Earthquake Engineering and the Alaskan Way Viaduct

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Principal Types of Earthquake Damage

Structural

Caused by excessive ground shaking
Strongly influenced by local soil conditions

Geotechnical

Caused by ground failure
Strongly influenced by local soil conditions

Principal Types of Earthquake Damage

Structural

Mexico City, 1985
Low bedrock accelerations
Strong amplification
Strong ground surface motio

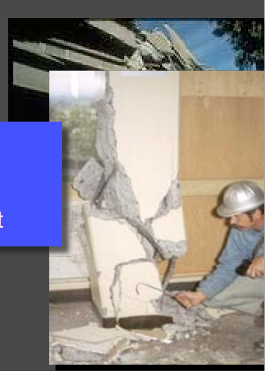
Principal Types of Earthquake Damage

Structural

Loma Prieta, 1989
Modest rock accelerations
Strong amplification
Strong ground surface motions

Principal Types of Earthquake Damage

Structural



San Fernando, 1971
Strong motion
Lack of transverse reinforcement

Engineering for Earthquakes

Structures

Engineering for Earthquakes

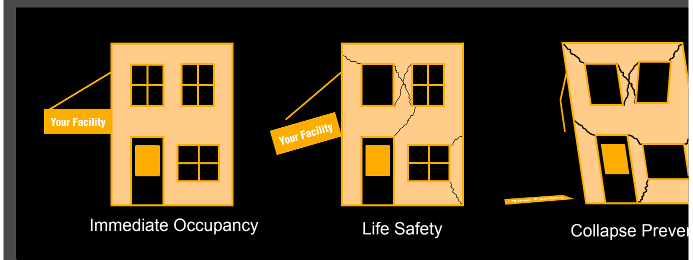
Structural Engineering Considerations

- Design of new structures
- Retrofitting of existing structures

Engineering for Earthquakes

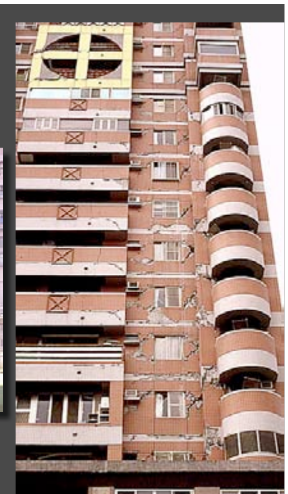
Design Considerations

Performance objectives



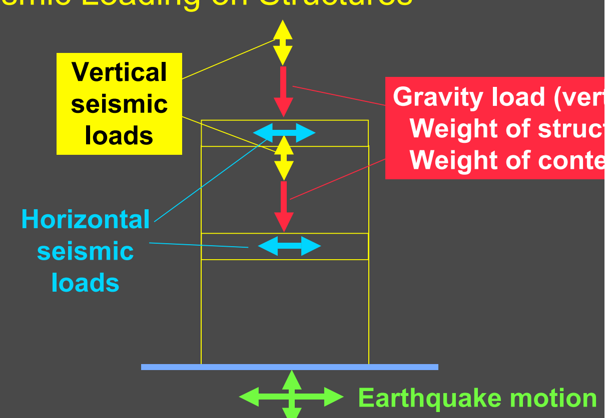
Immediate Occupancy

Life Safety

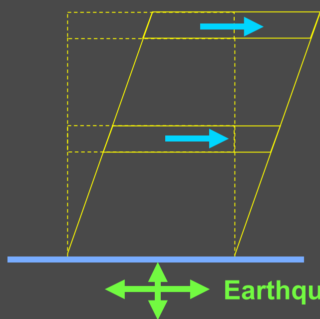


Collapse Prevention

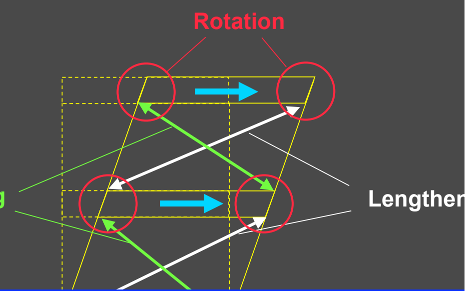
Seismic Loading on Structures



Seismic Loading on Structures



Seismic Loading on Structures



To prevent excessive movement, must restrain rotation and/or lengthening/shortening

Types of structures

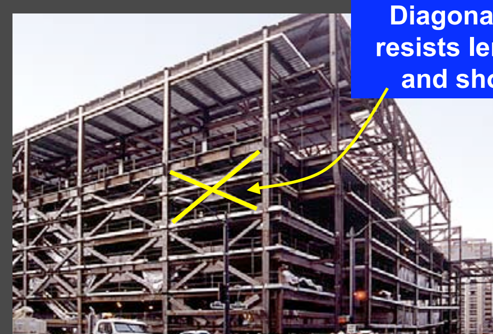
Moment frame

Strong beam/colu connectio resist rotatio

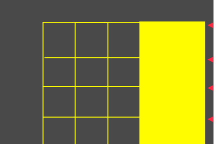
Types of structures

Braced frame

Diagonal bracing resists lengthening and shortening



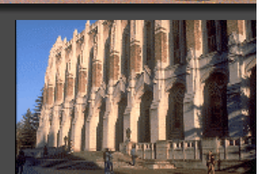
Concrete Shear Wall



Shear wall resists rotation and lenthening/ shortening

Structural Materials

Masonry
- Very brittle if unreinforced
- Common in older structures
- Common facing for newer structures



