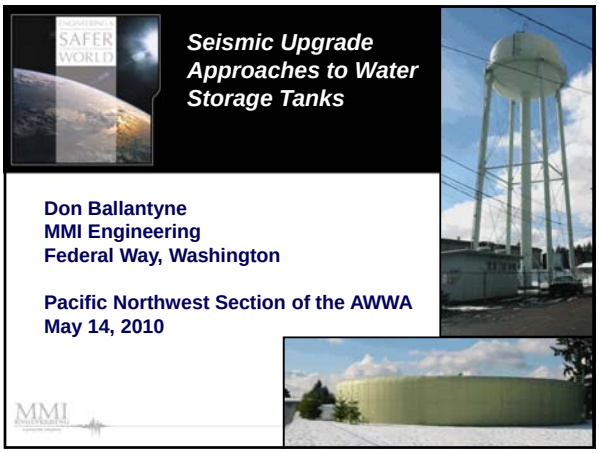
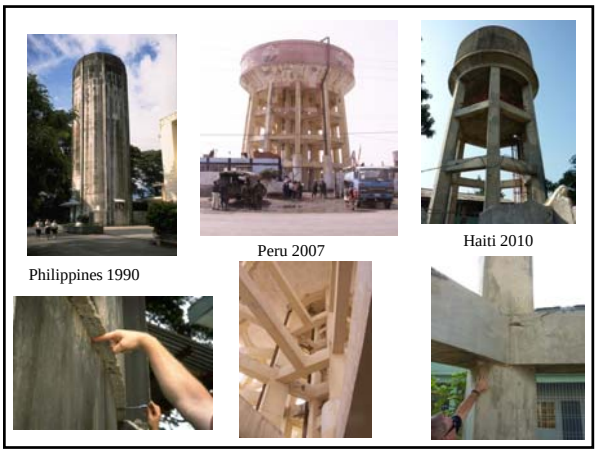




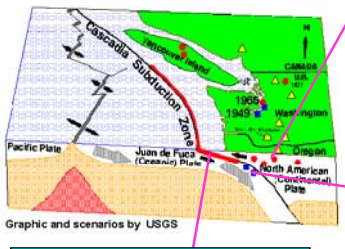
Overview

- Reasons to seismically upgrade tanks
- Pacific Northwest Seismicity
- Earthquake loads
- Ground level steel tanks
- Steel Standpipes
- Elevated Steel Tanks
- Small tanks
- Wire and tendon wrapped tanks
- Cast-in-place concrete tanks

Reasons to Seismically Upgrade Tanks

- Enhance system reliability
  - Post-earthquake fireflow
  - Minimize customer business interruption
  - Post-earthquake potable water
- Life safety
- Reduce restoration time
- Integrate with tank coating projects

Pacific Northwest Earthquake Source Zones

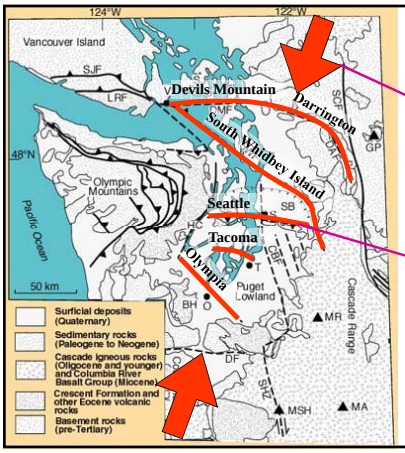


1) Crustal Earthquakes (<15 miles deep) occur within the North American Plate on faults such as Seattle, Tacoma, and South Whidbey Island.

2) Deep Earthquakes (>40 miles deep) occur within the subducting Juan de Fuca Plate. Five M6 events in the last century. Nisqually Earthquake.

3) Cascadia Subduction Earthquakes occur about every 500 years at the boundary between the Juan de Fuca and North American plates. An M9 event occurred on January 26, 1700.

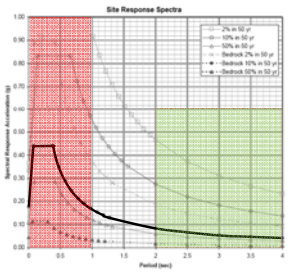
Crustal Faulting

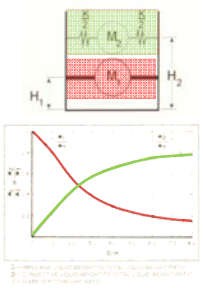


Shortening of about 0.4 inches/year, about ½ of which may result in crustal earthquakes.

