

April 29, 2015



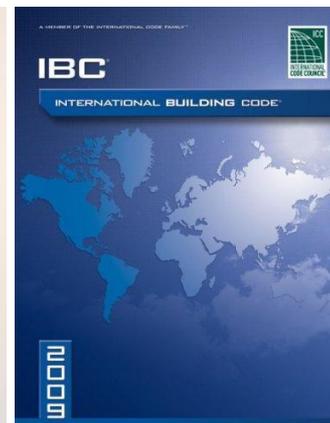
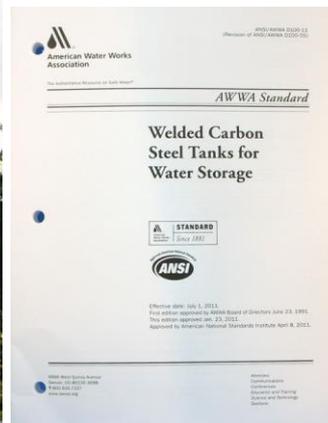
SEISMIC RETROFIT OF STEEL RESERVOIRS

Jon Conner, PE, SE, RH2 Engineering

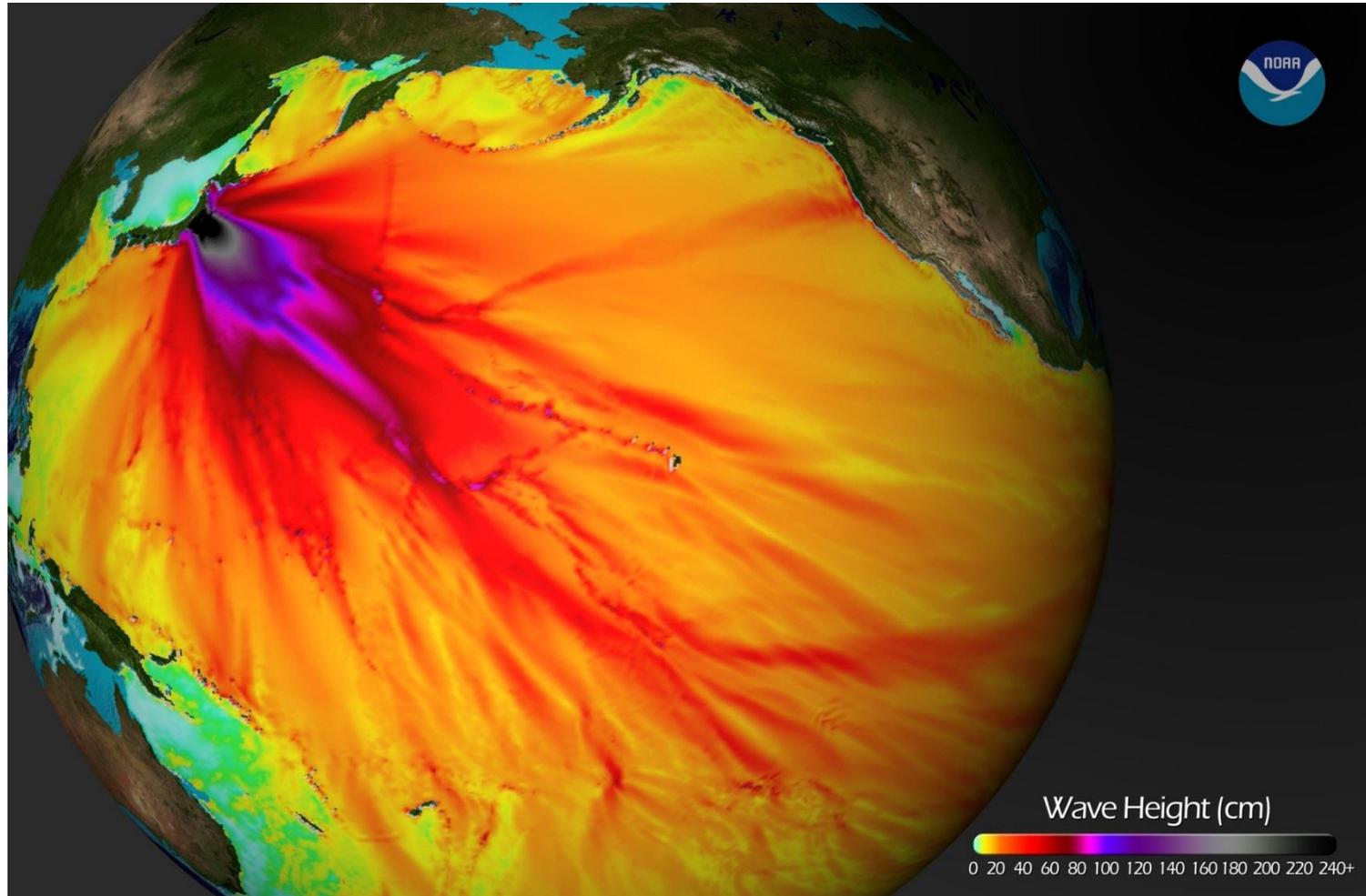
SEISMIC RETROFITS



- Changes in design forces
- Ground motions
- Structural design
- Damage/failure modes
- Retrofit examples & options
- Detailing



WHAT'S AT RISK?



Japan 2011: 9.0 Magnitude EQ

Tsunami Impact

JAPAN 2011 EARTHQUAKE

- Subduction zone fault moved 164 ft laterally, 33 ft up
- \$309 billion in damage
- Tsunami waves up to 33 ft high reached 6 miles inland
- 18,500 killed
- Nuclear power crisis
- Damage due to water



SEATTLE AREA EARTHQUAKES

- Cascadia Subduction Zone Quakes
 - Occur as Juan De Fuca plate subducts under the North American Plate
 - Extends from near the coast to the Cascades
 - Produces 3 Types of quakes
 - Crustal quakes: Shallow, N. American Plate faults (Seattle)
 - Deep Intraplate: Most common for WA & OR (~every 30 yrs)
 - 2001 Nisqually (\$40M), 1965 (\$50M) 1949 (\$100M)
 - Megathrust – largest type in the world
 - Potential for M9+ and affect Canada to California