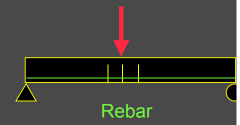
Structural Materials

Timber

Structural Materials

Concrete

- Heavy, brittle by itself
- Ductile with reinforcement



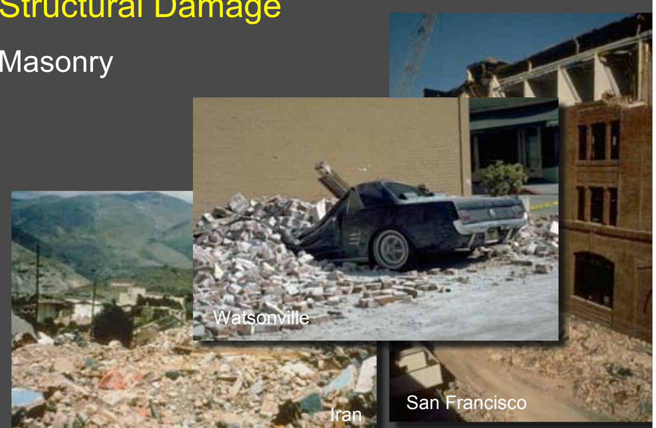
Structural Materials

Steel

- Light, ductile
- Easy connections

Structural Damage

Masonry



Structural Damage

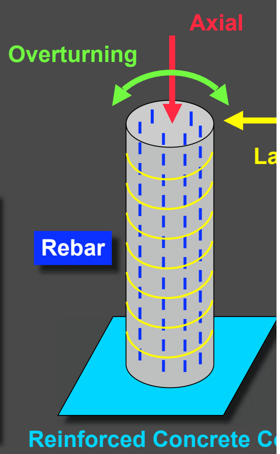
Timber

Structural Damage

Timber

Structural Damage

Reinforced Concrete

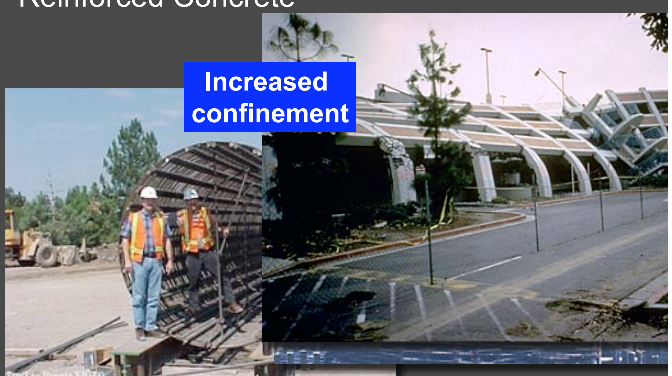


Structural Damage

Reinforced Concrete

Structural Damage

Reinforced Concrete



Structural Damage

Steel

Principal Types of Earthquake Damage

Liquefaction

Occurs in loose, saturated sands

Grain structure collapses

↓

Pore pressure increases

↓

Effective stress decreases

↓

Strength and stiffness decrease

Principal Types of Earthquake Damage

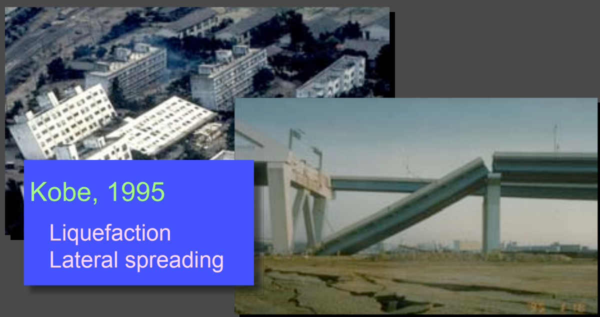
Liquefaction

Niigata, 1964

Liquefaction
Bearing failure

Principal Types of Earthquake Damage

Liquefaction



Kobe, 1995

Liquefaction
Lateral spreading

Principal Types of Earthquake Damage

Liquefaction

Niigata, 1964

Liquefaction
Lateral spreading
Pile foundation failure

Principal Types of Earthquake Damage

Liquefaction

Principal Types of Earthquake Damage

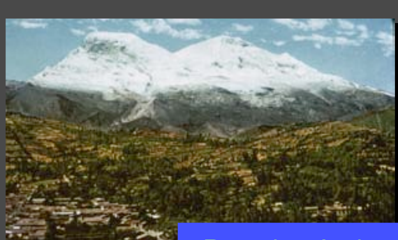
Landslides

Can occur due to liquefaction

Can occur in non-liquefiable soil

Principal Types of Earthquake Damage

Landslides



Peruvian Andes, 1970

Principal Types of Earthquake Damage

Landslides

Yungay, Peru

Principal Types of Earthquake Damage

Landslides


Yungay, Peru

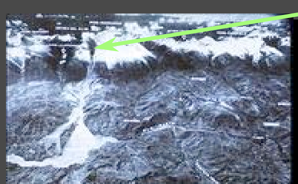
Principal Types of Earthquake Damage

Landslides

Peruvian Andes, 1970

Principal Types of Earthquake Damage

Landslides



Source

Peruvian Andes, 1970

Principal Types of Earthquake Damage

Landslides

Source

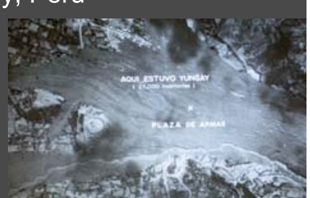
Yungay

Peruvian Andes, 1970

Principal Types of Earthquake Damage

Landslides

Yungay, Peru



Before

After

Principal Types of Earthquake Damage

Retaining Structure Failures

Active pressure on back of wall increases

Passive pressure on front of wall decreases

↓

Wall translates and/or rotates

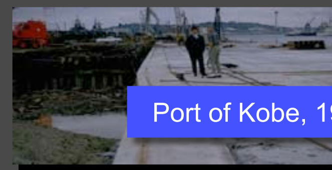
Principal Types of Earthquake Damage

Retaining Structure Failures

Port of Seattle, 1965

Principal Types of Earthquake Damage

Retaining Structure Failures



Port of Kobe, 1995

Principal Types of Earthquake Damage

Retaining Structure Failures

Port of Kobe, 1995

Principal Types of Earthquake Damage

Lifelines

Gas
Electrical power
Water
Sewer
Storm drain
Data

Highways
Bridges
Ports

Principal Types of Earthquake Damage

Lifelines

Gas
