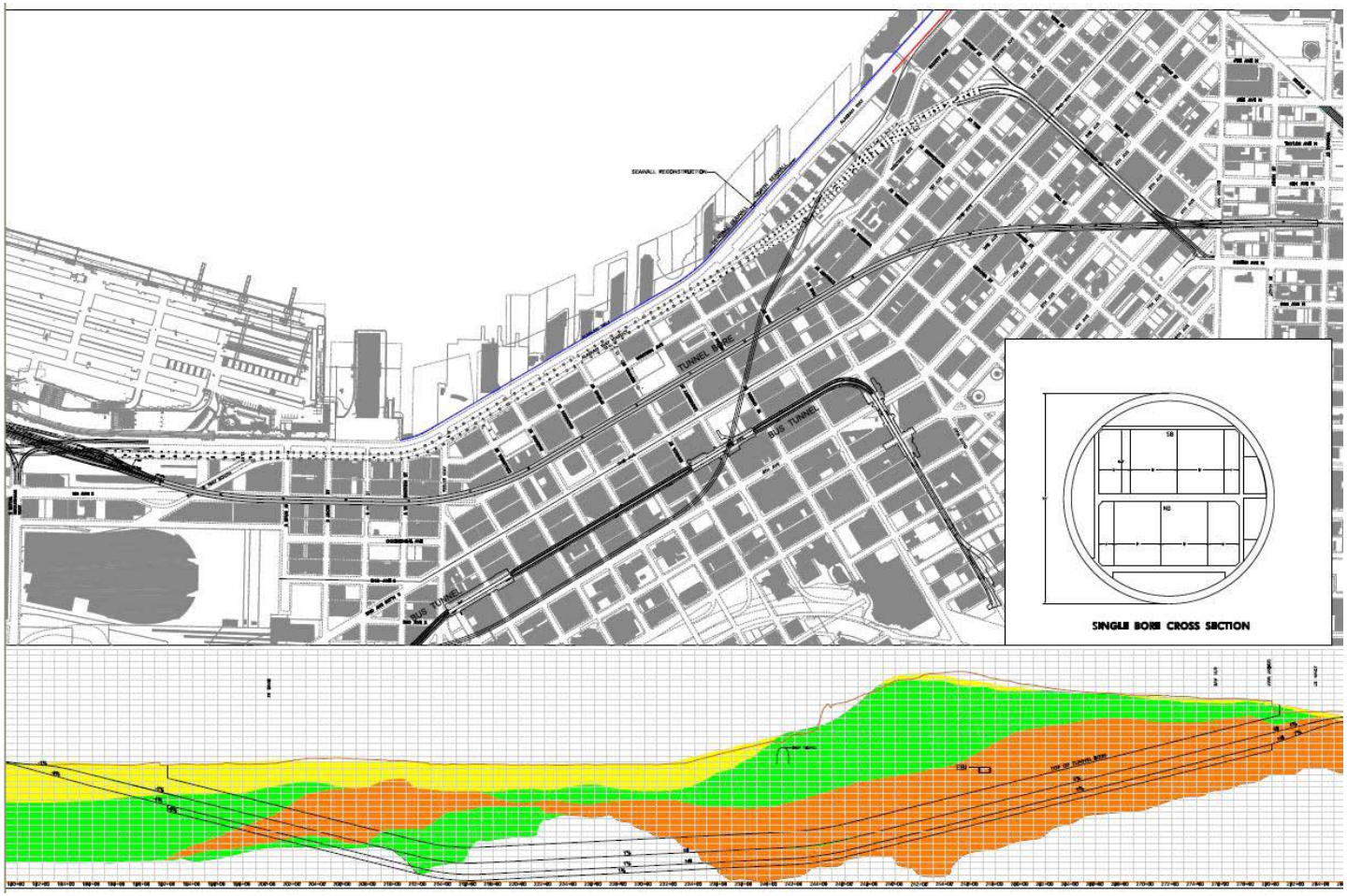


Importance of Glacial Deposits

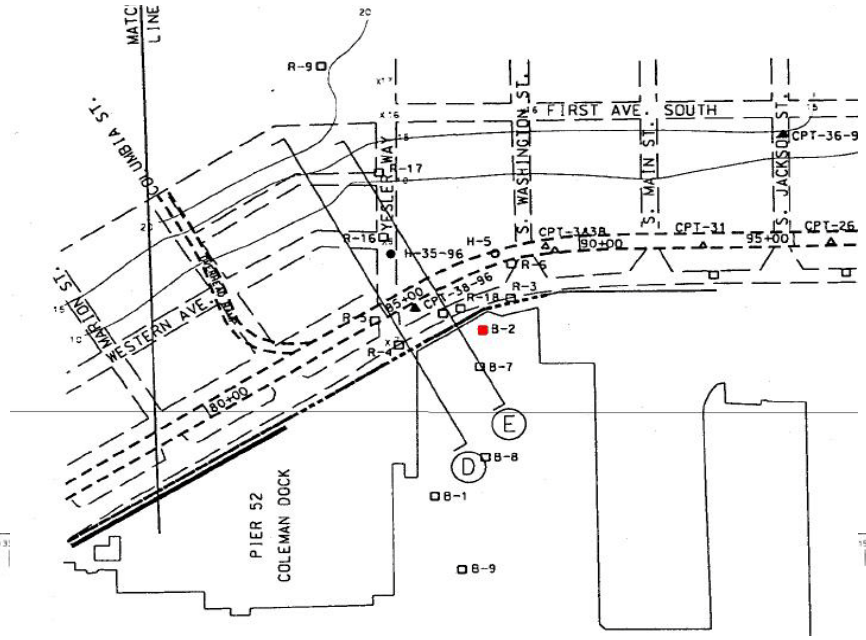


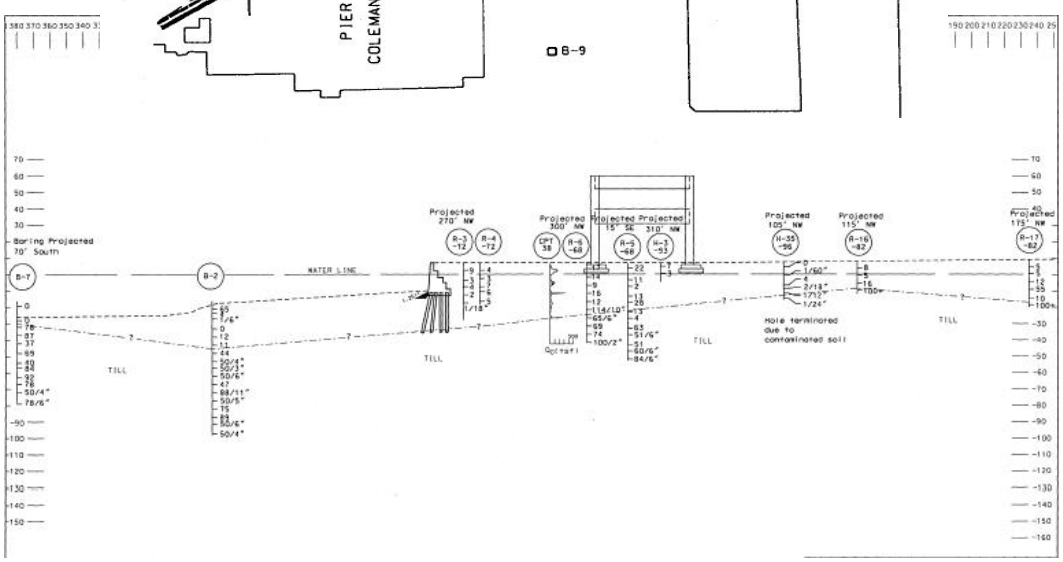
- Very important to engineers out in the field
- Important for conducting drilling

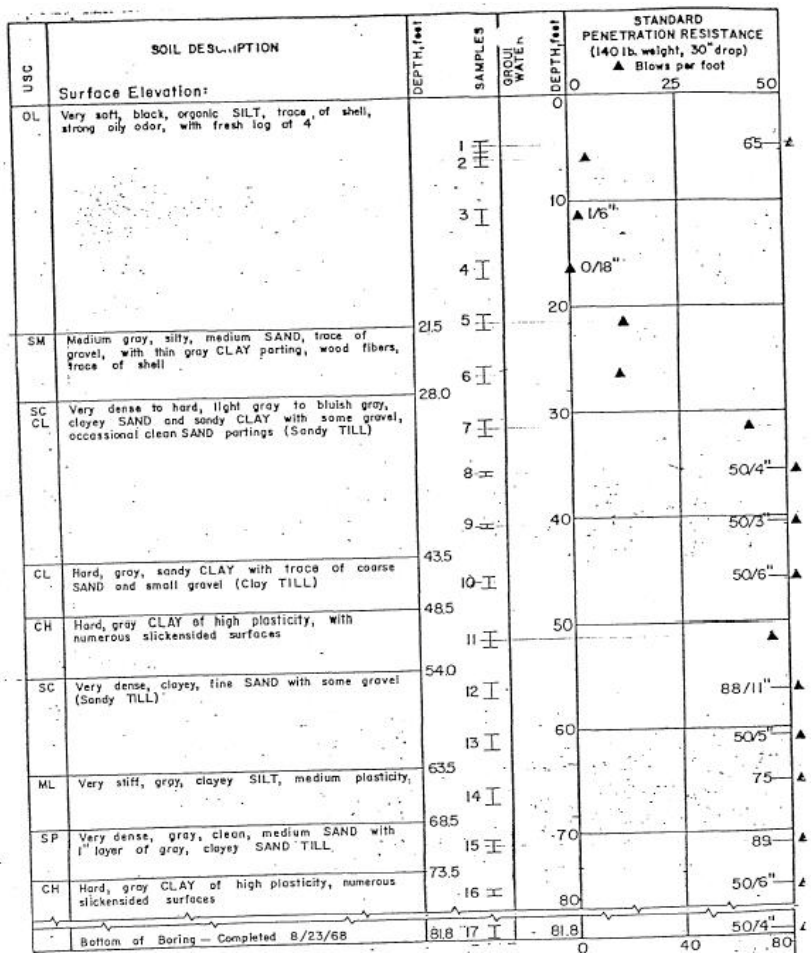
DOT: Tunnel Location & Estimated Cross-Section