SEATTLE AREA EARTHQUAKES

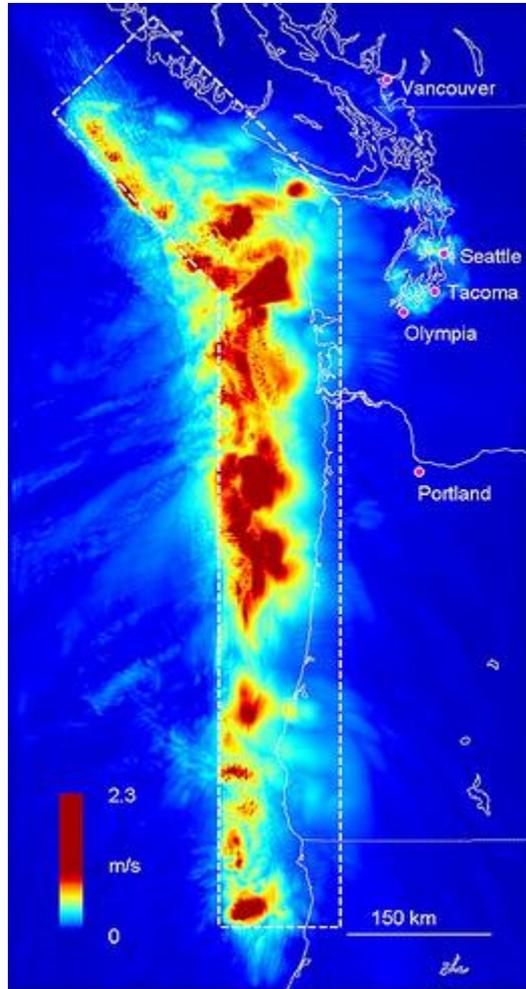
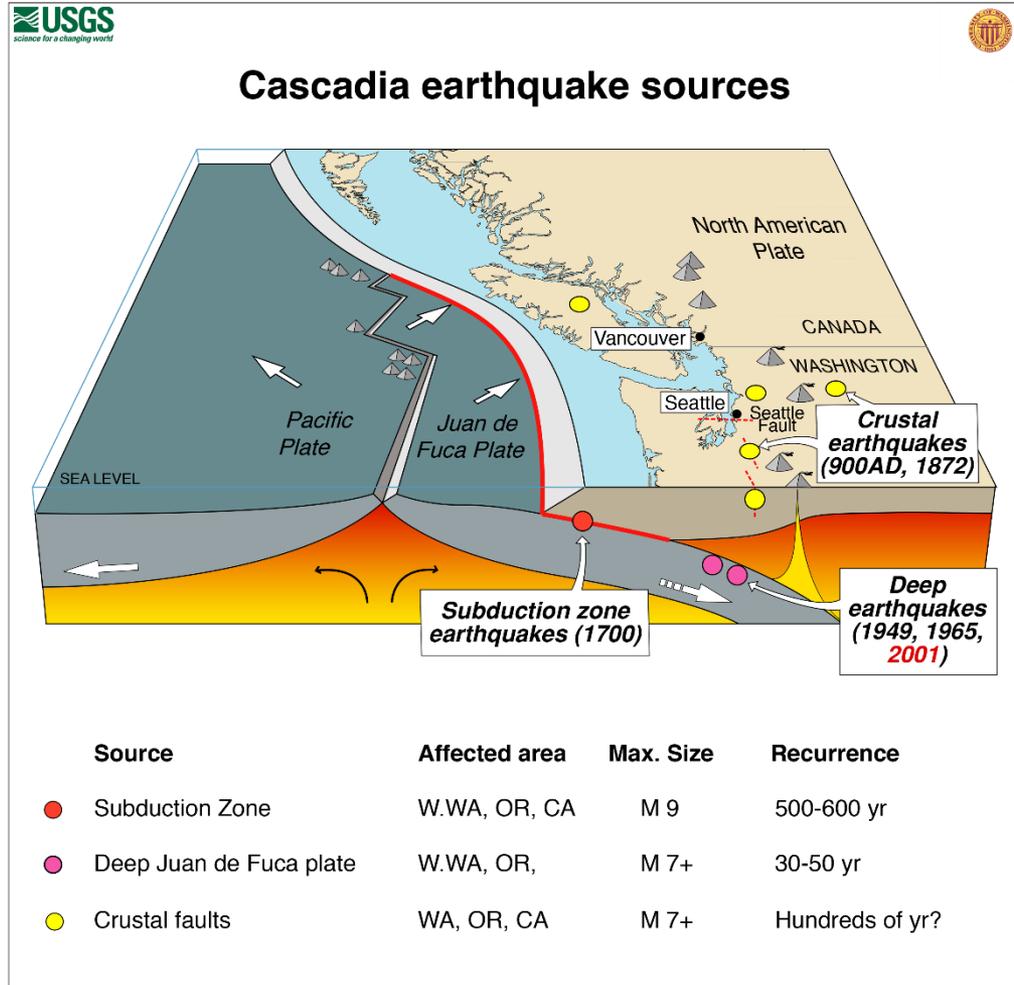
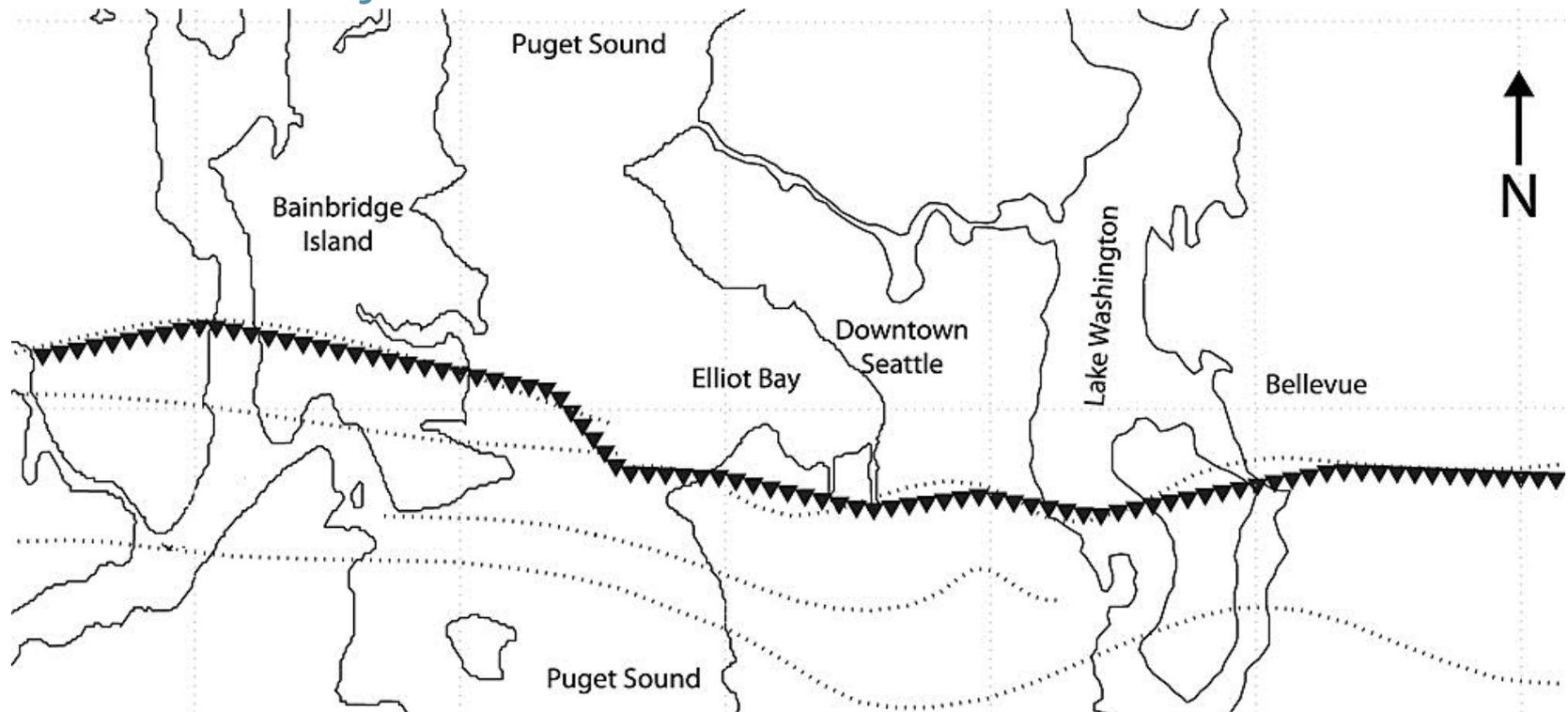