Electrical power
Water
Sewer
Storm drain
Data

Required for physical health

Highways
Bridges
Ports

Principal Types of Earthquake Damage

Lifelines

Gas
Electrical power
Water
Sewer
Storm drain
Data

Required for physical health

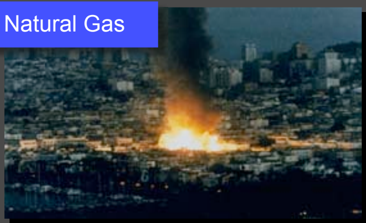
Highways
Bridges
Ports

Required for economic health

Principal Types of Earthquake Damage

Lifelines

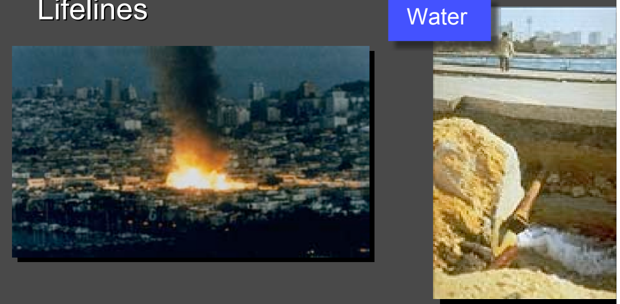
Natural Gas



Principal Types of Earthquake Damage

Lifelines

Water



Principal Types of Earthquake Damage

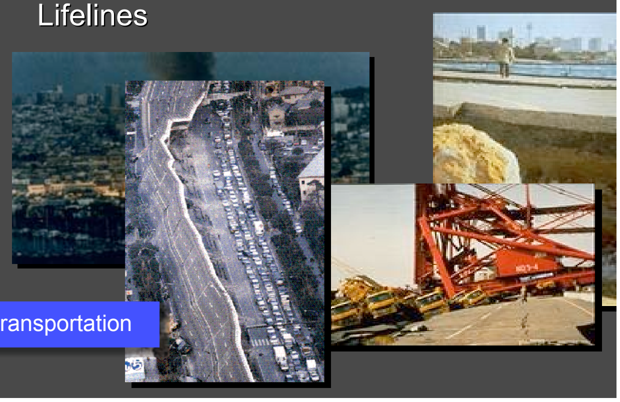
Lifelines

Ports

Principal Types of Earthquake Damage

Lifelines

Transportation



Alaskan Way Viaduct

- 2.2 miles long
- 86,000 vehicles per day
- North of Yesler
  - Designed by City of Seattle
  - Constructed in 1950
- South of Yesler
  - Designed by Washington State DOH
  - Constructed in 1956

Alaskan Way Viaduct

Alaskan Way Viaduct

Alaskan Way Viaduct

Alaskan Way Viaduct

Alaskan Way Viaduct

Alaskan Way Viaduct

Seismic Vulnerability Concerns

- Loma Prieta earthquake
  - M=7.1
  - 100 km south of Oakland
- Cypress Structure
  - Highway 17 in Oakland
  - Double-deck reinforced concrete structure
  - Similar age
  - Similar design requirements
  - Pile supported due to soft surficial soils

Cypress Structure

Cypress Structure

Alaskan Way Viaduct Investigations

- 1990 WSDOT internal review
- 1991-92 UW review
- 1993-95 UW/WSDOT investigation
- 1995-96 WSDOT seawall investigation

UW / WSDOT Investigation

- Structural Engineering Aspects
- Geotechnical Engineering Aspects

WSDOT Seawall Investigation

- Seawall performance
- Effects on AWV
- Remediation strategies

Geotechnical Engineering Investigation

- Site characterization
- Seismic hazard analysis
- Ground response analyses
- Foundation response characteristics
- Evaluation of liquefaction hazards

Site Characterization

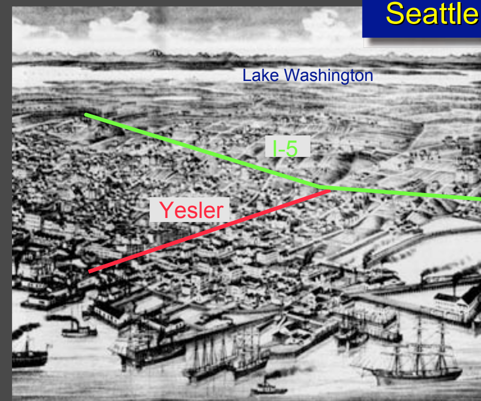
- Review of historical records
- Review of previous subsurface investigations
- Supplemental subsurface investigations
  - SPT
  - CPT
  - Seismic cone
  - Downhole seismic

Historical Records

Seattle, 1888

Historical Records

Seattle, 1884



Looking NW fro
Beacon Hill

Looking north
along waterfro

Looking eas
from Elliot Ba

Tideflat Reclamation

Tideflats, 1896

Tideflat Reclamation

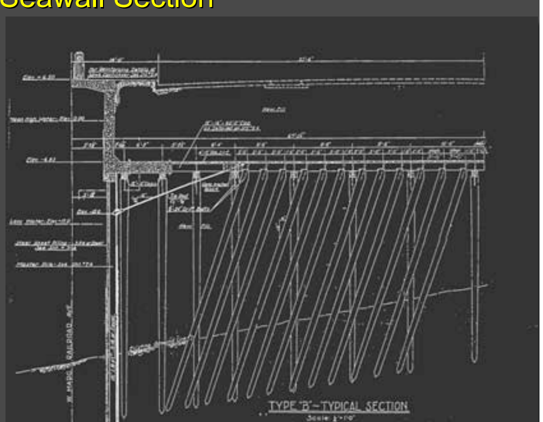
Railroad Avenue - 1920s

Railroad Avenue - 1920s

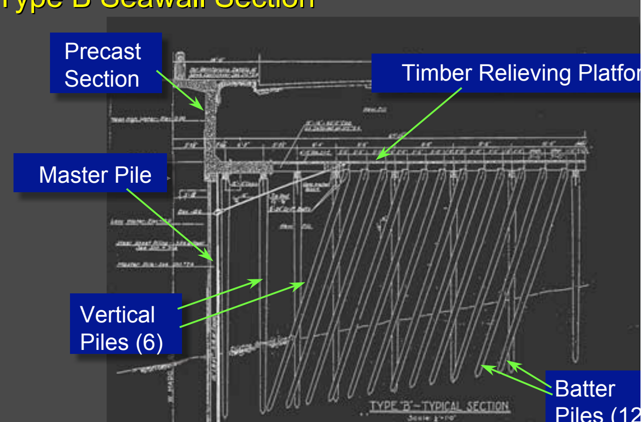
Seattle Seawall

- 12,000 lb/ft lateral thrust
- Four different wall types
  - Timber pile-supported relieving platform (2)
  - Pile-supported concrete wall
  - Fill and rip rap wall
- Total cost: $1.4 million