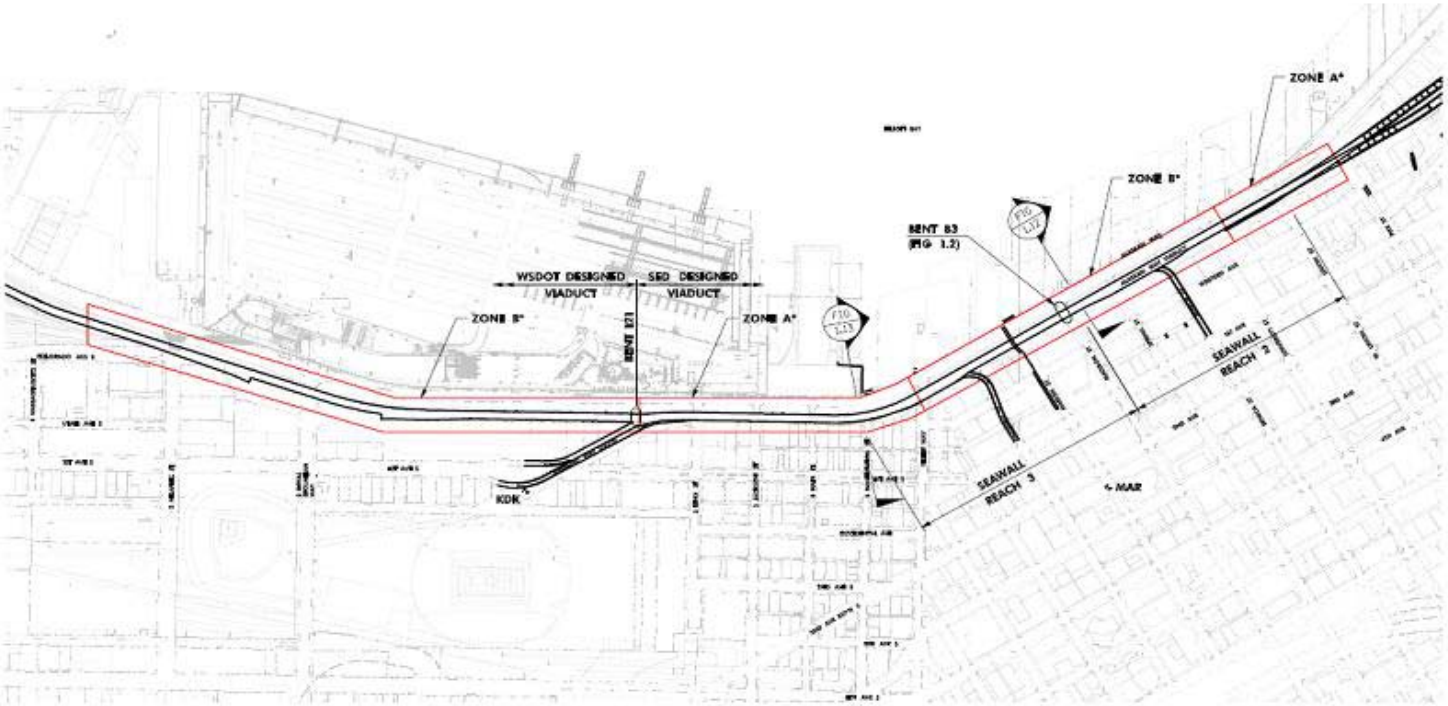
Waterfront Map, Boring, Cross-Section







Viaduct Map



* HORIZONTAL SITE SPECIFIC DESIGN RESPONSE SPECTRA ZONE DESIGNATIONS (SHANNON & WILSON, 2004)

ALASKAN WAY VIADUCT & SEAWALL REPLACEMENT PRO

ALASKAN WAY VIADUCT
SEISMIC VULNERABILITY ANALYSIS

PLAN: ALASKAN WAY VIADUCT & SEAWALL

Fig 1.12

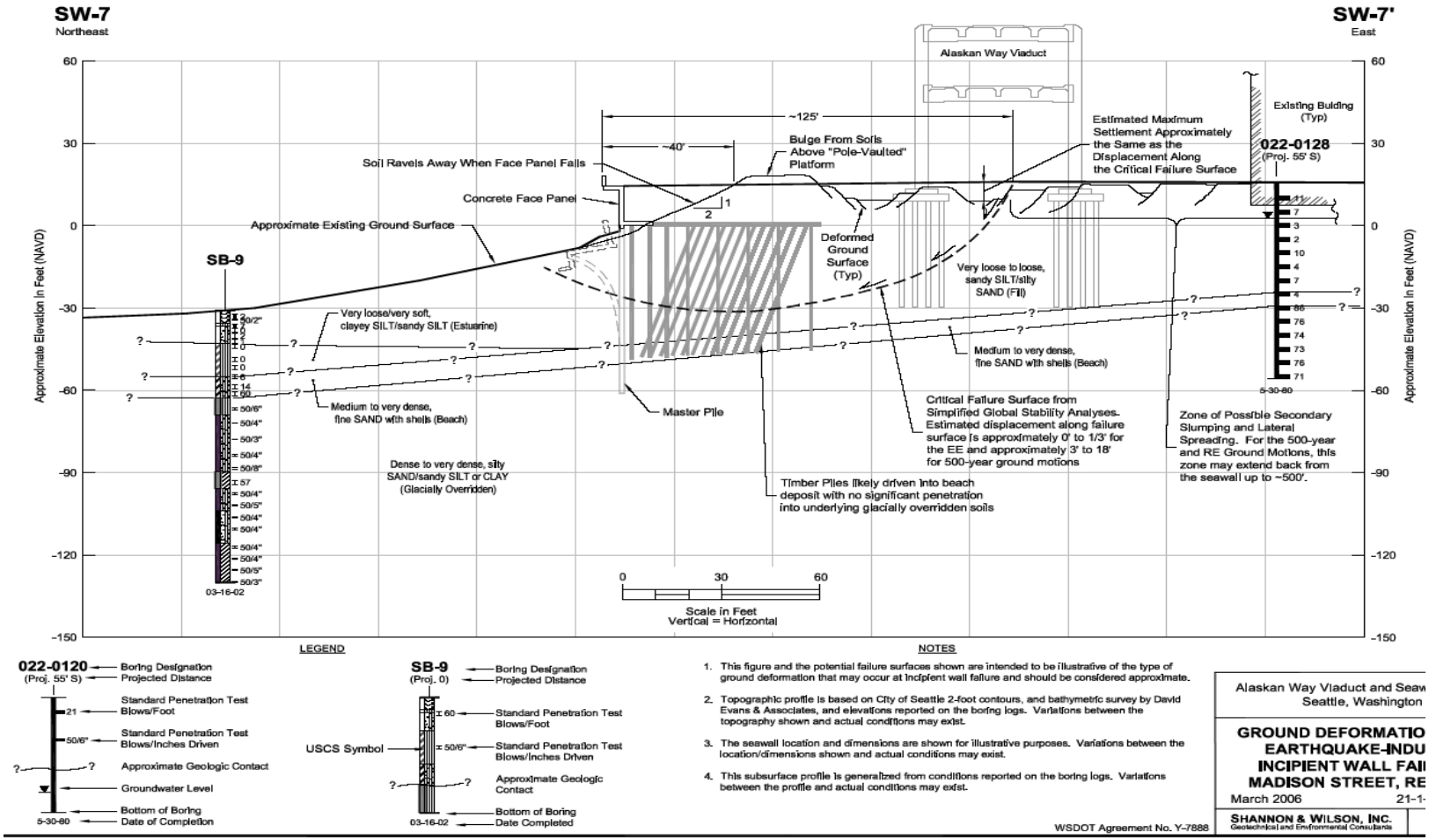
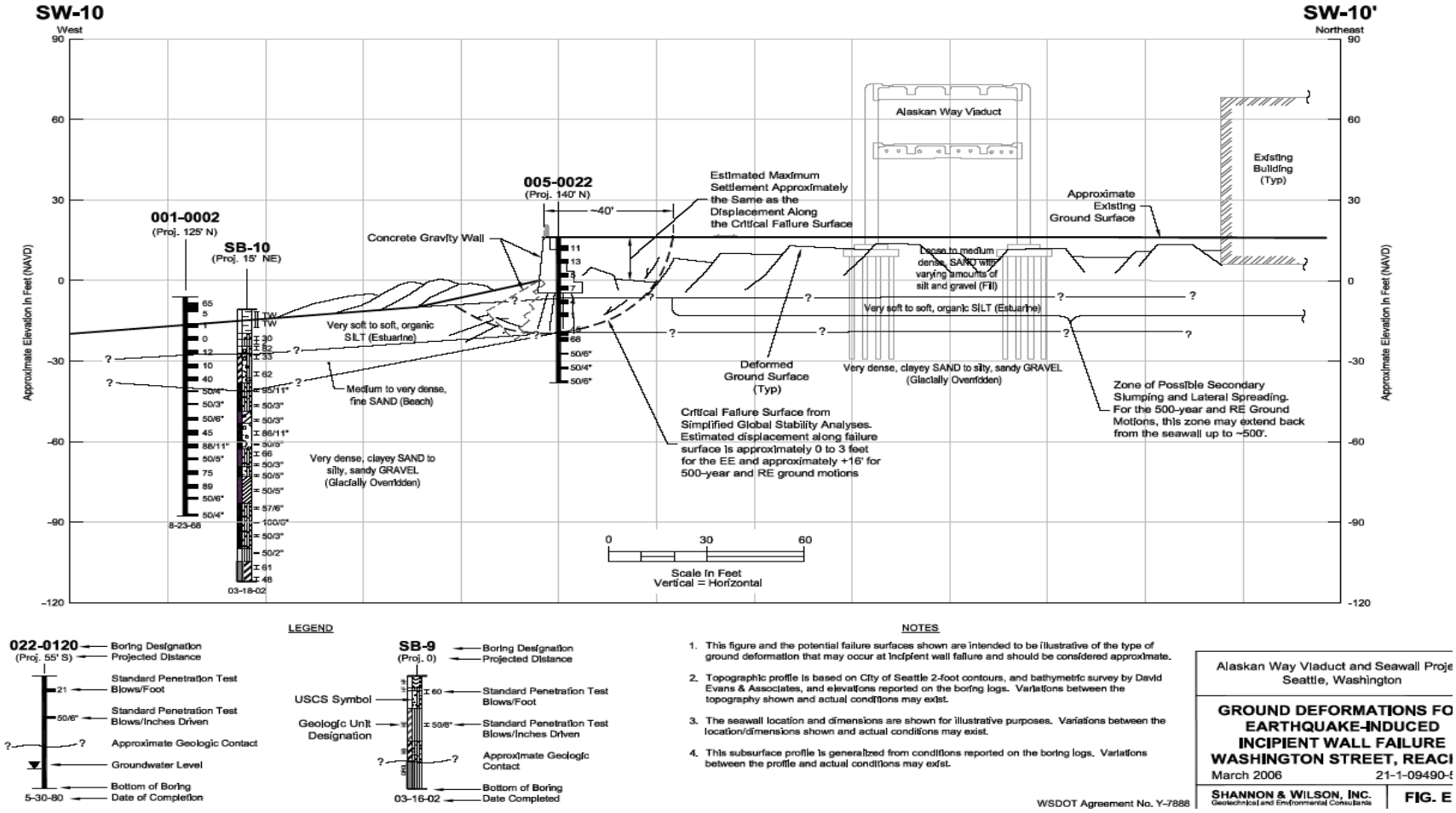