Photo by Kim Olsen
San Diego State University



SEATTLE AREA EARTHQUAKES

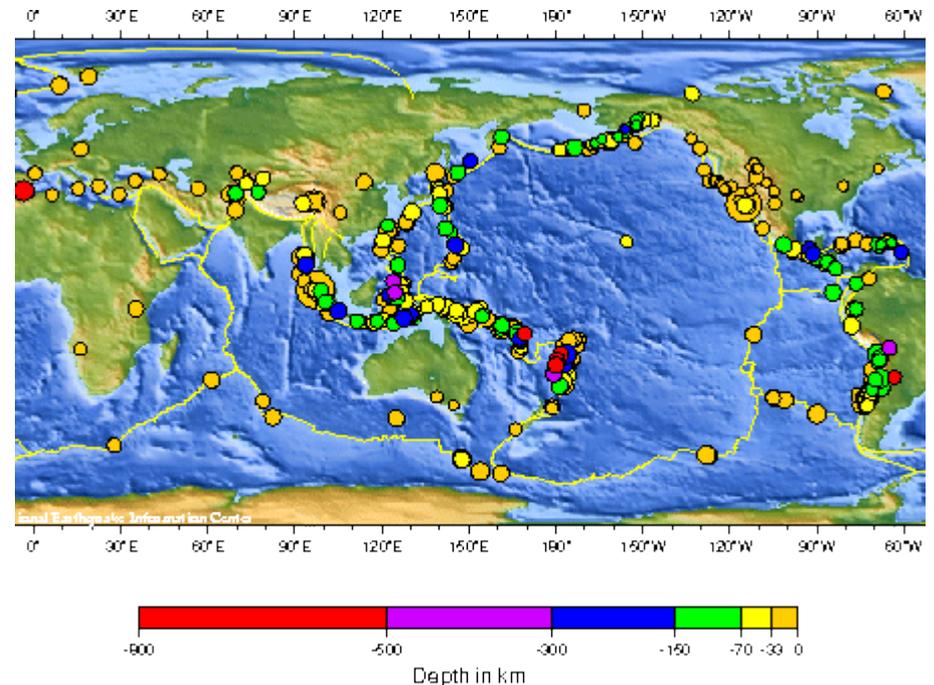
- Seattle Fault – <7.5 M Crustal
 - Greatest risk to Seattle but rare (4 in the last 3,000 yrs)
 - Subsequent landslides, Puget Sound tsunami & fires are a major concern



ARE WE HAVING MORE/BIGGER EQS?

Significant EQs Since 2010

- 8.2 M 4/1/14, Chile
- 8.3 M 5/24/13, Sea of Okhotsk
- 8.0 M 2/6/13, Solomon Is
- 7.0 M 4/12/12, California
- 8.6 M 4/11/12, Sumatra
- 7.6 M 7/6/11, Kermadec Is.
- 9.0 M 3/11/11, Japan
- 7.6 M 7/23/10, Phillipines
- 7.8 M 4/6/10, Indonesia
- 8.8 M 2/27/10, Chile



AVERAGE ANNUAL EARTHQUAKES WORLDWIDE

| Magnitude | Average Annually |
|--------------|------------------|
| 8 and higher | 1 |
| 7 – 7.9 | 15 |
| 6 – 6.9 | 134 |
| 5 – 5.9 | 1,319 |
| 4 – 4.9 | 13,000 |
| 3 – 3.9 | 130,000 |
| 2 – 2.9 | 1,300,000 |

- The magnitude of an earthquake is related to the length of the fault
- Longer fault = larger earthquake
- There is currently no known fault long enough to produce a “megaquake”
- Largest earthquake ever recorded was M9.5 in Chile on 1,000 mile fault

GENERALLY WITHIN THE NORMAL RANGE

But we have seen greater destruction...

Why?

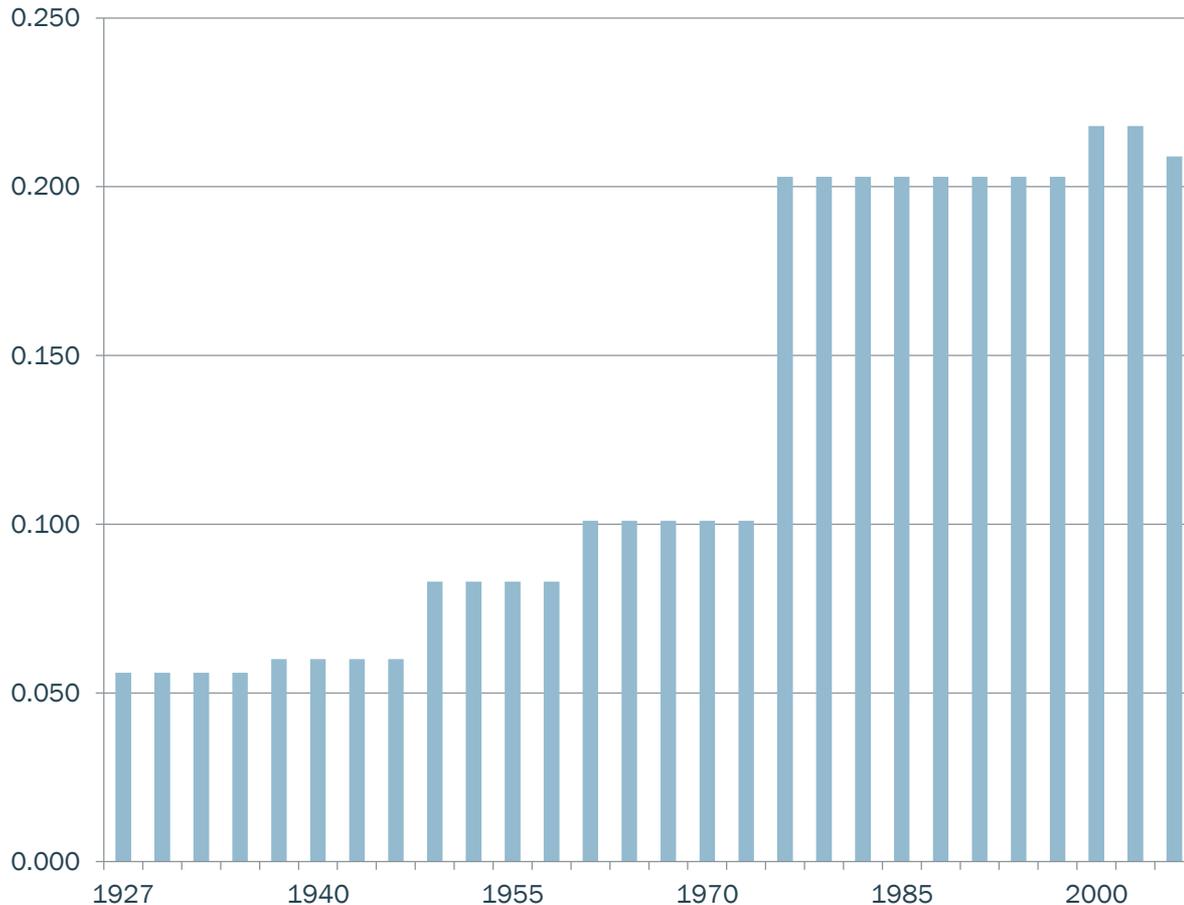
- Greater population density
- More Buildings
- EQs have occurred in areas with poor or outdated design