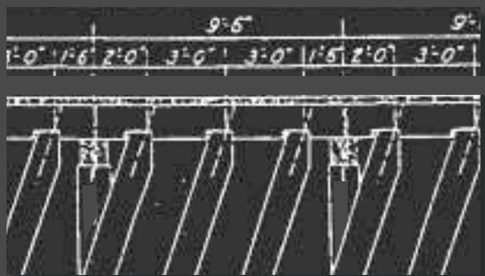
Type B Seawall Section



Type B Seawall Section



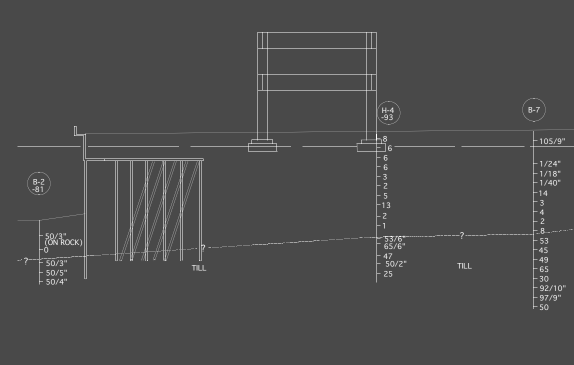
Pile/Platform Connection



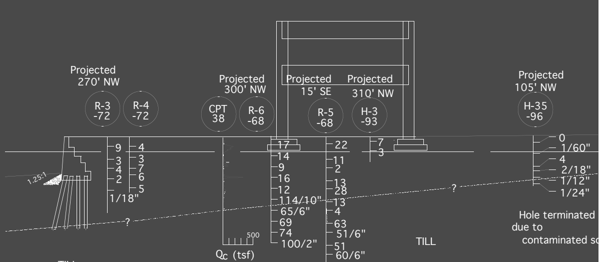
Seawall Construction

Seawall Construction

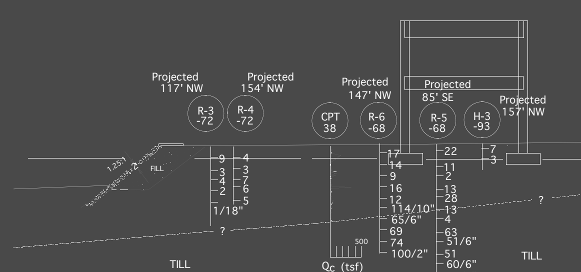
Type A Seawall Section



Pile-Supported Concrete Wall Section



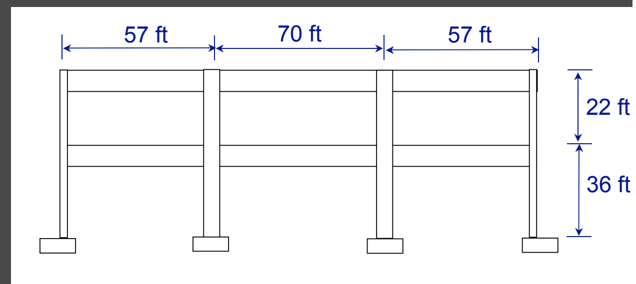
Fill and Rip Rap Wall Section



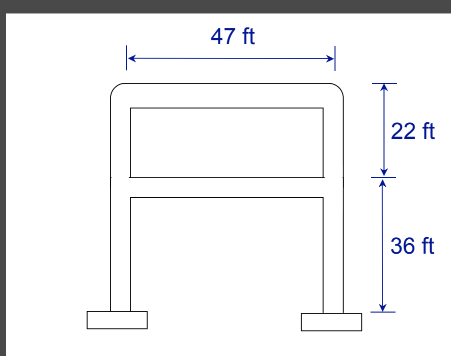
Alaskan Way Viaduct

- History
  - Originally intended as downtown bypass
  - Design began in 1948, bids opened 1949
  - Seattle section opened April 4, 1953
  - WSDOT section opened Sept 3, 1959
  - Seneca Street off-ramp opened 1961
  - Columbia Street on-ramp opened 1966
- Facts
  - 7,600 ft long
  - 58,867 yards of concrete, 7,460 tons of rebar
  - 171,410 ft of piling

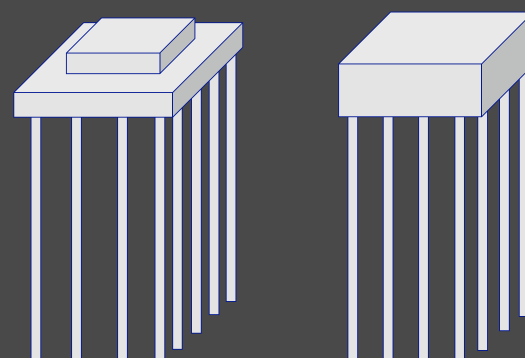
Typical Elevation (WSDOT Section)



Typical Interior Bent (WSDOT Section)