The last major crustal earthquake occurred in the region on the Seattle Fault 1,100 years ago. It resulted in a vertical offset of 7 meters.

Earthquake Loads





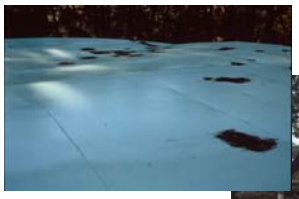
Damage Mechanisms All Tanks

- Broken rigid pipe due to uplift or settlement
  - Side - provide flexibility
  - Bottom – setback from wall
- Roof/Column damage from sloshing or inadequate anchorage
- Geotechnical/foundation
  - Cut/fill – uneven settlement
  - Slide
  - Liquefaction

Tank Moved and Separated Pipe

Los Angeles DWP 1995

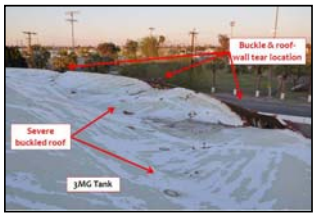
Roof Damage from Sloshing



Loma Prieta 1989

Limon Costa Rica 1991

Roof Damage from Sloshing



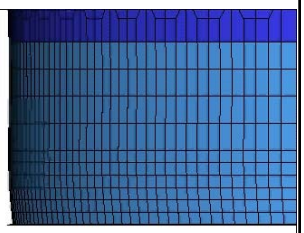
3 MG Tank, Calexico, 2010

1 MG Tank, Calexico, 2010

Roof Slid Off Tank

Los Angeles DWP 1995

Uplift Modeling/ Elephant's Foot Buckling



Landers 1992

Tank Rupture

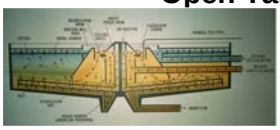
Los Angeles DWP 1994

Elephant's Foot Buckling

Santa Clarita 1994

Santa Clarita 1994

Sloshing Damage in Open Tank



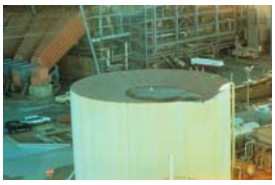
Rinconada WTP 1989

Elephant's Foot Buckling

Costa Rica 1991

Nisqually 2001

Bottom Seam Split Spilling Contents



Moss Landing, 1989

Wine Tank Drained Causing Implosion

Argentina, 1977

Anchor Bolt Pull-out/ Elephant's Foot Buckling

Jensen WTP Los Angeles DWP 1995

Anchor Bolt Stretching

Seattle 1965

Broken Anchor Strap

Manchester WD, Nisqually, 2001

Steel Tank/ Standpipe Mitigation

- Adequate anchors prevent uplift; inadequate anchors may stretch
- Add or upgrade anchor/foundation to resist uplift
- Stiffen bottom with concrete inside
- Check structural capacity of tank shell to transfer load/resist wrinkling; add stiffeners if required
- Limit bending moment on shell at anchor connection with adequate chairs
- Unanchored steel tanks with a H/D ratio <0.5 usually OK structurally - Provide pipe flexibility

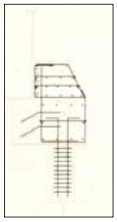
Well Anchored Standpipe

Lakehaven Utility District

Add Additional Anchorage if Required

Portland Water Bureau

Add Foundation to Prevent Uplift



Stiffen Tank Bottom with Concrete Donut

Provide Pipe Flexibility for Unanchored Tanks

Elevated Tank Damage Mechanisms

- Foundation not sized to resist overturning; individual piers not connected with tie beams
- Cross bracing
  - Connection weaker than cross brace
  - Cross-bracing under sized
  - Desirable to have ability to stretch to absorb energy for multiple cycles
  - Columns undersized