SW-7
Northeast
SW-7'
East
Alaskan Way Viaduct
~125'
~40'
Bulge From Soils Above "Pole-Vaulted" Platform
Estimated Maximum Settlement Approximately the Same as the Displacement Along the Critical Failure Surface
Existing Buildng (Typ)
022-0128
(Proj. 55' S)
Soil Ravels Away When Face Panel Fails
Concrete Face Panel
Approximate Existing Ground Surface
SB-9
Deformed Ground Surface (Typ)
Very loose to loose, sandy SILT/silty SAND (Fill)
Very loose/very soft, clayey SILT/sandy SILT (Estuarine)
Medium to very dense, fine SAND with shells (Beach)
Master Pile
Critical Failure Surface from Simplified Global Stability Analyses. Estimated displacement along failure surface is approximately 0' to 1/3' for the EE and approximately 3' to 18' for 500-year ground motions
Zone of Possible Secondary Slumping and Lateral Spreading. For the 500-year and RE Ground Motions, this zone may extend back from the seawall up to ~500'.
Dense to very dense, silty SAND/sandy SILT or CLAY (Glacially Overridden)
Timber Piles likely driven into beach deposit with no significant penetration into underlying glacially overridden soils
Approximate Elevation in Feet (NAVD)
03-16-02
5-30-80
Scale in Feet
Vertical = Horizontal
LEGEND
022-0120
(Proj. 55' S)
Boring Designation
Projected Distance
Standard Penetration Test Blows/Foot
Standard Penetration Test Blows/Inches Driven
Approximate Geologic Contact
Groundwater Level
Bottom of Boring
Date of Completion
SB-9
(Proj. 0)
USCS Symbol
Date Completed
NOTES
1. This figure and the potential failure surfaces shown are intended to be illustrative of the type of ground deformation that may occur at incipient wall failure and should be considered approximate.
2. Topographic profile is based on City of Seattle 2-foot contours, and bathymetric survey by David Evans & Associates, and elevations reported on the boring logs. Variations between the topography shown and actual conditions may exist.
3. The seawall location and dimensions are shown for illustrative purposes. Variations between the location/dimensions shown and actual conditions may exist.
4. This subsurface profile is generalized from conditions reported on the boring logs. Variations between the profile and actual conditions may exist.
WSDOT Agreement No. Y-7888
Alaskan Way Viaduct and Seaw
Seattle, Washington
GROUND DEFORMATIO
EARTHQUAKE-INDU
INCIPIENT WALL FAI
MADISON STREET, RE
March 2006
21-1-
SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

Fig 1.13



LEGEND

NOTES

1. This figure and the potential failure surfaces shown are intended to be illustrative of the type of ground deformation that may occur at incipient wall failure and should be considered approximate.
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WSDOT Agreement No. Y-7888

Alaskan Way Viaduct and Seawall Proje
Seattle, Washington

GROUND DEFORMATIONS FO
EARTHQUAKE-INDUCED
INCIPIENT WALL FAILURE
WASHINGTON STREET, REACH

March 2006 21-1-09490-

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. E

Seismicity and the Alaskan Way Viaduct

- Viaduct built from 1949 through 1953
- Has sustained 2 earthquakes of Mw > 6.5 since 1965
- 1st EQ was in 1965: Mw=6.5; epicenter only 15 miles from Viaduct
- 2nd EQ was known as the Nisqually EQ in 2001

Nisqually Earthquake

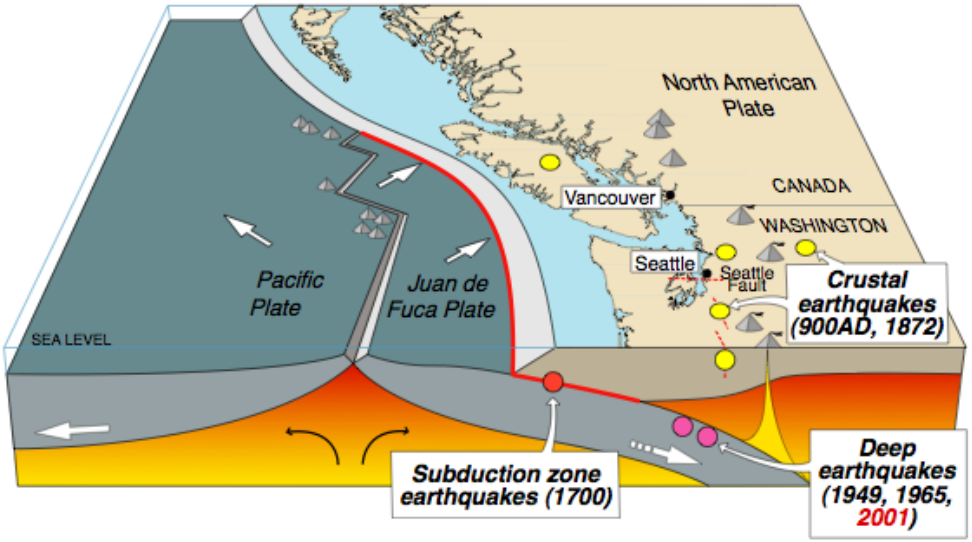
- *Date & Time of Occurrence:* Wednesday
- February 28, 2001 at 10:54:32.78 AM(PST)
- *Magnitude:* Mw=6.8
- Moment Magnitude:

$$M_{\mathrm{w}} = \frac{2}{3}\log_{10}(M_0) - 10.7$$

[M_0 is the seismic moment in dyne centimetres (10^{-7} Nm)]

- *Depth:* 52.40 km
- *Location:* 47.1525N 122.7197W

Cascadia earthquake sources

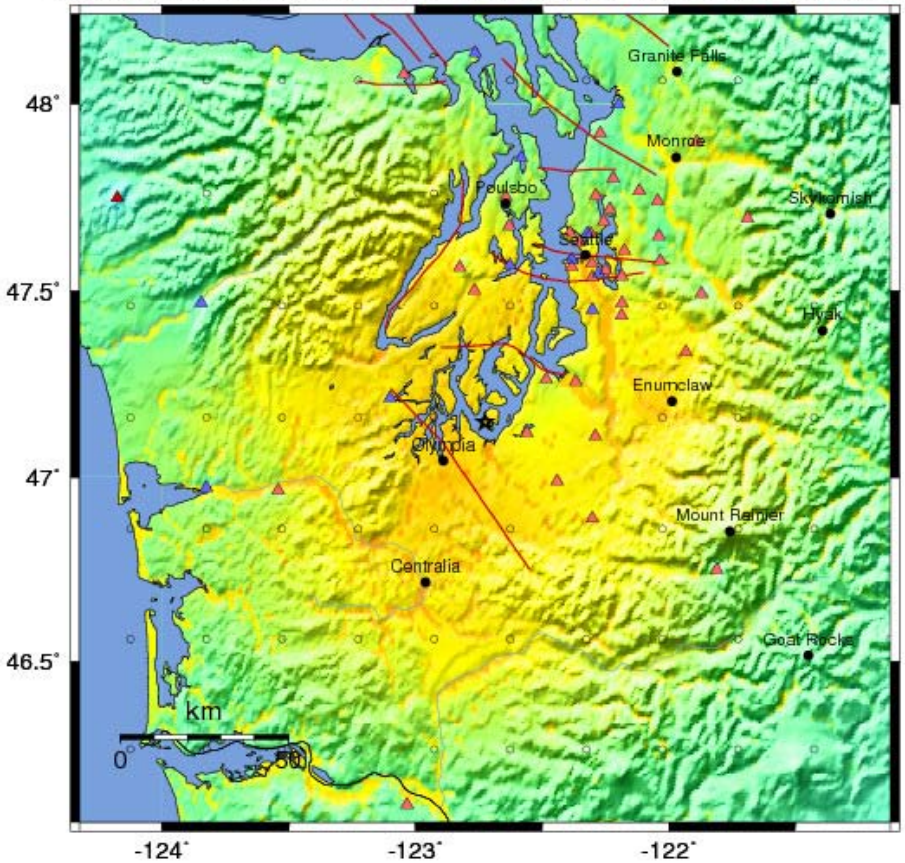


	Source	Affected area	Max. Size	Recurrence
●	Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
●	Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
●	Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?