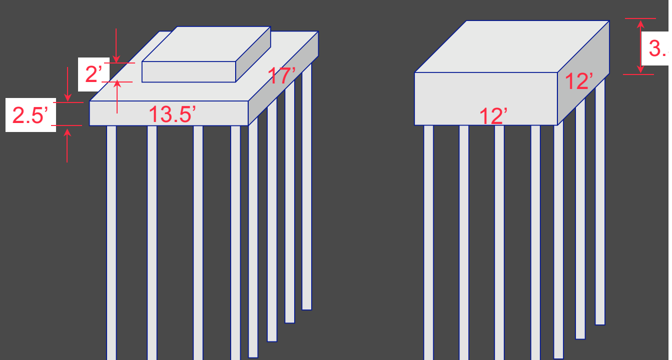
Foundations



WSDOT Section

Seattle Section

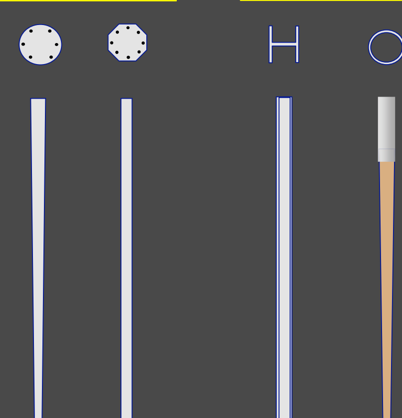
Foundations



Seattle Section

WSDOT Section

Seattle Section WSDOT Section



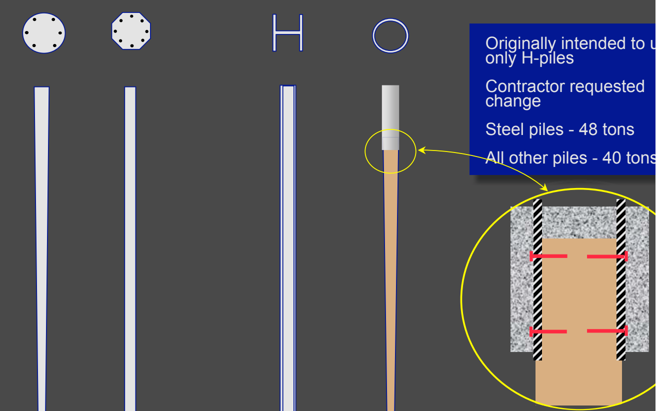
Originally intended to u only H-piles

Contractor requested change

Steel piles - 48 tons

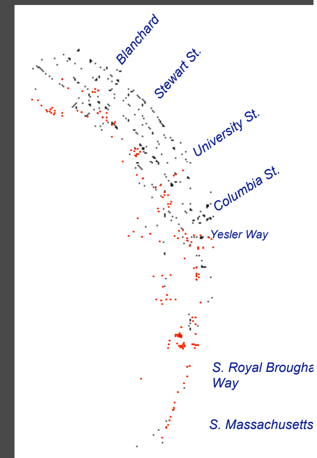
All other piles - 40 tons

Seattle Section   WSDOT Section

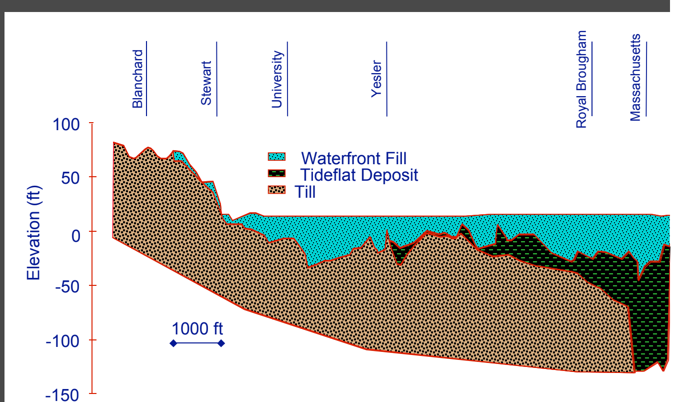


Subsurface Data

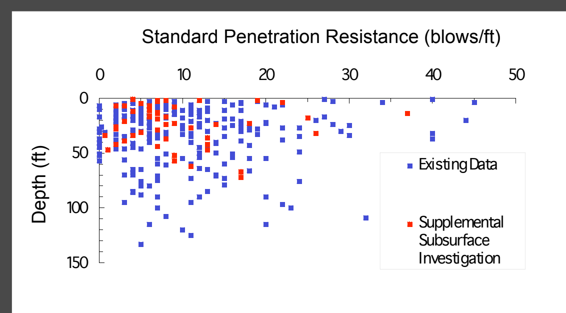
- 50 shallow borings by SED in 1948
- 17 deep borings by WSDOH in mid-1950s
- Various borings by others
- 8 borings with SPT
- 16 CPT soundings with seismic cone
- 2 deep borings with downhole seismic



Subsurface Profile

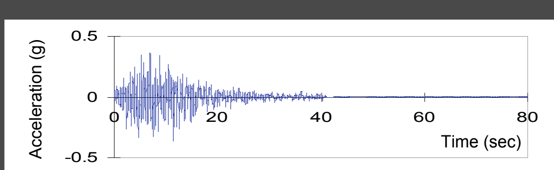


Uncorrected SPT Resistance

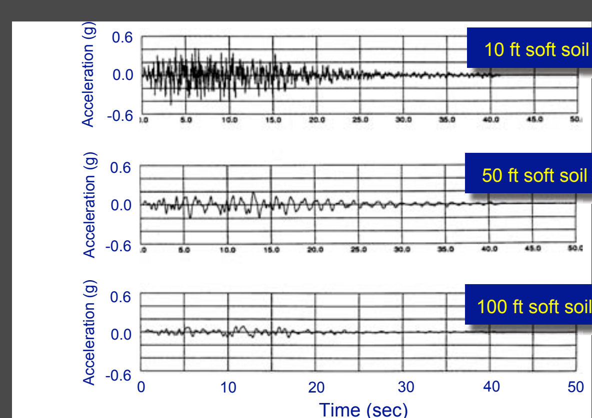


Input Motions

- PSHA (10% in 50 yrs = 475-year return period)
  - Peak acceleration
  - Spectral velocities
  - Bracketed duration
- Design-level response spectrum
- Quasi-synthetic time histories
- Deconvolution to produce 3 “bedrock” motions