Elevated Tank Tension Rods Stretch

Bremerton, Nisqually 2001

Elevated Tank Tension Rods Break

Scotts Mills Oregon, 1993

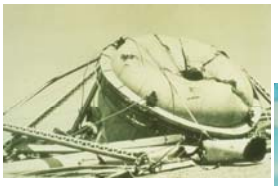
Elevated Tank Failure Progression

- Cross brace fails
- Redistributes load to other braces resulting in torsional moment
- Domino effect
- Columns buckle
- Tank collapses within foundation circle

Elevated Tank Collapses, Damages Police Station

Tank and Police Station
Philippines 1990

Elevated Tanks Collapse



Kern County1952

Imperial Valley, CA 1979

Elevated Tank Solutions

- Upgrade foundation, bracing, columns
- Innovative approaches
  - Base isolation – Seattle Public Utilities
  - Energy absorbing cross bracing – Kent, Renton

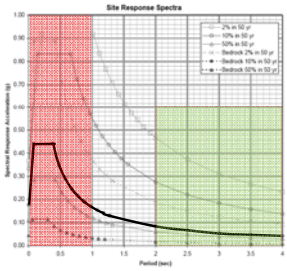
Strengthen Bracing

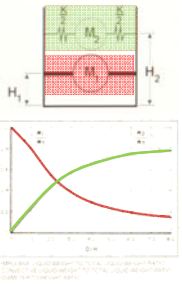
Highline Water District

Strengthen Bracing

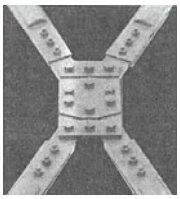
Seattle Public Utilities

Earthquake Loads





Energy Dampers



City if Renton/
Reid Middleton

Base Isolation

Seattle Public Utilities Myrtle Tank

Steel Tank Design Standards

- Published first Journal AWWA November 1935
- Dynamic analysis tank sloshing – Housner 1957-63
- Prior to 1979 – equivalent static load as per purchaser
- 1984 – seimsi provisions in Section 13, only mandatrory in Zone 4
- Most recently updated in 2005

Small Unanchored Tanks Slide

Los Angeles DWP 1971

Limon Costa Rica 1991

Small Tank Legs Need to Provide Lateral Load Path

Limon Costa Rica 1991

Wire-Wrapped/Tendon Concrete Tank Damage Mechanisms

- Reinforcing corrosion or
- Inadequate reinforcing for earthquake loading
  - Stop leakage then re-wrap
- Roof/wall joint not designed to transfer shear
- Wall/bottom joint not design to transfer shear; movement required during filling
  - Earthquake cables used beginning 1970s
  - Passive soil pressure may restrain load on buried tanks
- Add curb or special anchorage

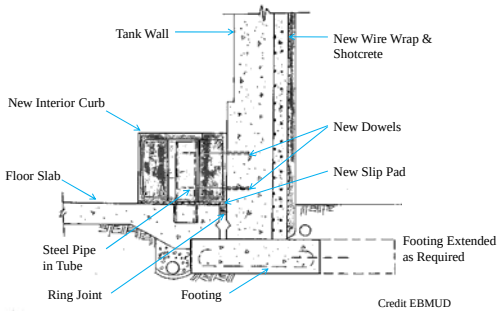
Wire Wrapped Concrete Reservoir Failed Due to Corrosion

Purissima Hills, CA 1989

New Concrete Tank Seismic Cables

Credit DYK

Wall Section with New Interior Curb



Credit EBMUD

Interior Sliding Restraint Concrete Curbs

Credit EBMUD

Concrete Tank – Hoop Stress

Credit DYK

Credit EBMUD

Cast-In-Place Concrete

- Flat walls carry loads in shear or bending
- Sometimes bending moment carried to foundation
- Design per ACI-350

New Tank Standards

- AWWA D100-05 Welded Carbon Steel Tanks for Water Storage
- AWWA D110-04 Wire & Strand Wound, Circular, Pretressed Concrete Water Tanks
- AWWA D115-06 Tendon-Prestressed Concrete Water Tanks
- International Building Code - 2009
- ACI 350-06 – Analysis, Design and Construction Practices in Environmental Engineering Concrete Structures
- API 650 – Welded Steel Tanks for Oil Storage

Questions ?

Don Ballantyne
MMI Engineering
Dballantyne@MMIEngineering.com