Haiti, 7.0 M, 1/12/10

HISTORICAL CHANGES IN WA DESIGN

BASE SHEAR (% G) FOR WESTERN WA



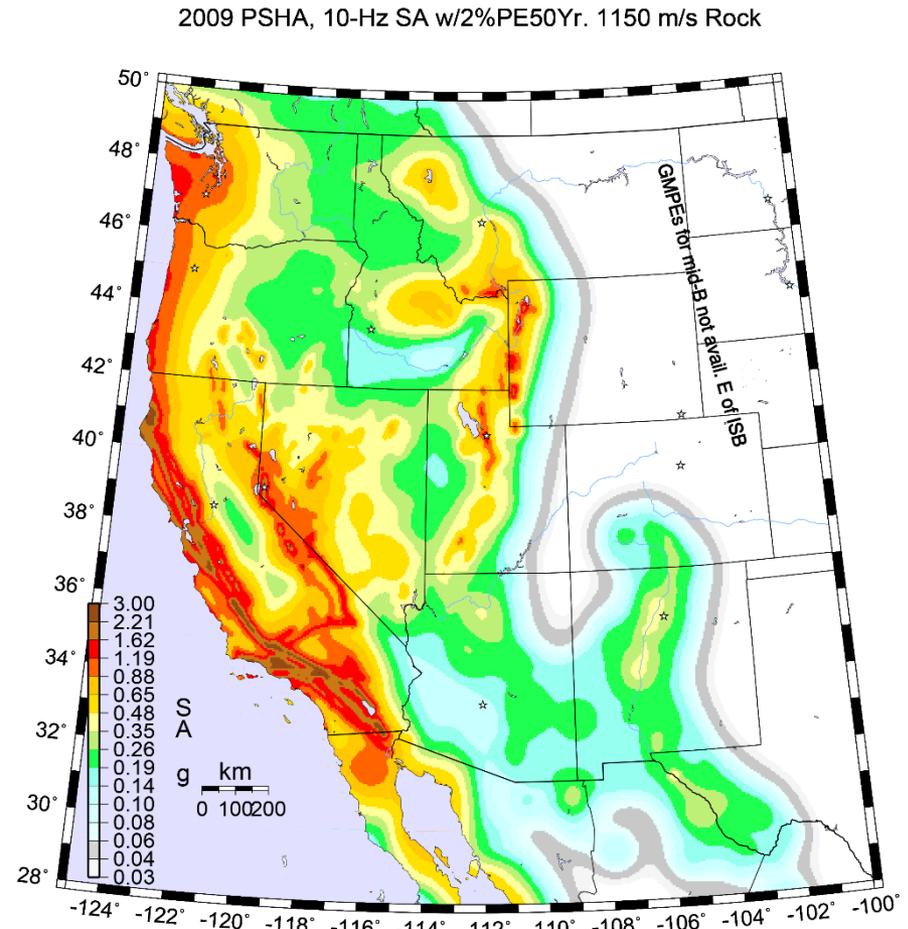
1974: UBC adopted

1976: Importance Factor &
Drift Limits added

2000: IBC adopted, now
per USGS EQ info

GROUND MOTION

- Based on ASCE 7 (US)
 - Site-specific based on location and soil type
 - Also used by IBC
- Max Considered EQ
 - 2% probability in 50 years
 - 2,500-year return
 - Previously 500-year return
- Developed by USGS & local professionals

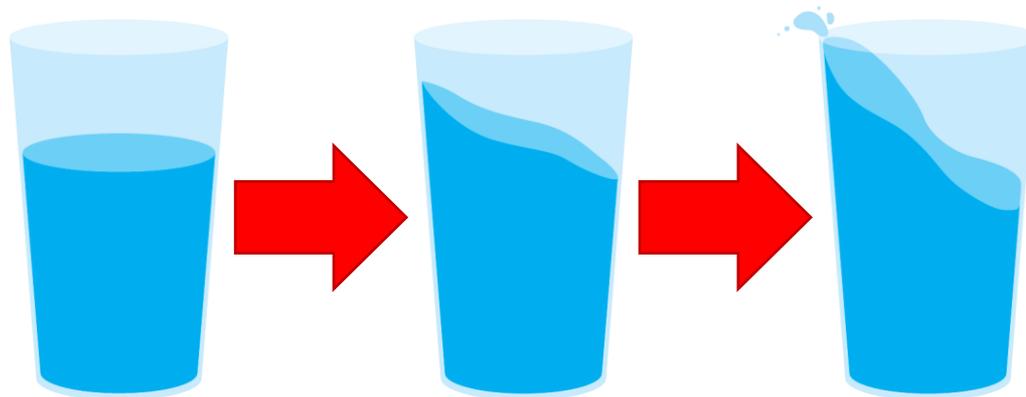
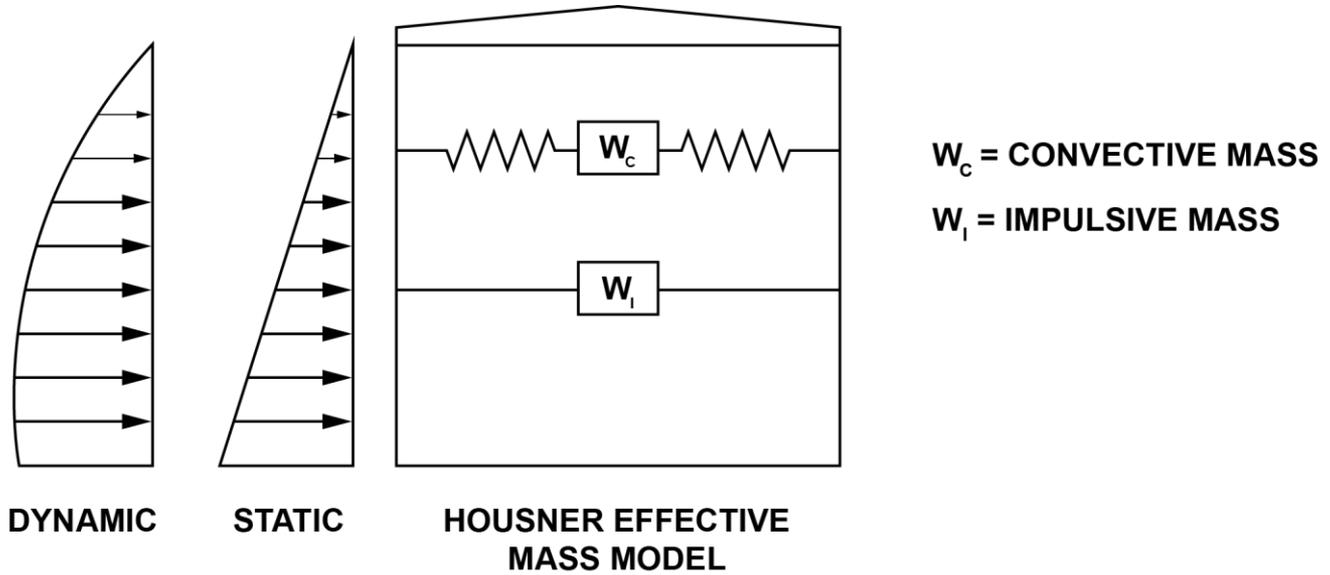


GMT 2010 Sep 23 10:11:00 USGS PSHA WUS crustal and subduction sources. Site Vs30 1150 m/s. 10 Hz SA with 2% in 50 yr PE.