ShakeMap [Mercalli Scale]

PNSN ShakeMap : 17.0 km NE of Olympia, WA

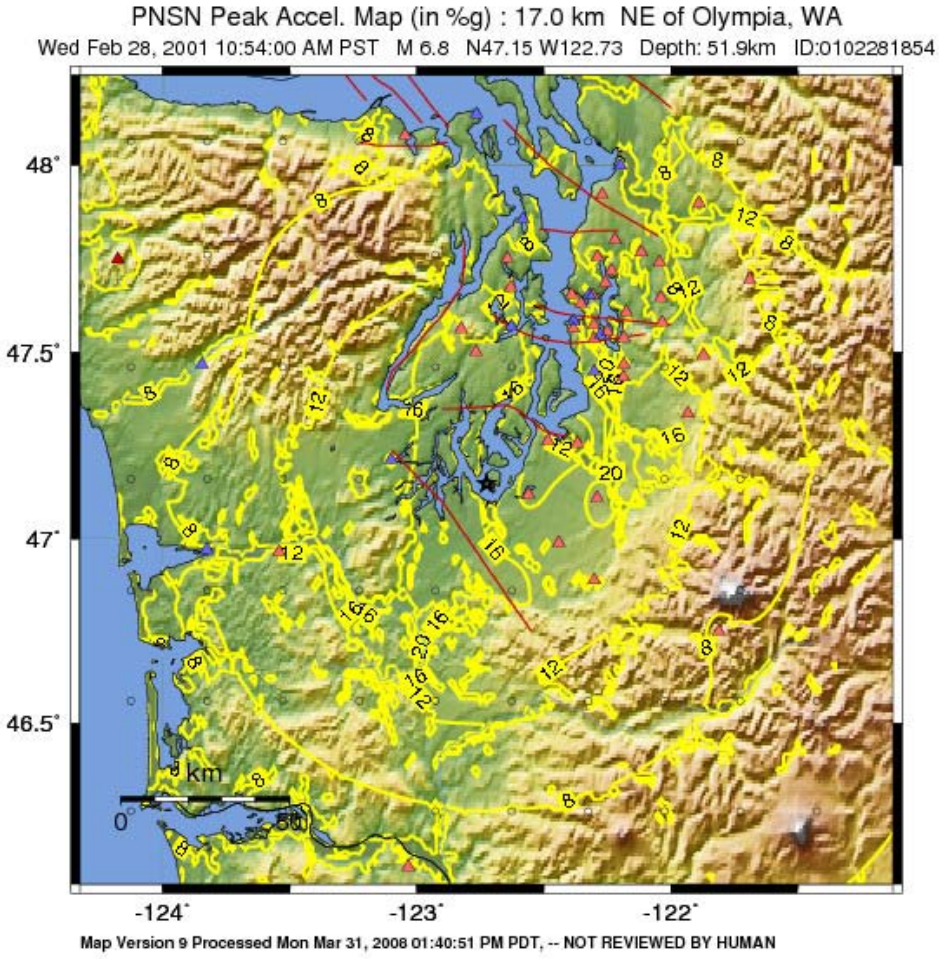
Wed Feb 28, 2001 10:54:00 AM PST M 6.8 N47.15 W122.73 Depth: 51.9km ID:0102281854



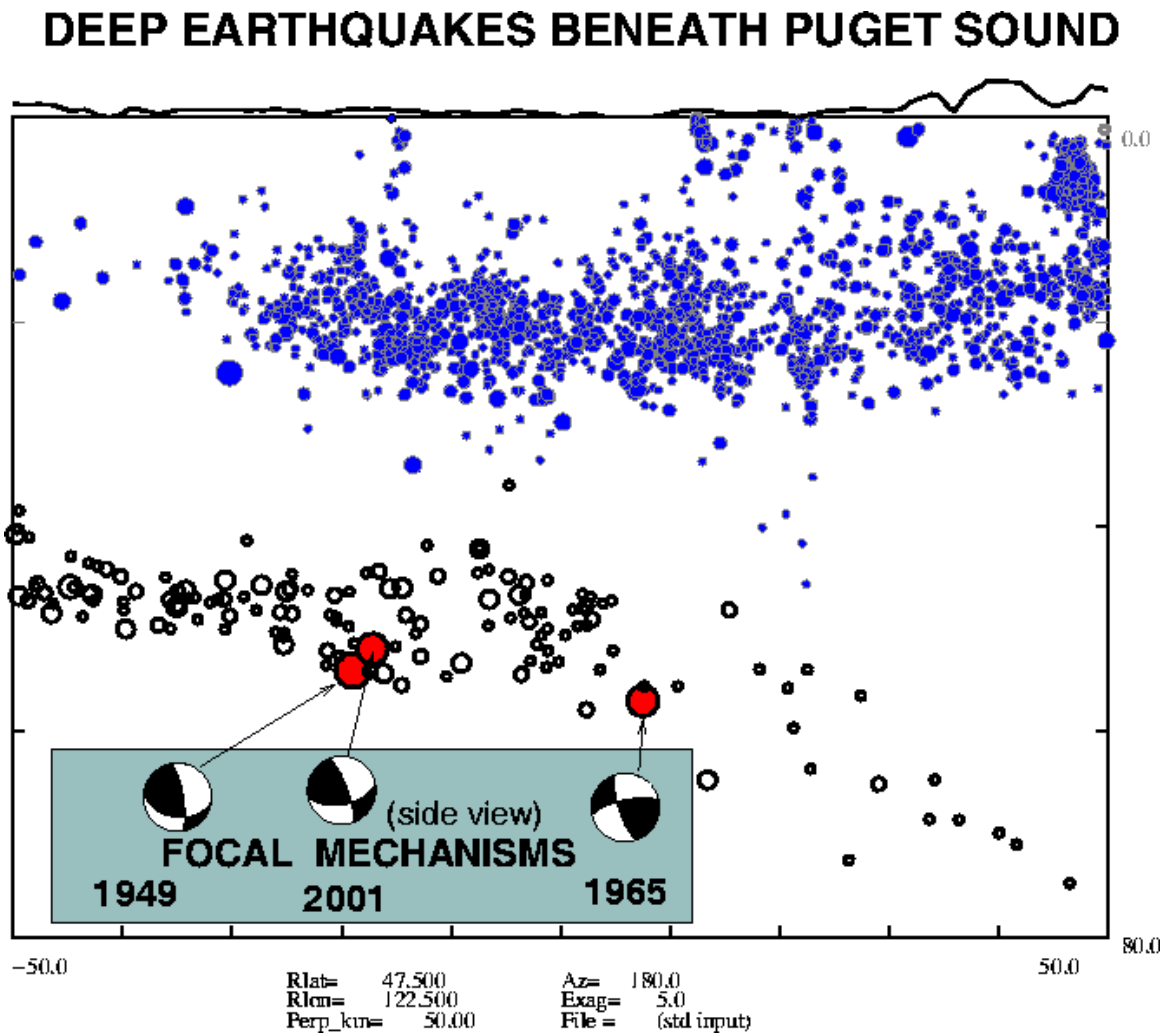
Map Version 9 Processed Mon Mar 31, 2008 01:40:51 PM PDT, -- NOT REVIEWED BY HUMAN

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

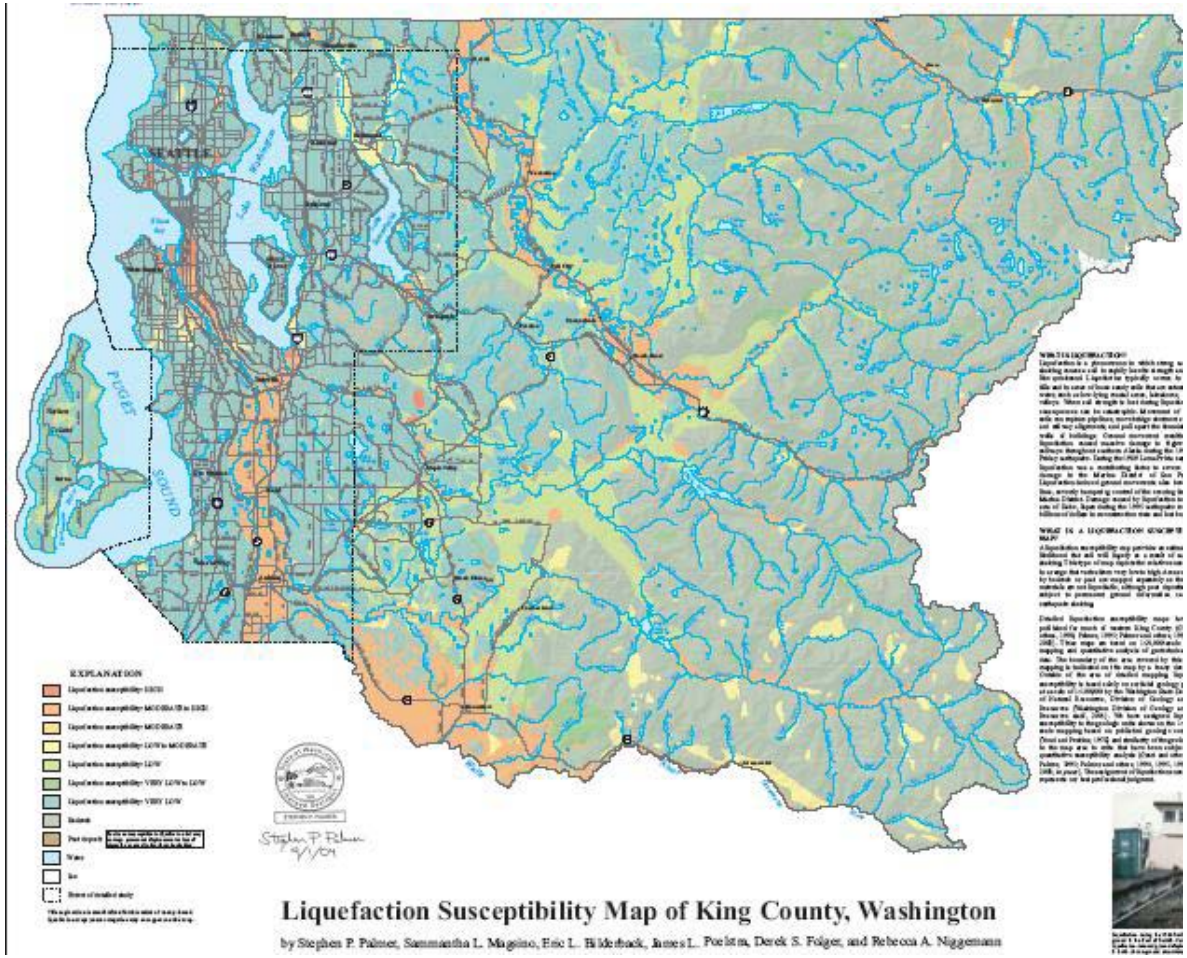
Peak Ground Accelaration [%g]