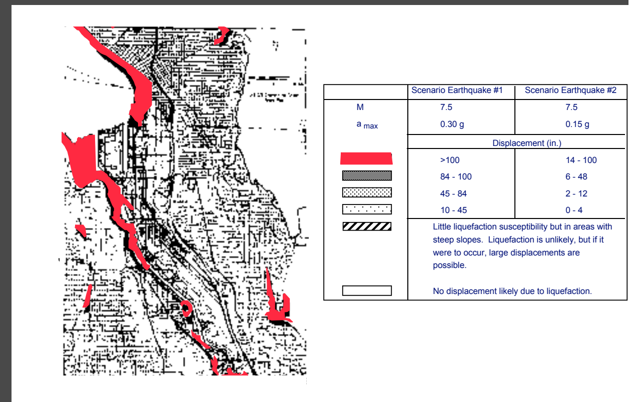
Ground Surface Motions



Liquefaction Susceptibility

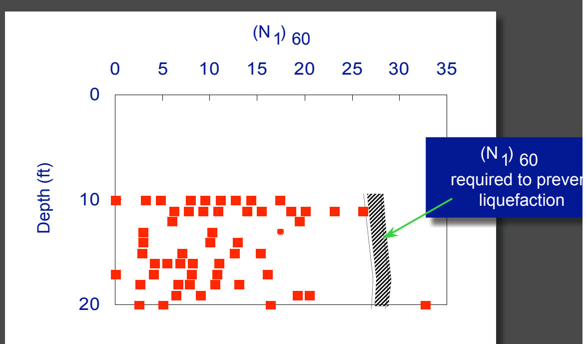
- Historical evidence
  - Sand boils in 1949 and 1965
  - Broken pipes in 1949 and 1965
  - Lateral movements in 1965
- Construction techniques
  - Hydraulic filling
  - Dumping through water
- Previous investigations
  - Mabey and Youd (1991)
  - Grant et al. (1992)

Mabey and Youd (1991)



Liquefaction Evaluation

Standard Penetration Test



Liquefaction Evaluation

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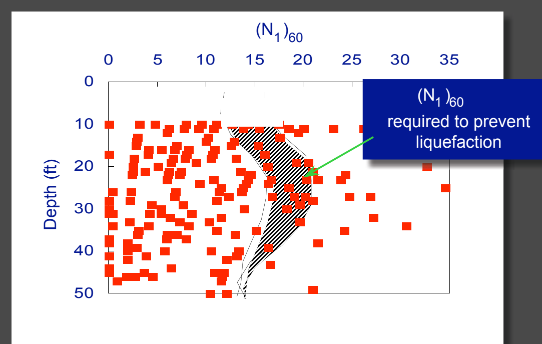
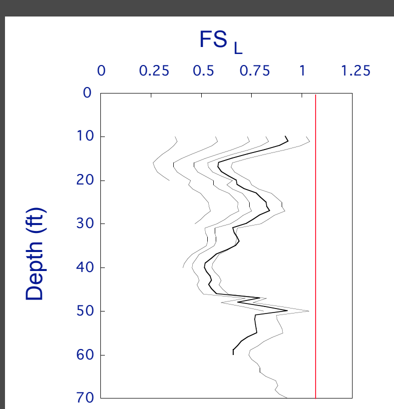
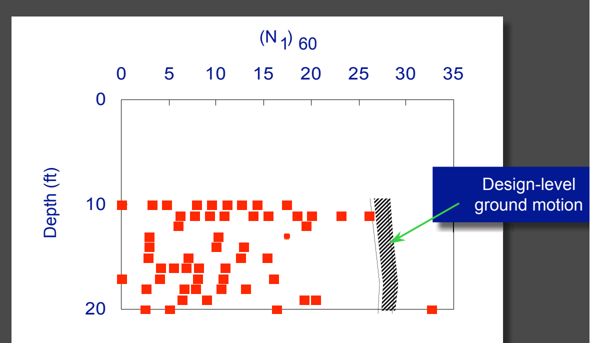


SPT-Based Factor of Safety



Liquefaction Evaluation

Comparison with 1965 observations



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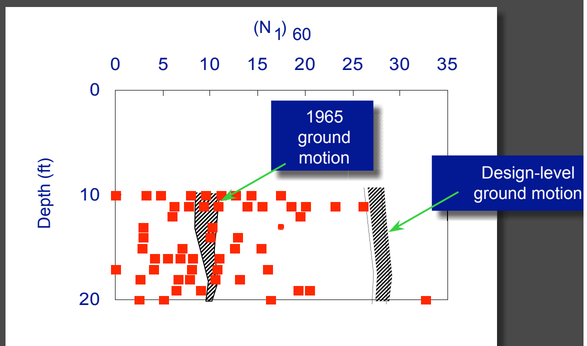

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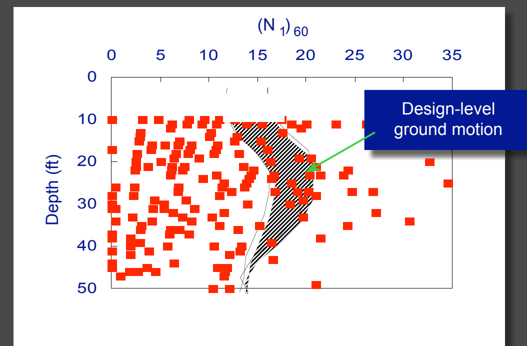

Liquefaction Evaluation

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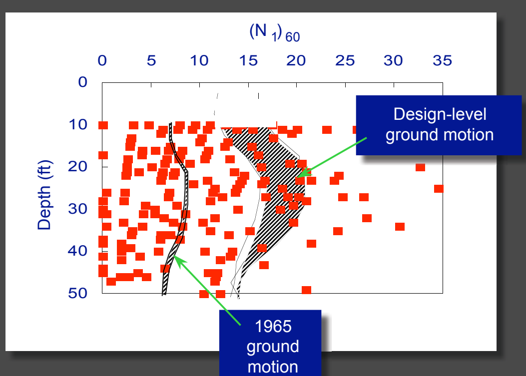
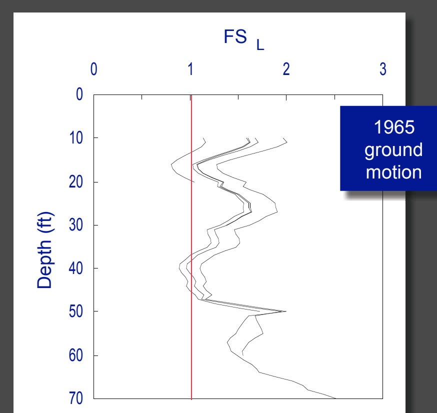