SEISMIC DESIGN NOTES

- Structures are designed to experience some damage without collapsing
- Essential facilities are designed for 50% higher loads than ordinary facilities
- Current code uses a cost-versus-risk approach

DESIGN MODEL



WATER RESERVOIR CONCERNS

- Older reservoirs are most at risk
 - Design loads have been increased based on new information
 - Seismic-resistant details have improved
 - Construction practices and materials have improved

STEEL RESERVOIRS AT RISK

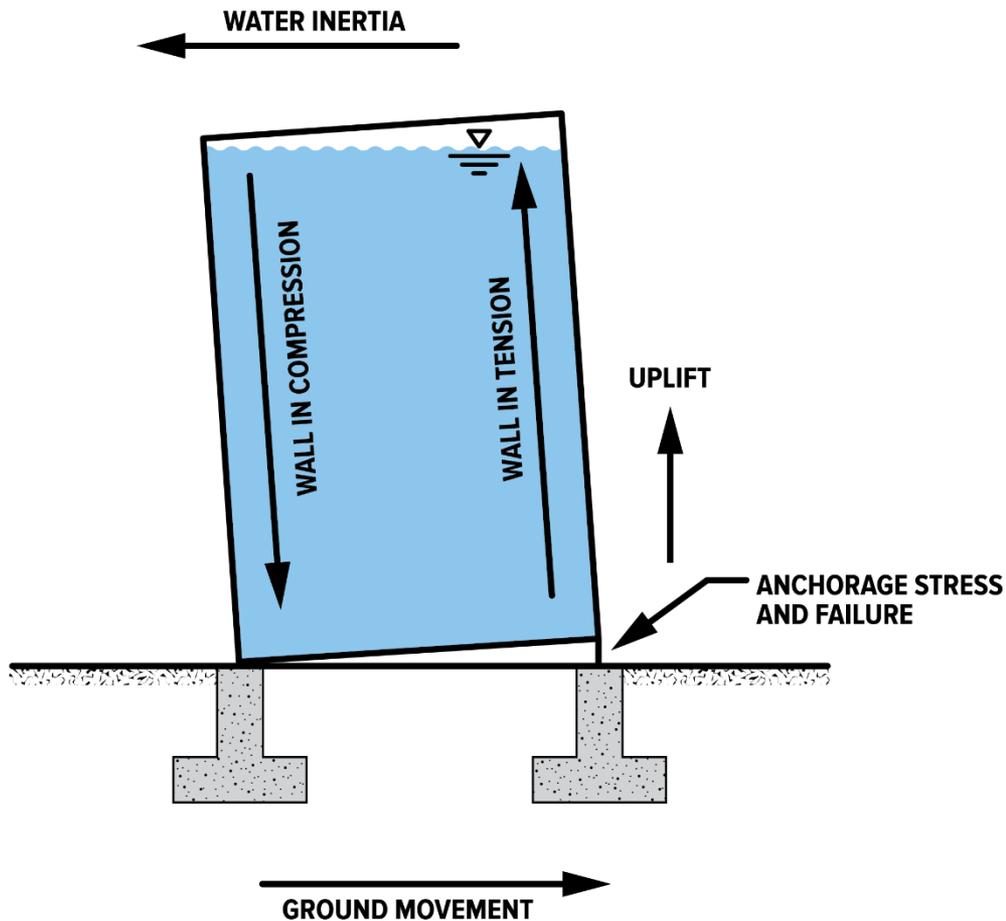


- Older reservoirs (Pre-1980s)
- Tall and slender
 - Diameter less than 1.5x height
- Inadequate foundation size
- Inadequate anchorage
 - Straps or small diameter bolts