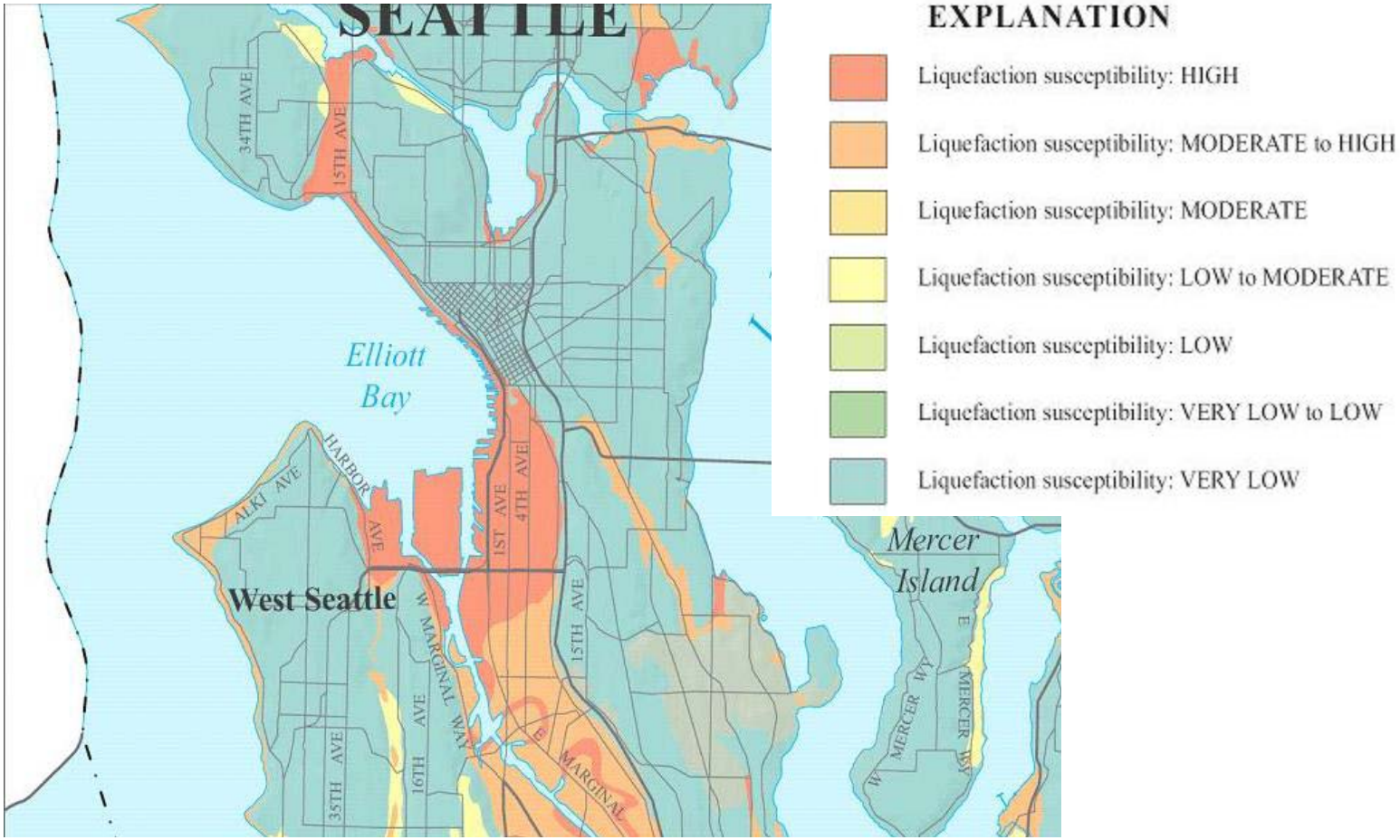
Deep EQ's since 1949



Liquefaction Susceptibility



Liquefaction Susceptibility of Downtown Seattle



Liquefaction Hazard

- *Definition:* softening and/or weakening of a soil layer due to the generation of excess pore water pressure. ($u\uparrow, \sigma'\downarrow$)

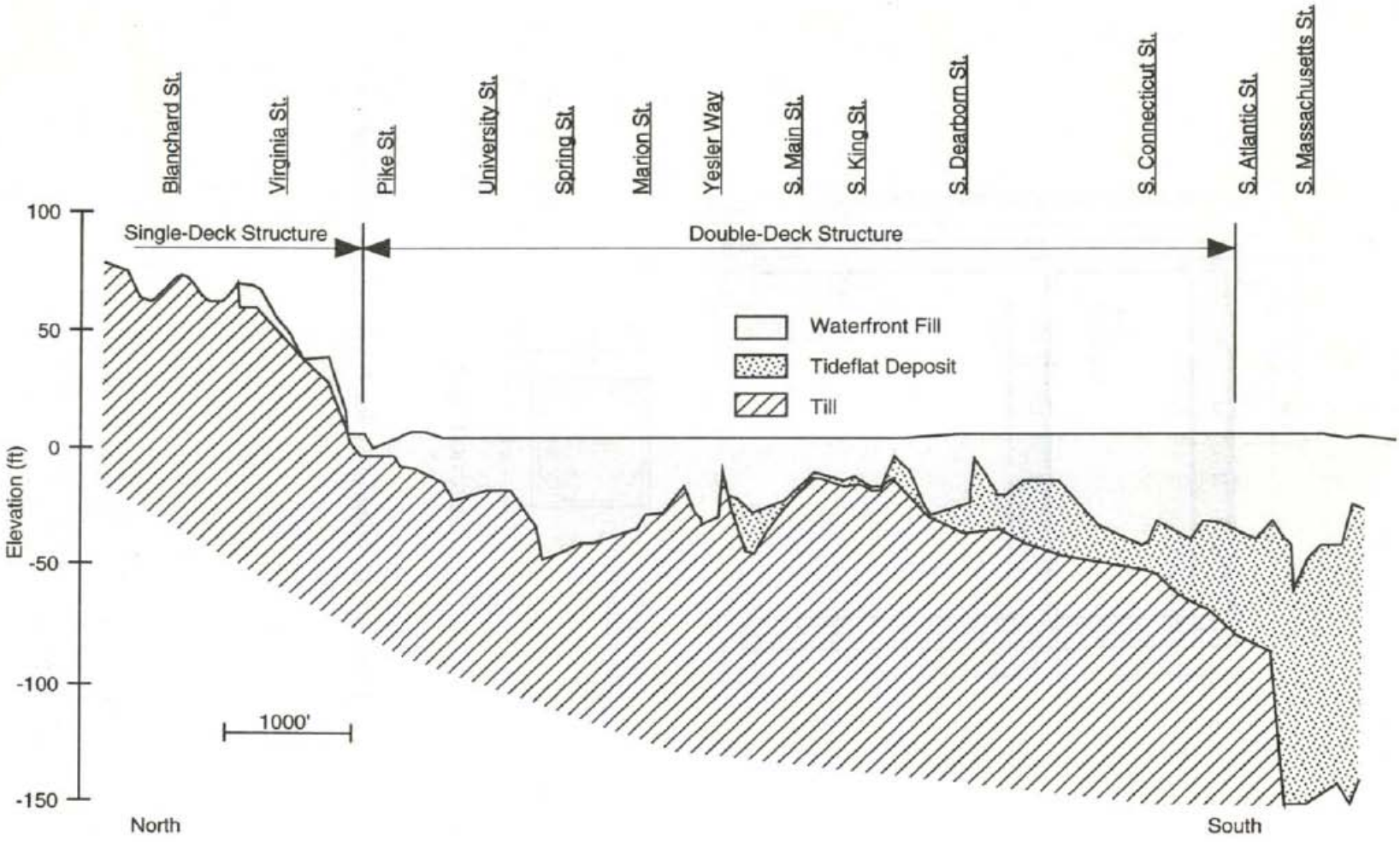
- *Susceptibility Criteria:*

  - Geologic ~ Hydraulic fill and tide flat deposits are present for approximately the first 50 feet below the existing viaduct.

  - Compositional ~ Loose sand below the water table.

    – Uniform graded soils with rounded particles most susceptible.

Alignment Cross-Section



- *History:*
  - Liquefaction occurred during the 2001 Nisqually earthquake.
    - Viaduct settled 5+ inches.
      - A function of porewater pressure dissipation and particle rearrangement upon termination of ground motions.
      - Increased lateral load weakened seawall structure.
- *Mechanisms:*
  - <u>Flow liquefaction</u>: static shear stress in soil deposit is greater than the steady-state residual strength of the soil. Loose sands only.
  - <u>Cyclic mobility</u>: cyclic shear stresses from ground motions induce excess porewater pressure causing the steady-state strength to be exceeded momentarily. This results in incremental deformation known as lateral spreading.

- Consequences of future liquefaction event:
  - Lateral spreading would significantly increase lateral load on already weakened seawall.
  - Further settlement would cause increased stress on and deformation of the Viaduct structure and foundation.
  - Failure of local sections of the structure at a minimum.
- Seawall replacement:
  - Greatly reduces probability of liquefaction induced failure and subsequent displacement of retained soils.

Case Study: Cypress Street Viaduct

- Located in Oakland, CA
- Opened in 1957
- Two-level multi-lane highway.
- Single and double column steel-reinforced concrete structure
- Pile foundation
- Built on fill and “bay mud”

Case Study: Cypress Street Viaduct

- Damaged spectacularly in the 1989 Loma Prieta earthquake (6.9 MMS).

Case Study: Cypress Street Viaduct

- 42 people were killed, and many more were injured as portions of the upper roadway fell onto the lower roadway, crushing the vehicles there.

Case Study: Cypress Street Viaduct

- Built on fill, and bay mud, the structure was subjected to amplified ground movements during the earthquake.

- The primary cause of failure was the lack of steel reinforcing connections between the upper and lower column segments.