SPT-Based Factor of Safety



Effects of Liquefaction

- Sand boils - expected over most of length
- Post-earthquake settlement
  - Up to 1” in fill above water table
  - Up to 25” in soft, saturated soils
- Vertical pile movement
  - Tip capacity reached at $r_u = 0.6$
  - Tips of southernmost piles in liquefiable soil
- Lateral pile movement
  - Depends on lateral soil movement
  - 10”-12” expected to cause bending failure
  - Lateral soil movement depends on seawall movement

All movements variable due to variability of soil profile

Seawall Investigation

Estimation of permanent deformations due to liquefaction

- Transverse profile characterization
  - 5 additional borings (2 offshore)
  - 3 additional CPT soundings
- Seawall structure characterization
  - Member sizes
  - Member properties
  - Connection strengths
- Computational model
  - Soil
  - Seawall
  - Soil-seawall interaction

⇨ *FLAC*

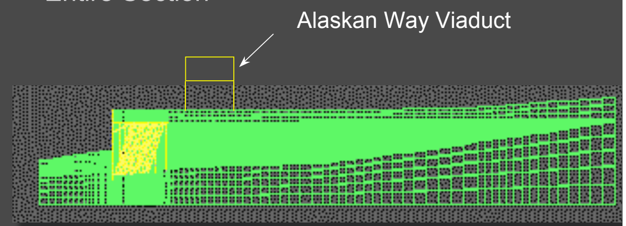
FLAC

Fast Lagrangian Analysis of Continua

- Explicit finite difference code
- Large-strain capabilities
- Several soil constitutive models
- Structural elements (beams, piles, cables)
- Interface elements (normal and shear)
- Coupled stress-deformation and flow capabilities
- Incremental construction modeling
- Graphical display of results
- Dynamic option
- Creep option
- FISH programming language