POSSIBLE FAILURE MODES

1. Anchorage failure

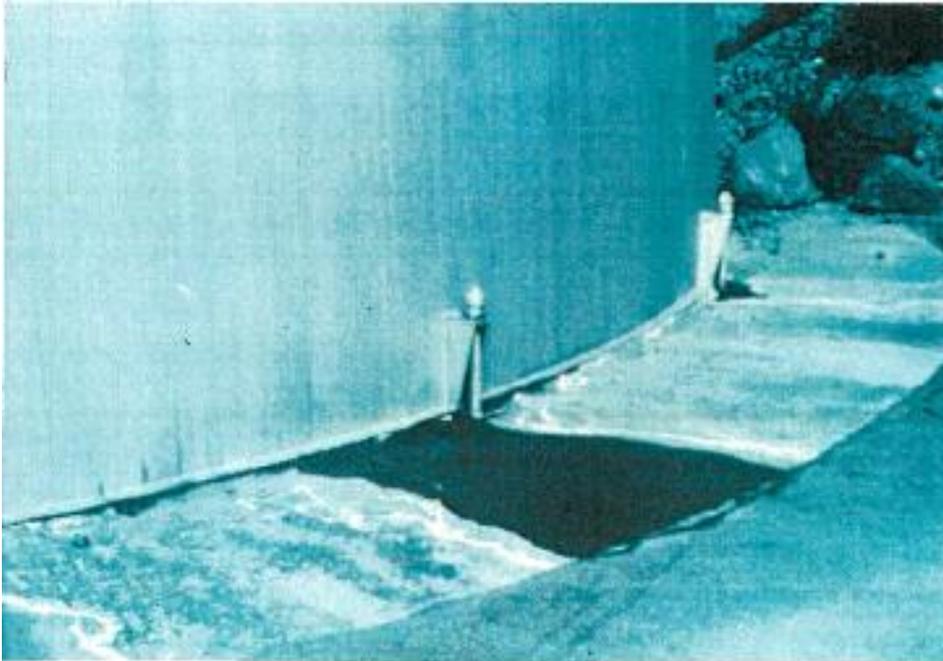
- Primary: Anchorage stress



POSSIBLE FAILURE MODES

1. Anchorage failure

- Secondary: Floor cracking



Small Diameter Bolts



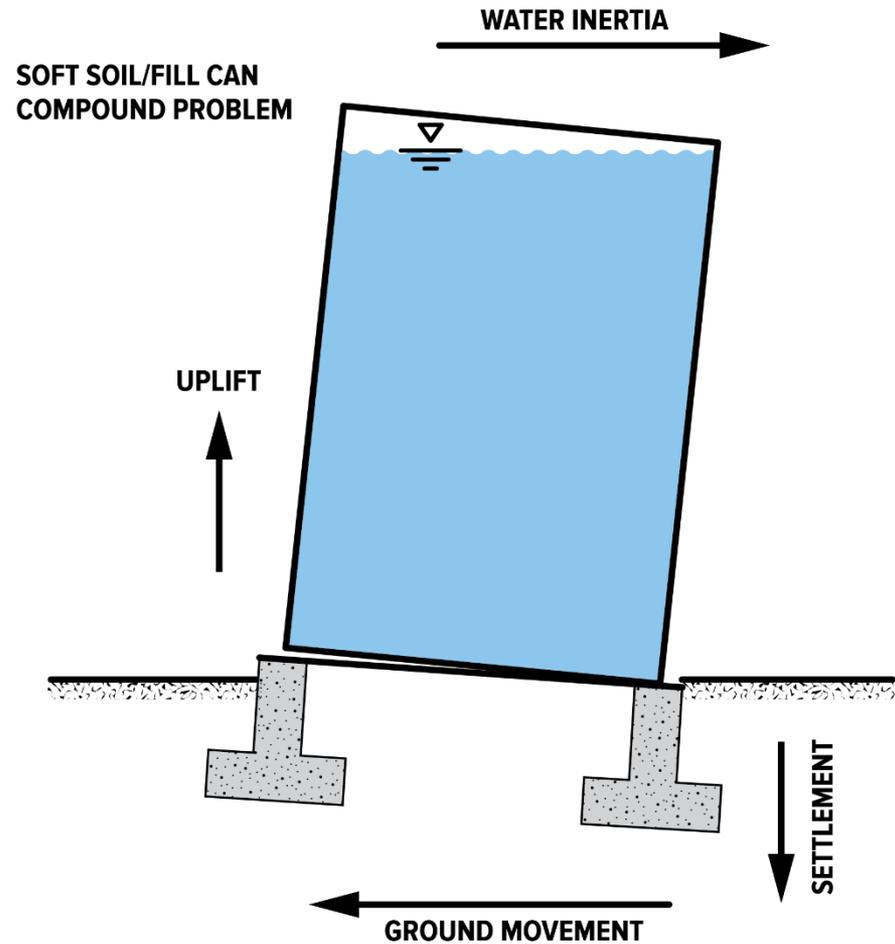
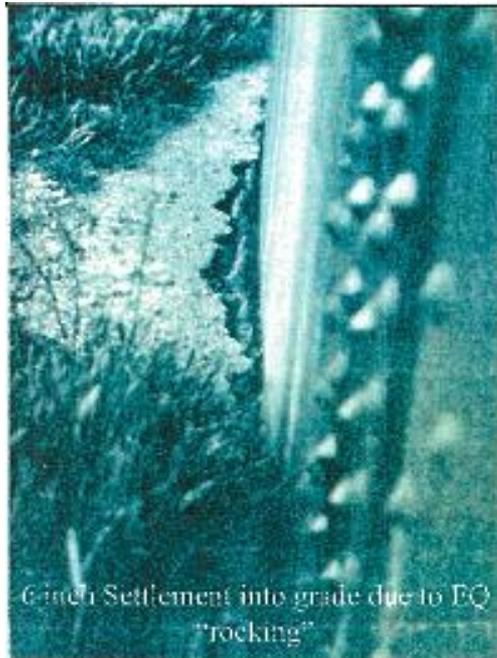
Anchor Straps

Large Diameter Bolts with Anchor Chairs



POSSIBLE FAILURE MODES

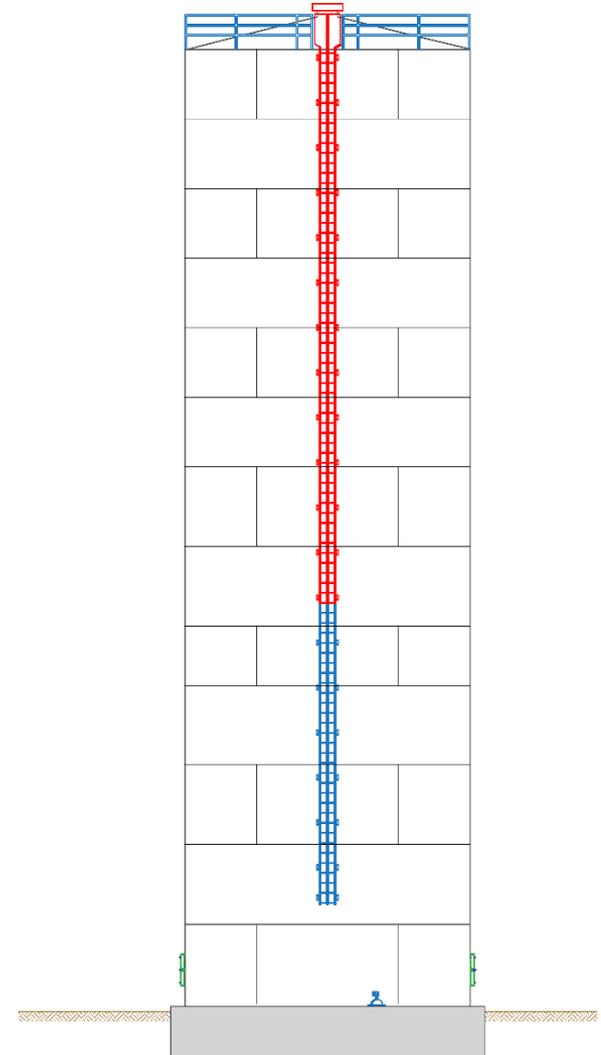
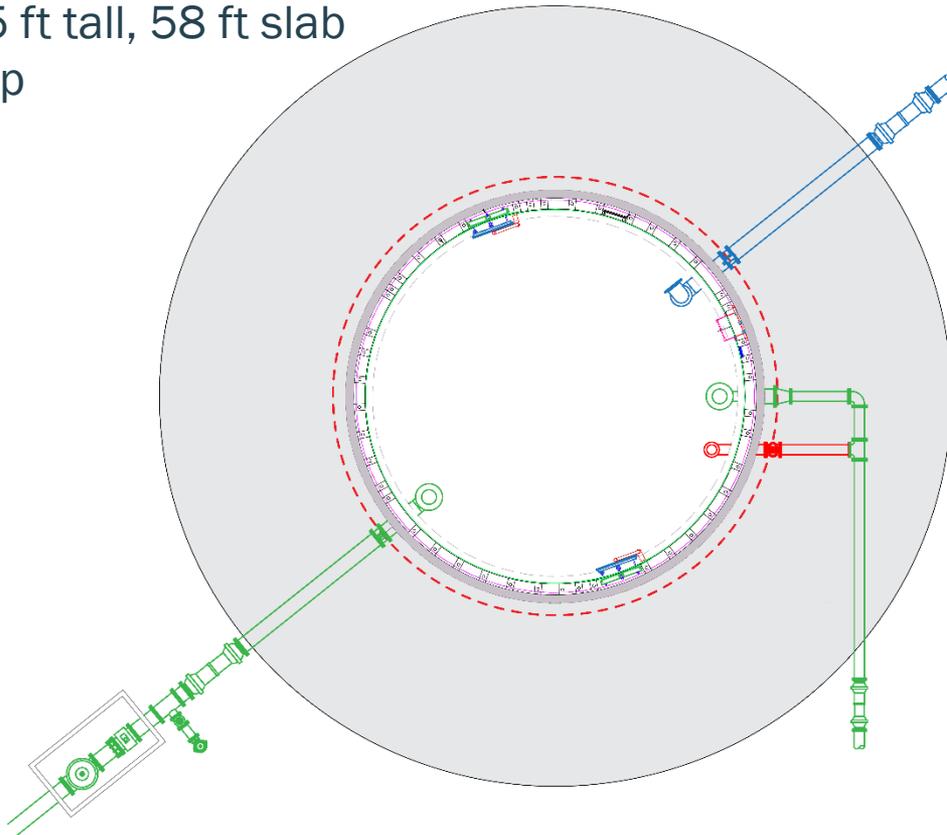
2. Soil failure (Inadequate Foundation)