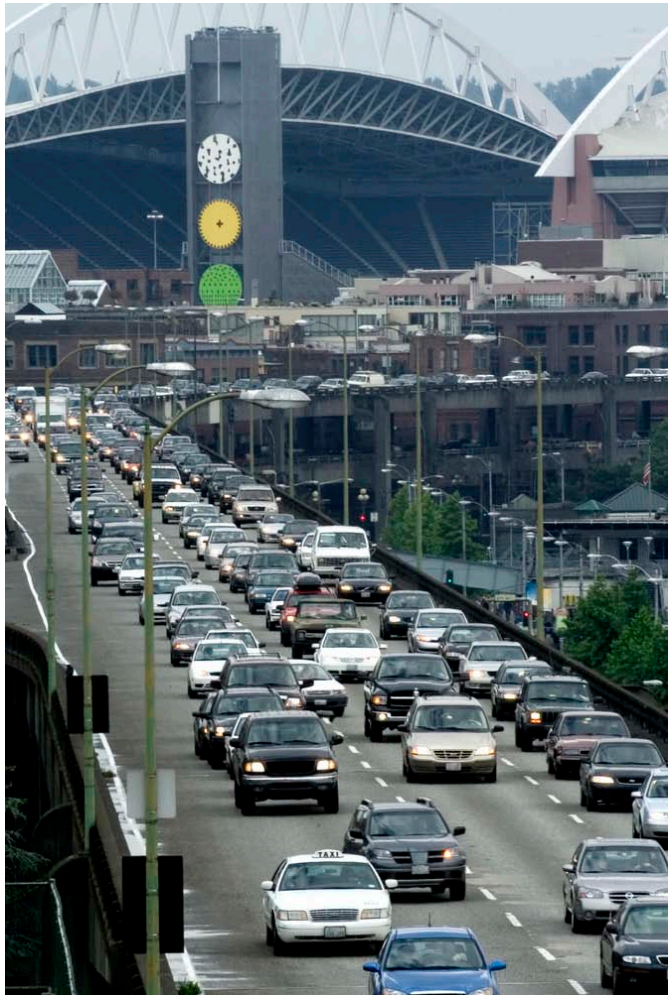
Case Study: Cypress Street Viaduct

- A quote from the mayor's board of inquiry:

  "The reinforcement in the columns and girders was generally poorly detailed by current standards and reflects the engineering profession's lack of understanding regarding the inelastic response of reinforced concrete members at the time when these structures were designed. … A lack of redundancy and the inadequate reinforcement detailing are two of the major seismic deficiencies in these freeway structures."

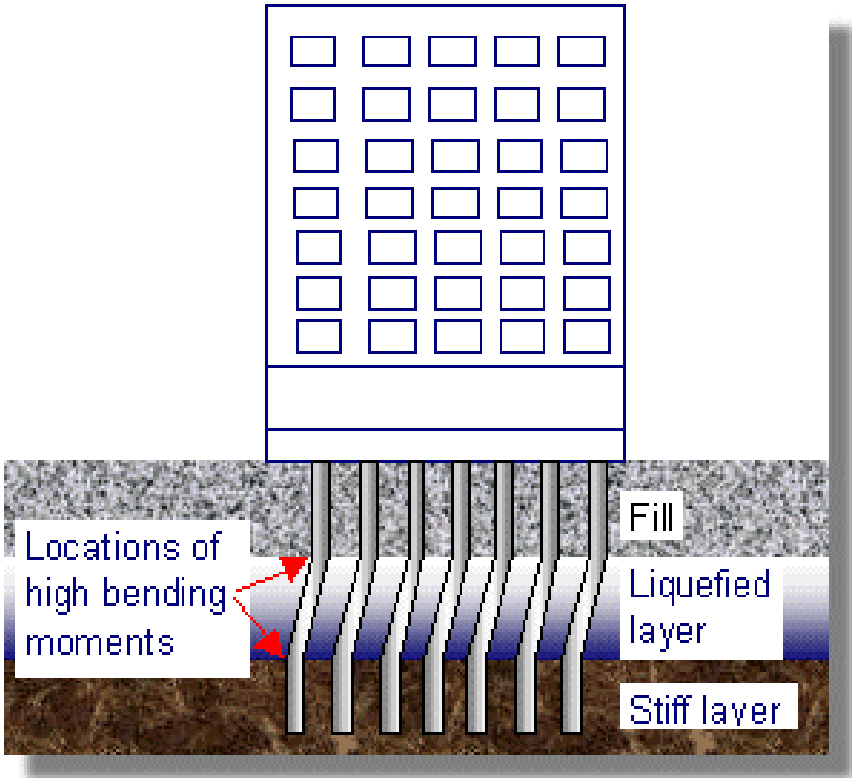
- Essentially saying: People didn't know how to build earthquake-resistant structures back then.

Building a Liquefaction Resistant Alaskan-Way Viaduct



- Three Aspects to Consider for Construction:
  - Avoid soils susceptible to liquefaction. (not possible in this case)
  - Improve the soil being tunneled into or built upon. (i.e. drainage options to eliminate pore pressure within soil)
  - Build a liquefaction resistant Structure.
    - Improve ductility to allow for potentially large deformations via seismic activity and failure due to liquefaction.
    - Account for vertical and horizontal loads and moments.
    - Design a drainage system into the structure to prevent liquefaction within the soil.

- Improving the Ductility of Structure or Subsurface Tunnel.
  - Increase ductility of the structure by connecting the structure within the liquefiable layer to a stiffer layer via reinforced pile foundations.
    - Allows superstructure to move as a whole when liquefaction causes failure within the soil during seismic events.
  - Improve ductility within the connection of the tunnel to the pile foundations via seismic bearings or similar ductile connection.



http://www.ce.washington.edu/%7Eliquefaction/html/how/resistantstructures.html

- Accounting for Moments, Vertical loads and Horizontal deformation due to Liquefaction:
  - Moment within the Viaduct Structure due to liquefaction can be significantly reduced via ductile connections to the pile foundations (i.e. Seismic Bearings if construction is above the surface).
  - Horizontal loads can be reduced with the use of large reinforced pile foundations connected to a stiff foundation to allow for lateral deformation without failure.
  - Vertical compression loads due to liquefaction will be accounted for within the structural design of the reinforced concrete piles extending to the stiff foundation. Vertical tension loads will not be accounted for unless expansive clays exist between the liquefiable layer and the stiff foundation below surface, or under the tunnel structure.

Examples of Bored Tunnels

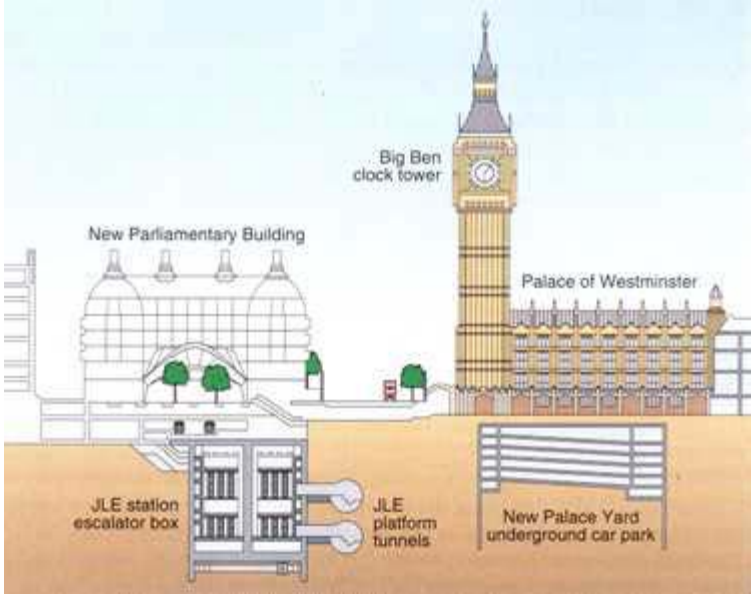
Groene Hart Tunnel

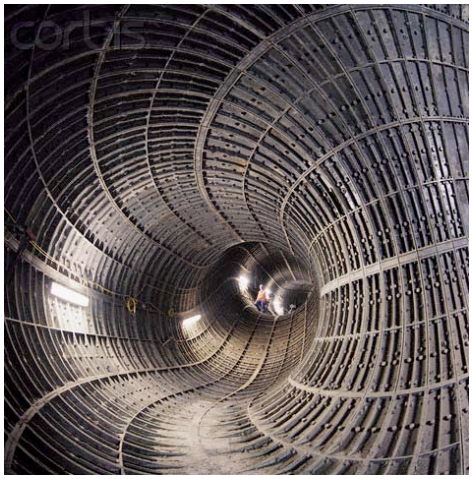
- Due for completion later this year
- Diameter 15 meters
- 8.5 km
- Why use TBM?
- Similarities to Alaskan Way

M30 Madrid

- 15m-diameter TBM
- €3.9bn
- Completed 2007
- Earth Pressure Balance Shield System
- Similarities to Alaskan Way

London Jubilee Line Extension





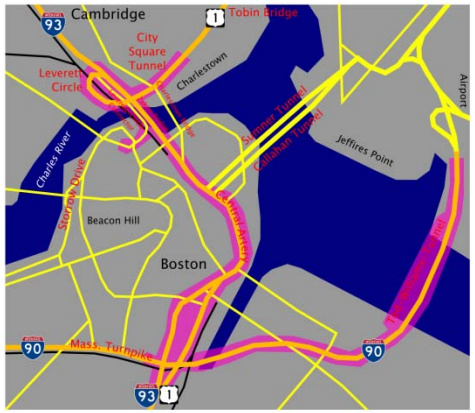
- $375 m/km
- 1.4 billion GBP over budget (67%)
- 2 years late (40%)
- “Time and cost overruns could have been minimized with a more established strategy at the beginning of the project.” Arup Report

(Reference: T&T, October 2000, p19)

City of Miami Port Tunnel

- Deal collapsed December 2008
- "Nobody anticipated this kind of increase. This is just a reality of doing business in 2008. You just have to get used to it." MTA Board Chairman Dale Hemmerdinger ENR, January 31, 2008