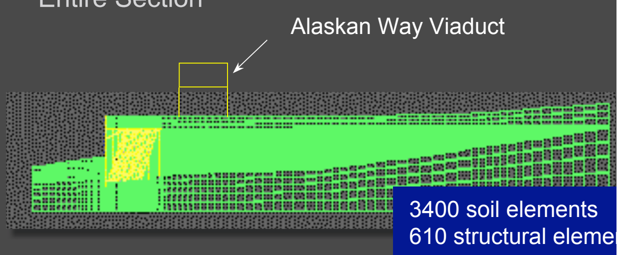
Type B Wall Model

Entire Section

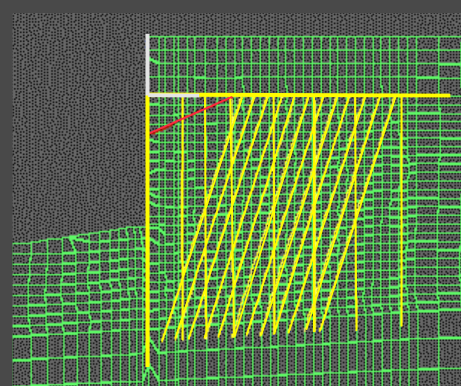


Type B Wall Model

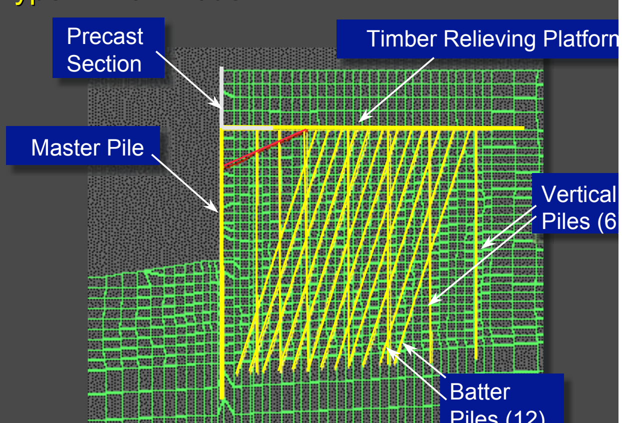
Entire Section



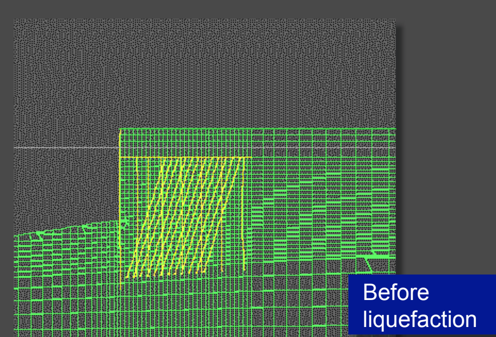
Type B Wall Model



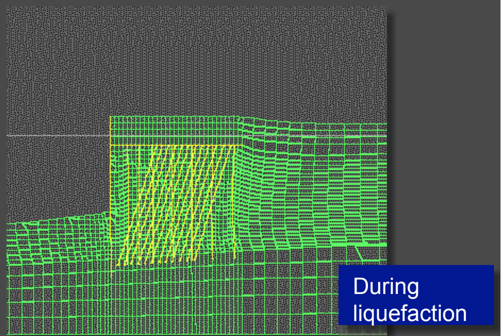
Type B Wall Model



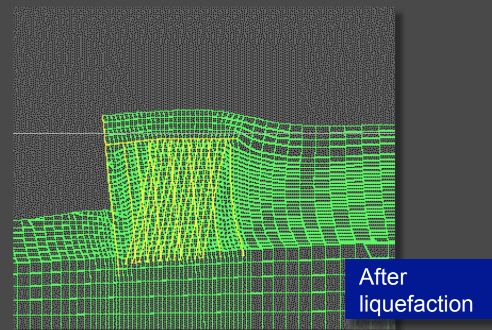
Type B Wall



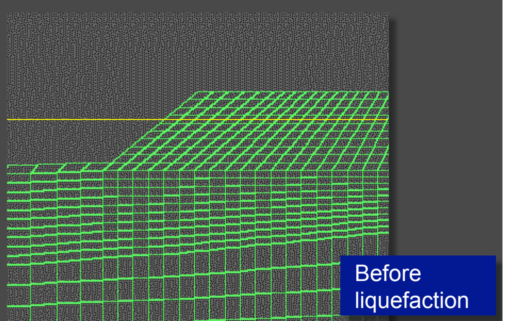
Type B Wall



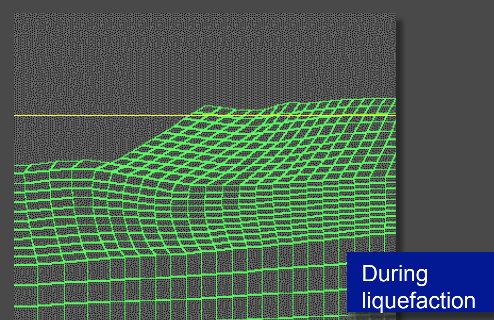
Type B Wall



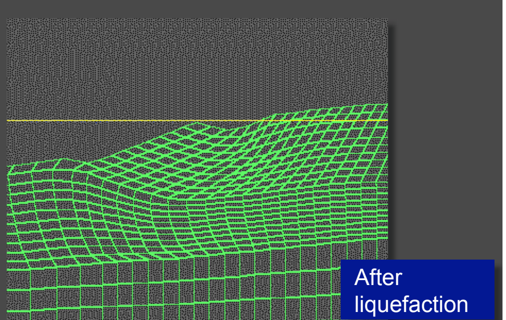
Fill and Rip Rap Wall



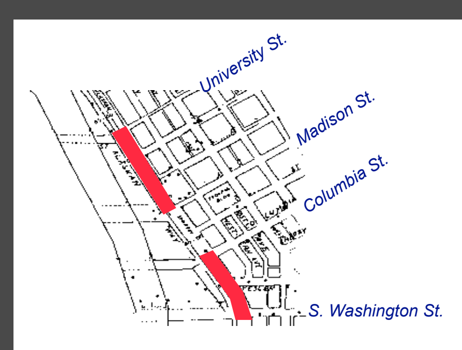
Fill and Rip Rap Wall



Fill and Rip Rap Wall



Zones of Large Lateral Movements

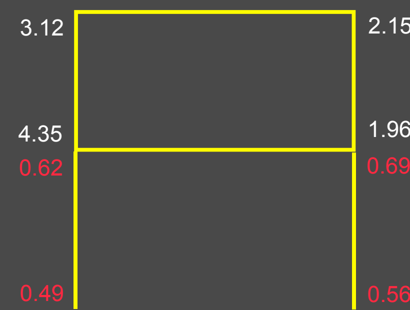


Structural Aspects of Seismic Vulnerability

- Dynamic Response Spectrum Analyses
- Nonlinear “Pushover” Analyses
- Investigated capacities and demands for:
  - Flexure (beams and columns)
  - Shear (beams and columns)
  - Splices
  - Joints
  - Pile Caps

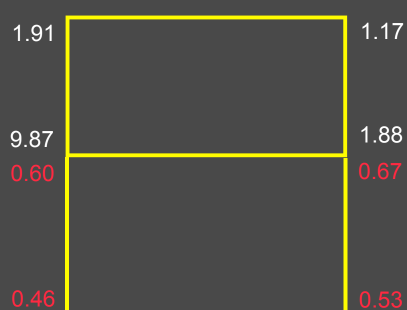
Capacity/Demand Ratios

Exterior Frame - Column Flexure



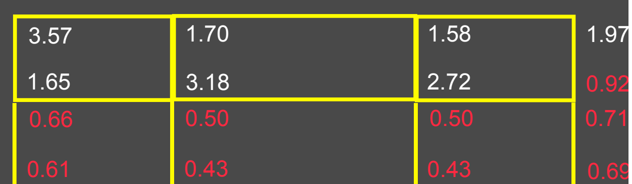
Capacity/Demand Ratios

Interior Frame - Column Flexure



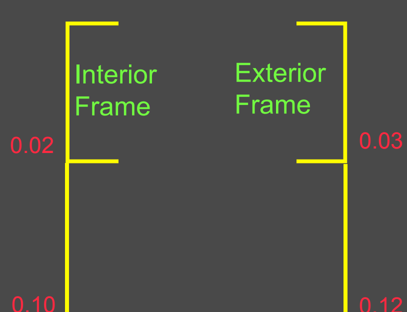
Capacity/Demand Ratios

Longitudinal Frame - Column Flexure

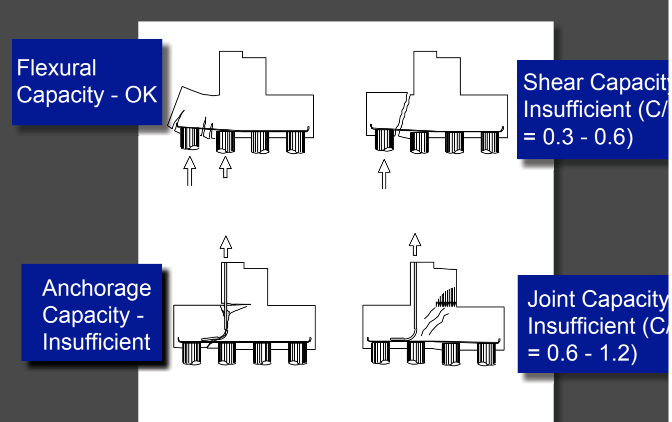


Capacity/Demand Ratios

Splices



Pile Caps



Summary of Structural Vulnerability

- Lower-level splices highly vulnerable
- Joints highly vulnerable
- Columns - shear capacity marginal
- Footings - vulnerable to brittle failure
- Special sections require additional investigation
  - Outrigger bents
  - On/off ramp sections

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Effects of liquefaction-induced lateral soil movements will dominate effects of shaking