STEEL RESERVOIRS: INADEQUATE FOUNDATIONS

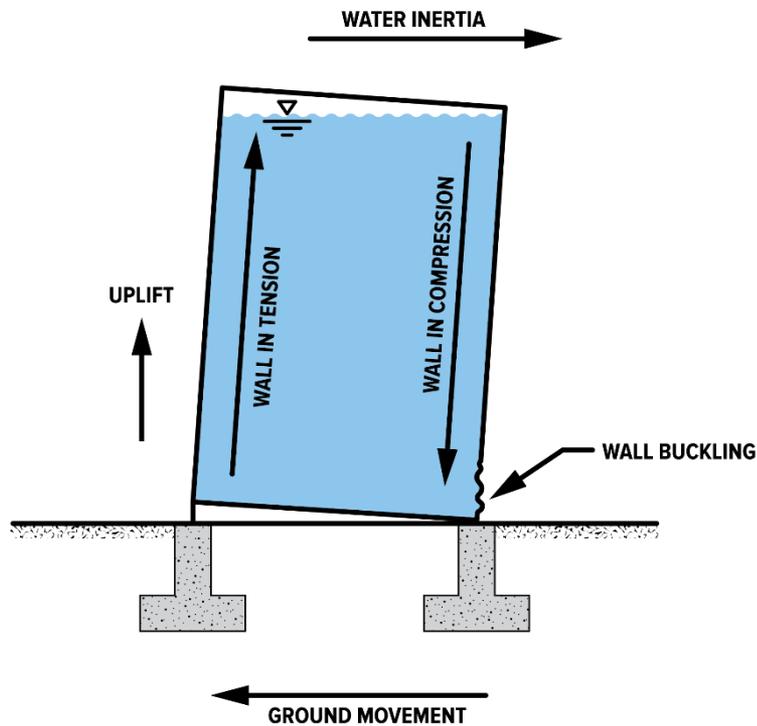
Original: 57 ft tall, 6 ft ringwall, 4 ft deep

New: 95 ft tall, 58 ft slab
8 ft deep



POSSIBLE FAILURE MODES

3. Shell buckling (Elephant Foot)



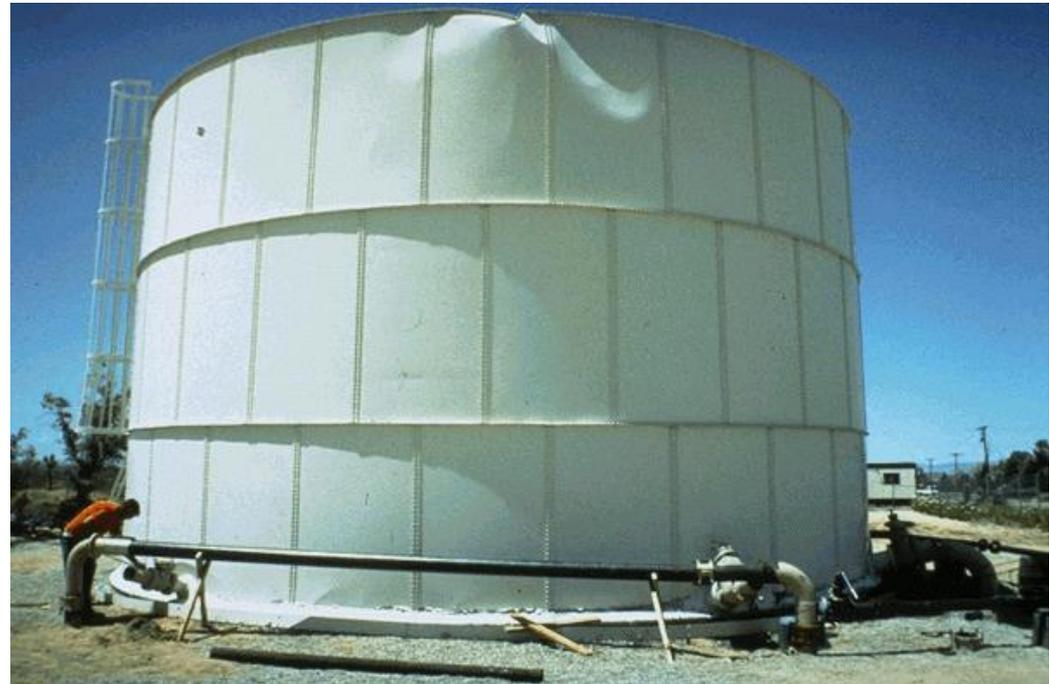
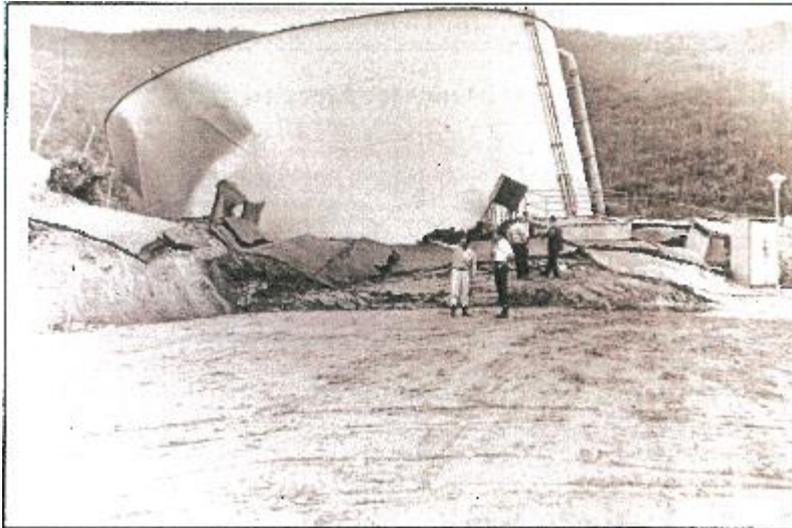
POTENTIAL BUCKLING SOLUTIONS