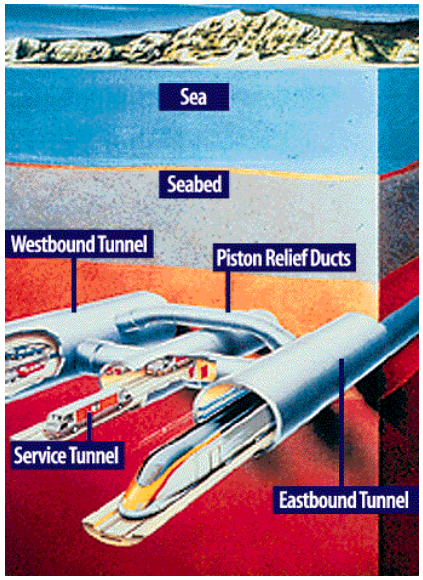
Boston Big Dig

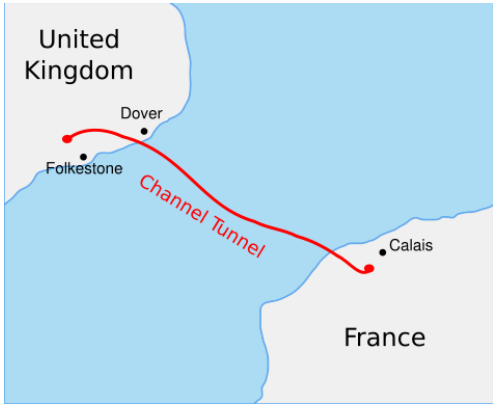


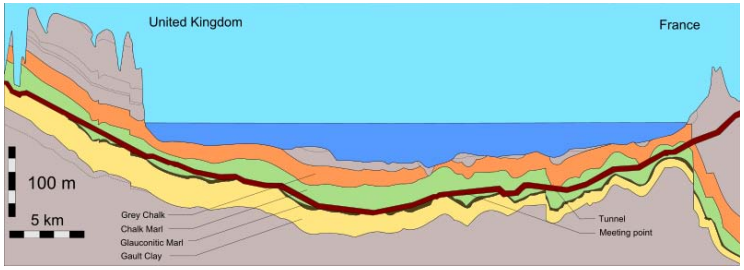
- 3.5 mile (5.6 km) tunnel under the city
- Had to find safest way to build the tunnel without endangering existing highway above
- $14.6 billion (143%)
- “wouldn’t it be cheaper to raise the city”
- Lessons learnt...

Channel Tunnel

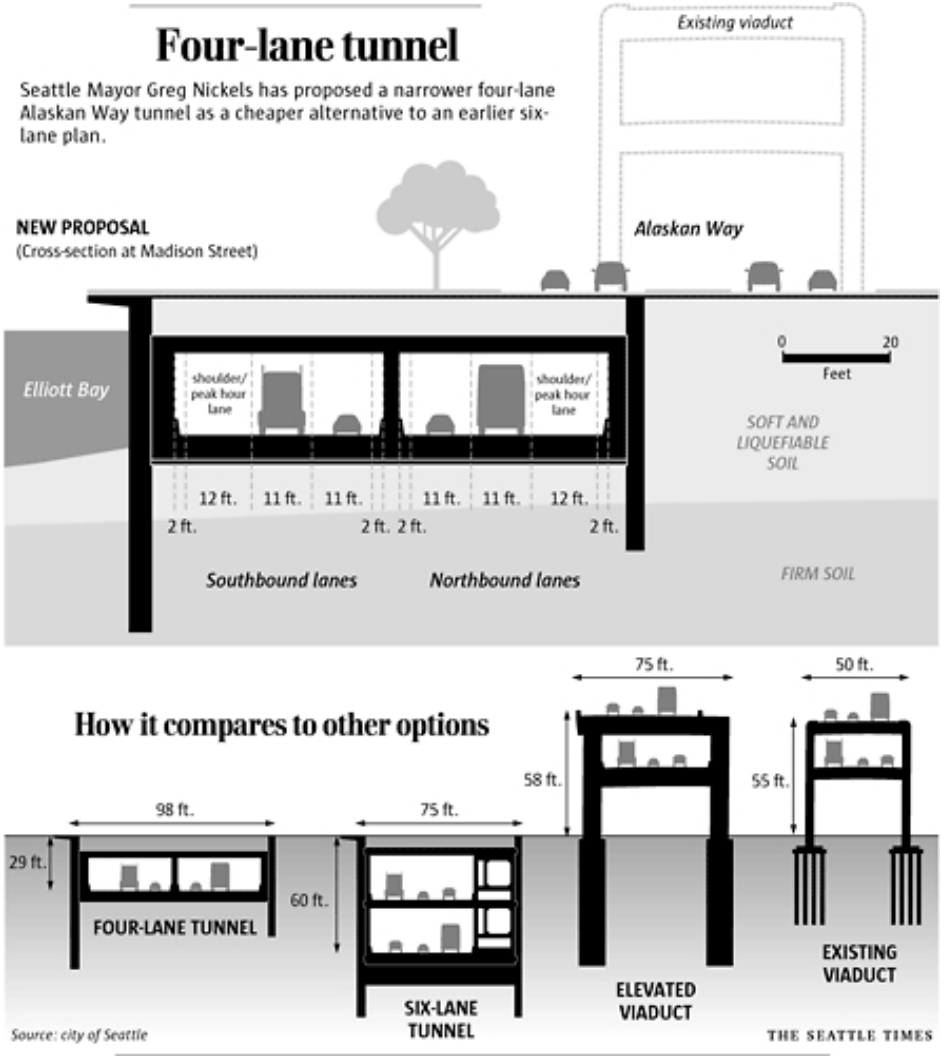
- 0.5-kilometre (31.4 mi)
- Up to 75 m (250 ft) deep
- The cost overran predictions by 80%
- Eleven TBMs working from both the UK and France cut through chalk marl
- Geology of the Channel







Design Alternatives



➢ Cut and cover tunnel alternative:

- **Steps:**
  1. Soil excavated.
  2. Tunnel constructed.
  3. Soil placed on top.

- **Challenges:**

  - Tunnel would have to resist huge lateral earth pressures from future seismic event and downward flowing groundwater. West tunnel wall would serve as seawall replacement.

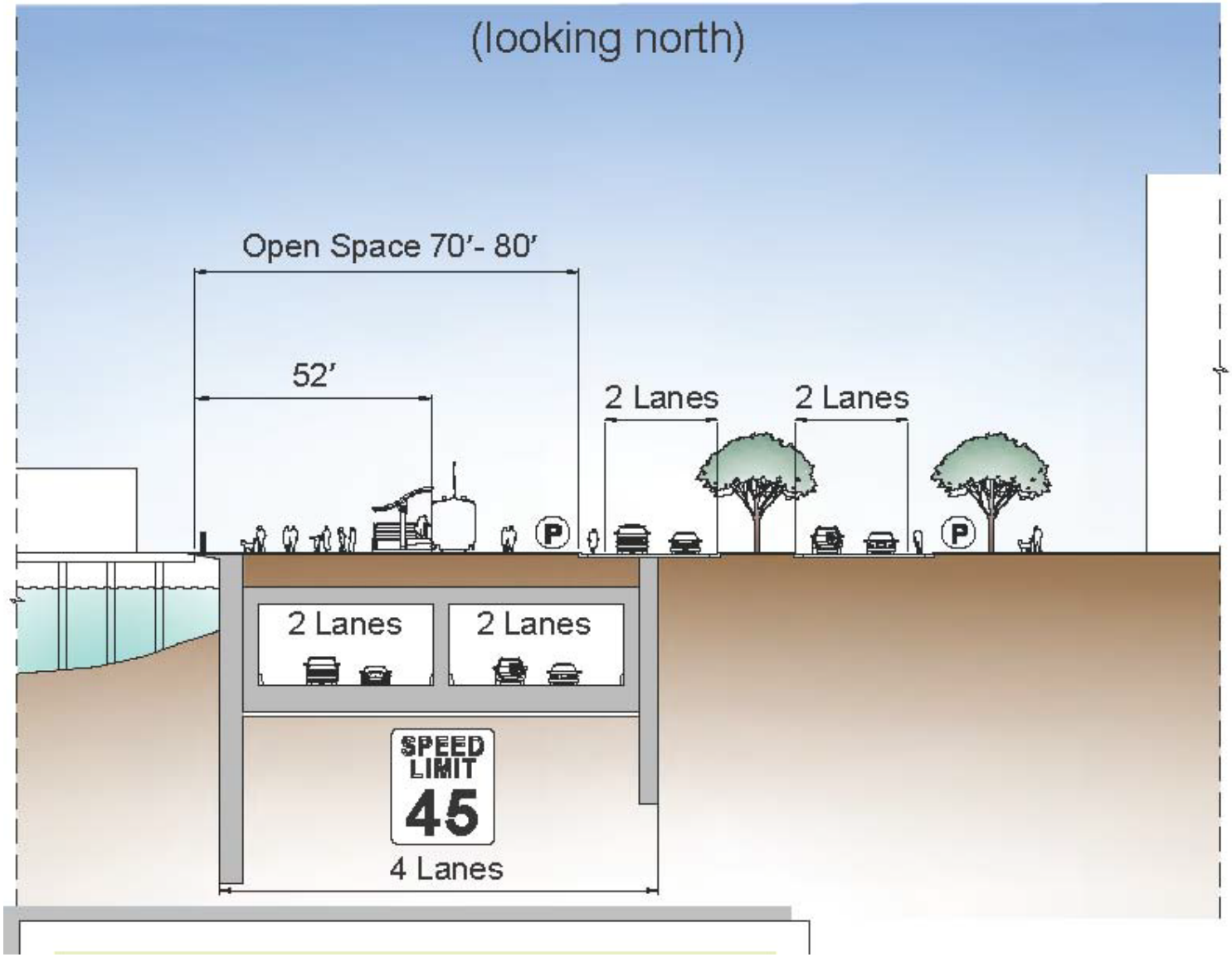
  - Dewatering of the excavation would be a massive undertaking given the high groundwater table and proximity to Puget Sound.

  - Cracking of structure must be closely monitored during design-life to protect against saltwater inflow and subsequent corrosion.

  - Cracking may cause water inflow and potential flooding.

  - Utility relocation extensive due to location.

