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 2.4 m.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 (65-15 ka)
Fraser Glaciation advancement and result
Plate Tectonics & Faults

- Cascadia subduction zone
- Seattle Fault
- Seattle Fault Zone
What and where is the Seattle Fault Zone?

Seattle Fault Zone

The Seattle Fault Zone represents the area where several parallel strands of the Seattle fault have either broken the ground surface or caused deformation of geologic materials. In Seattle, evidence for offset along the Seattle fault consists of uplifted beach deposits, down-dropped tidal marshes, offset strata, and deformation such as sheared and tightly folded strata near the loading (northern) edge of the fault. The Seattle fault is one of several active crustal faults in the Puget Lowland undergoing further research. The location of the Seattle fault zone was derived from this geologic mapping and from Blakely and others (2002), and Brocker and others (2004).

Downtown Seattle Geological Map
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

**SOIL DESCRIPTION**

<table>
<thead>
<tr>
<th>Surface Elevation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0'</td>
<td>Very wet, black, organic Silt, trace of shell, stringy clay, with fresh log of 4'</td>
</tr>
<tr>
<td>12'</td>
<td>Medium gray, silty, medium sand, trace of gravel, with 10% gray clay matrix, some fibers, trace of shell</td>
</tr>
<tr>
<td>28'</td>
<td>Very dense, light gray to bluish gray, clayey sand and sandy clay with some gravel, occasional clean sand layers (Sandy TILL)</td>
</tr>
<tr>
<td>38'</td>
<td>Hard, gray, clayey clay with trace of coarse sand and small gravel (Clay TILL)</td>
</tr>
<tr>
<td>43'</td>
<td>Hard, gray, clayey clay of high plasticity, with numerous slickened surfaces</td>
</tr>
<tr>
<td>54'</td>
<td>Very dense, clayey, fine sand with some gravel (Sandy TILL)</td>
</tr>
<tr>
<td>62'</td>
<td>Very stiff, clayey silt, medium plasticity</td>
</tr>
<tr>
<td>68'</td>
<td>Very dense, clayey silt, medium sand with interlayer of gray, clayey sand TILL</td>
</tr>
<tr>
<td>88'</td>
<td>Hard, gray clay at high plasticity, numerous slickened surfaces</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (Feet)</th>
<th>Standard Penetration Resistance (440 lb. weight, 30' drop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5'</td>
<td>60'</td>
</tr>
<tr>
<td>10'</td>
<td>40'</td>
</tr>
<tr>
<td>15'</td>
<td>20'</td>
</tr>
<tr>
<td>20'</td>
<td>10'</td>
</tr>
<tr>
<td>25'</td>
<td>1/8'</td>
</tr>
<tr>
<td>30'</td>
<td>0/8'</td>
</tr>
</tbody>
</table>

*Revision of Dates: Completed 8/23/98*
Viaduct Map
Fig 1.12

SW-7
Northwest

SW-7
East

Approximate Existing Ground Surface

Concrete Face Panel

SW-9

Approximate Existing Ground Surface

Soil Erosion

Estimated Maximum Settlement: Approximately the same as the Displacement Along the Critical Failure Surface

Existing Building (Typ)

022-0128
Pnt, 59-5

Critical Failure Surface from Simplified Global Stiffness Analysis. Estimated displacement along failure surface is approximately 7 to 10' for the 500-year ground motions.

Zone of Possible Secondary Stiffening and Lateral Spreading. For the 500-year next RE, Ground Motions, this zone may extend back from the seawall up to ~30'.

022-0128

Form

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 infilled wall failure and should be considered approximate.

2. Topographic profiles are based on City of Seattle 3-D terrain, and geotechnical survey by Dake Daniel & Associates, and elevations reported on the boring logs. Variations between the terrain shown and actual conditions may exist.

3. The overall location and dimensions are shown for illustrative purpose. Variations between the location and dimensions shown and actual conditions may exist.

4. This subsurface profile is generated from conditions reported on the boring logs. Variations between the profile and actual conditions may exist.

WSDOT Agreement No. V-0985

GROUND DEFORMATION EARTHQUAKE-INDUCED INCIDENT WALL FAIL
MADISON STREET, (631)

SHANNON & WILLSON, INC.
(612-71)

March 2006

21-1
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:* $M_w=6.8$
• *Moment Magnitude:*

\[ M_w = \frac{2}{3} \log_{10} (M_0) - 10.7 \]

[M$_0$ is the seismic moment in dyne centimetres ($10^{-7}$ Nm)]

• *Depth:* 52.40 km
• *Location:* 47.1525N 122.7197W
Cascadia earthquake sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Affected area</th>
<th>Max. Size</th>
<th>Recurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subduction Zone</td>
<td>W.WA, OR, CA</td>
<td>M 9</td>
<td>500-600 yr</td>
</tr>
<tr>
<td>Deep Juan de Fuca plate</td>
<td>W.WA, OR,</td>
<td>M 7+</td>
<td>30-50 yr</td>
</tr>
<tr>
<td>Crustal faults</td>
<td>WA, OR, CA</td>
<td>M 7+</td>
<td>Hundreds of yr?</td>
</tr>
</tbody>
</table>
Peak Ground Acceleration [%g]
Deep EQ’s since 1949
Liquefaction Susceptibility Map of King County, Washington

by Stephen P. Palmer, Samantha L. Magistro, Eric L. Riedel, James L. Pavlin, Derek S. Fugger, and Rebecca A. Niggemann
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. \((u↑, \sigma'↓)\)

- **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:

- Flow liquefaction: static shear stress in soil deposit is greater than the steady-state residual strength of the soil. Loose sands only.

- Cyclic mobility: 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

Four-lane tunnel

Seattle Mayor Greg Nickels has proposed a narrower four-lane Alaskan Way tunnel as a cheaper alternative to an earlier six-lane plan.

NEW PROPOSAL
(Cross-section at Madison Street)

How it compares to other options

Source: city of Seattle
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.
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.
References

- Liquefaction, University of Washington
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