SR 99 Cut and Cover Tunnel



➢ Bored tunnel alternative:

- Calls for tunnel to be constructed within dense glacial till, well below liquefiable soils and away from seawall.

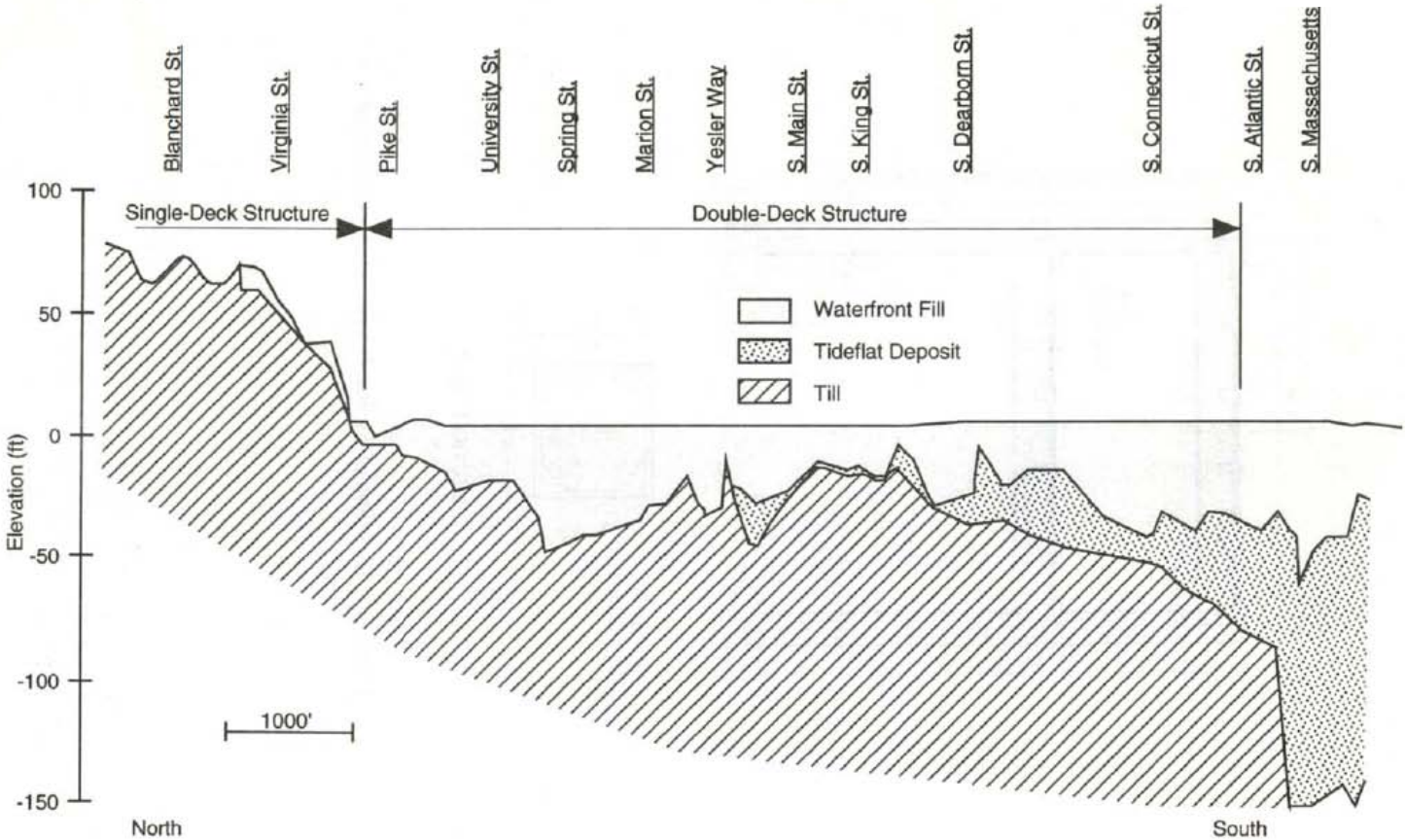
- Liquefiable soil present at south approach.

  – Deep-soil mixing with jet grout would increase the density and strength while greatly reducing the permeability of the soil. This is very expensive but effective proven effective. (Big Dig)

- Slurry walls at south approach would extend downwards to 100 feet or more below grade, thus subjecting them to significant lateral loads due to earth and hydrostatic pressure.

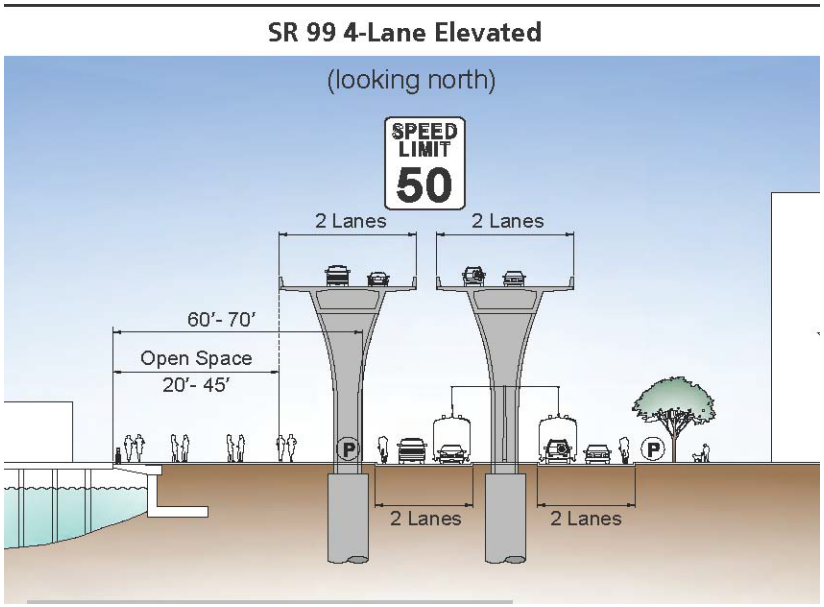
- Significant excavation required at north approach to reconnect with surface roads. This will require extensive excavation support and water retention system.

- Two-lane stacked bored tunnel



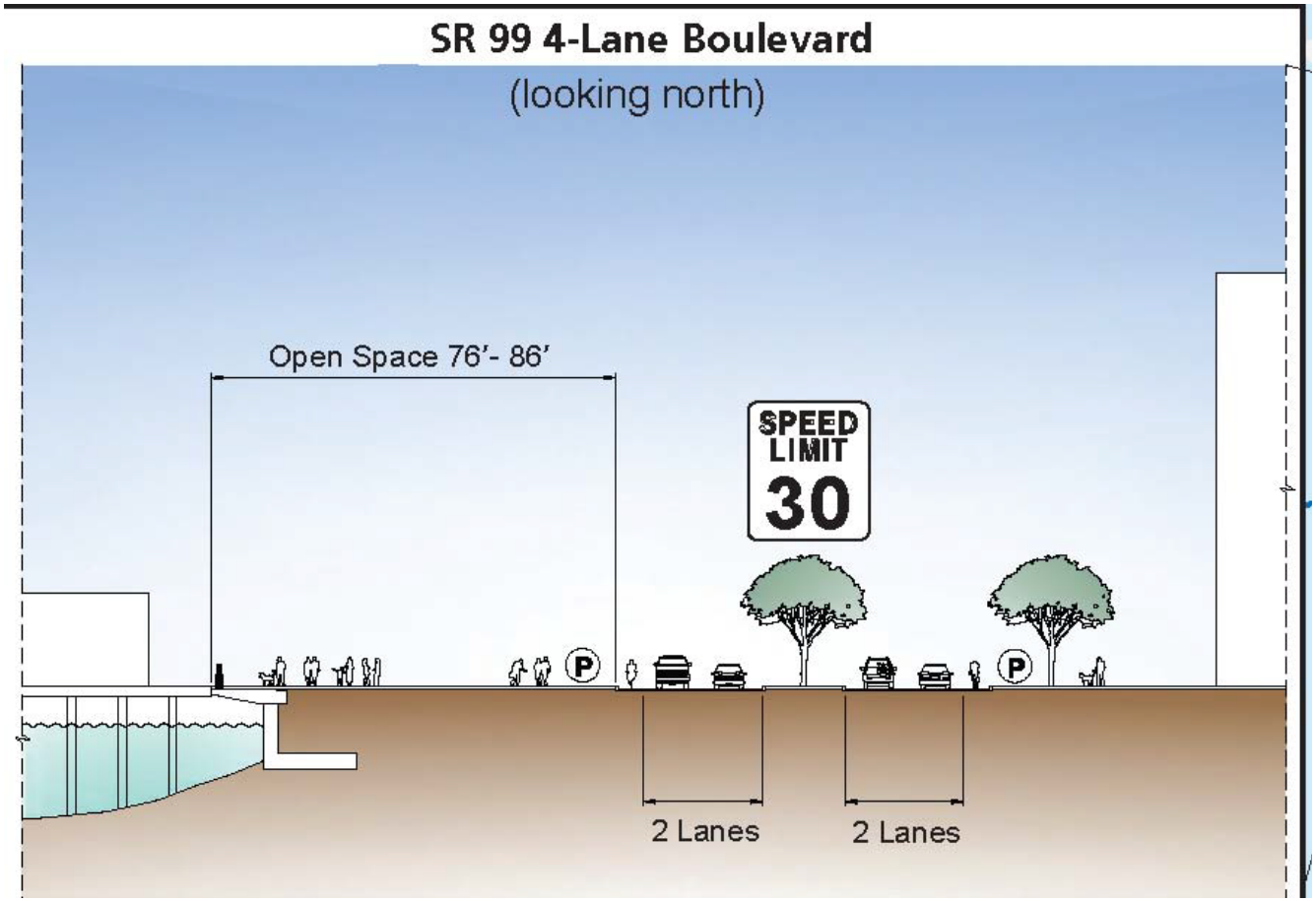
➢ Viaduct replacement alternative:

- Structure would be susceptible to and must resist liquefaction hazard.
  - Significant design challenges.
- Would be vulnerable to failure of new seawall.
- Aesthetic and commercial issues.



➢ Surface roads:

- Susceptible to liquefaction hazard and permanent ground deformations.
- Increased traffic congestion at waterfront area.



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