- Stiffen shell
- Add interior ballast ring
- Lower water level



POSSIBLE DAMAGE MODES

4. Sloshing damage
5. Soil stability



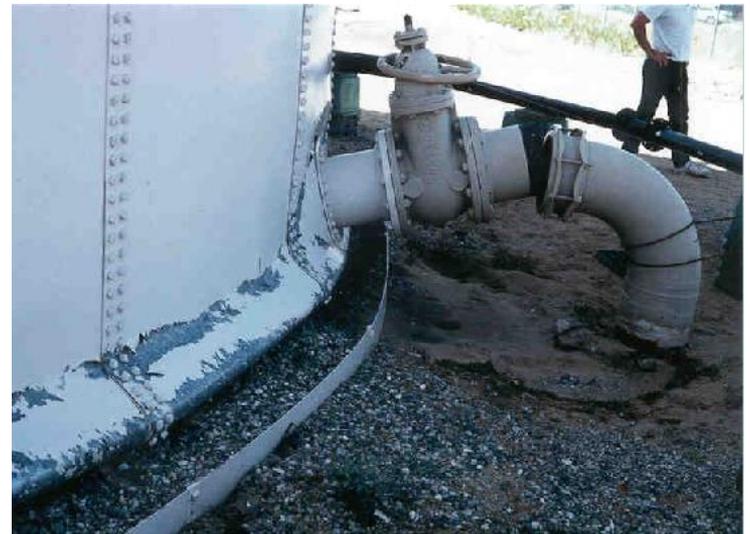
DETAILING

- Freeboard
- Ventilation
- Piping



PIPING CONNECTIONS

- Allow for relative displacements
- Prepare for emergency shut down
- Isolate damaged sections



FOUNDATION RETROFIT OPTIONS

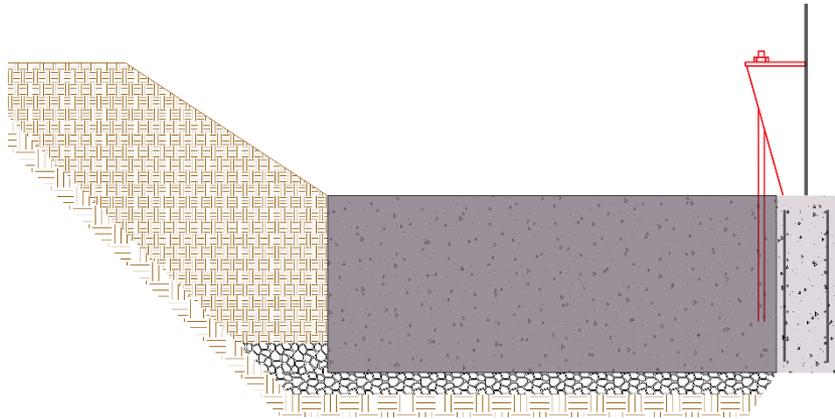
- Micropiles
 - Useful where site constraints make it difficult to expand the existing foundation
 - Expensive – can be up to \$10,000 per pile depending on depth
 - Piles provide both uplift resistance and bearing capacity



FOUNDATION RETROFIT OPTIONS

- Slab/Ringwall Expansion
 - Useful on large sites that can accommodate a larger foundation
 - Added weight helps resist overturning
 - Added surface area reduces soil bearing pressures
 - The existing foundation may be overstressed

FOUNDATION RETROFIT OPTIONS



FOUNDATION RETROFIT OPTIONS



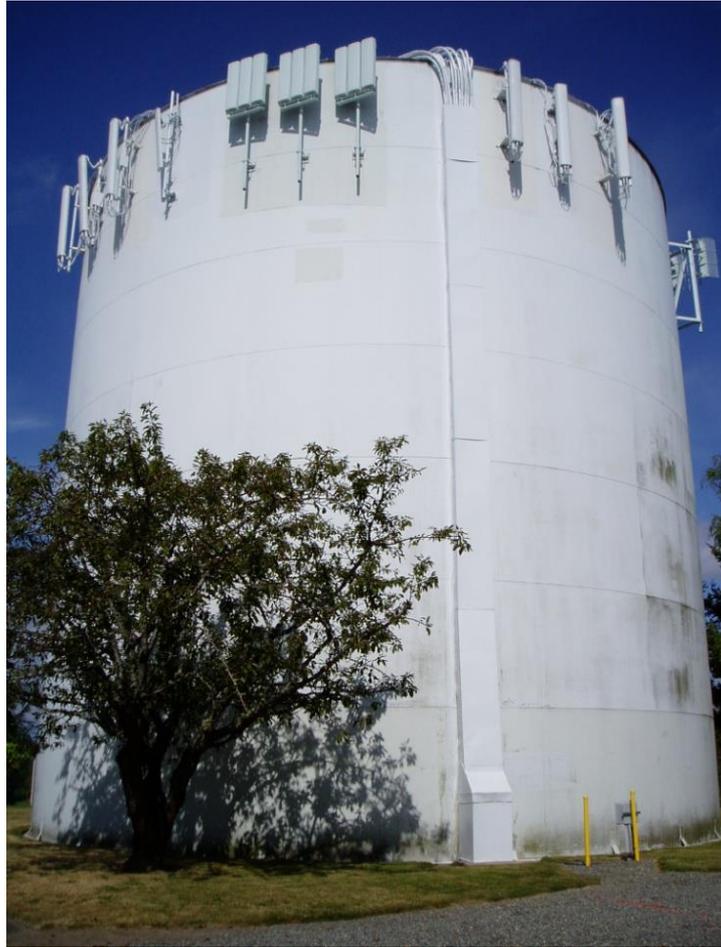
FOUNDATION RETROFIT OPTIONS

- New Slab Foundation

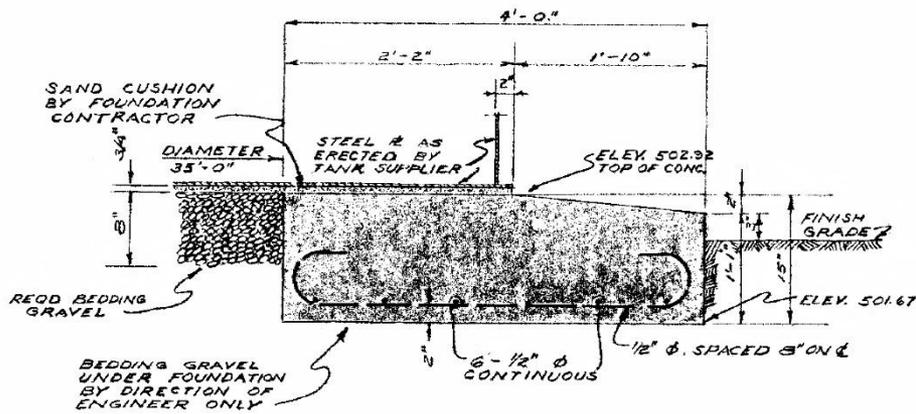
- Place a new slab above grade within the reservoir
- Added weight reduces overturning
- Useful if lower portion of reservoir is dead storage
- Concrete placed within the reservoir, rebar drilled through shell to connect exterior
- New steel floor and anchorage placed on top of new slab

MT. VIEW-EDGEWOOD WATER CO.

SOUTH RESERVOIRS

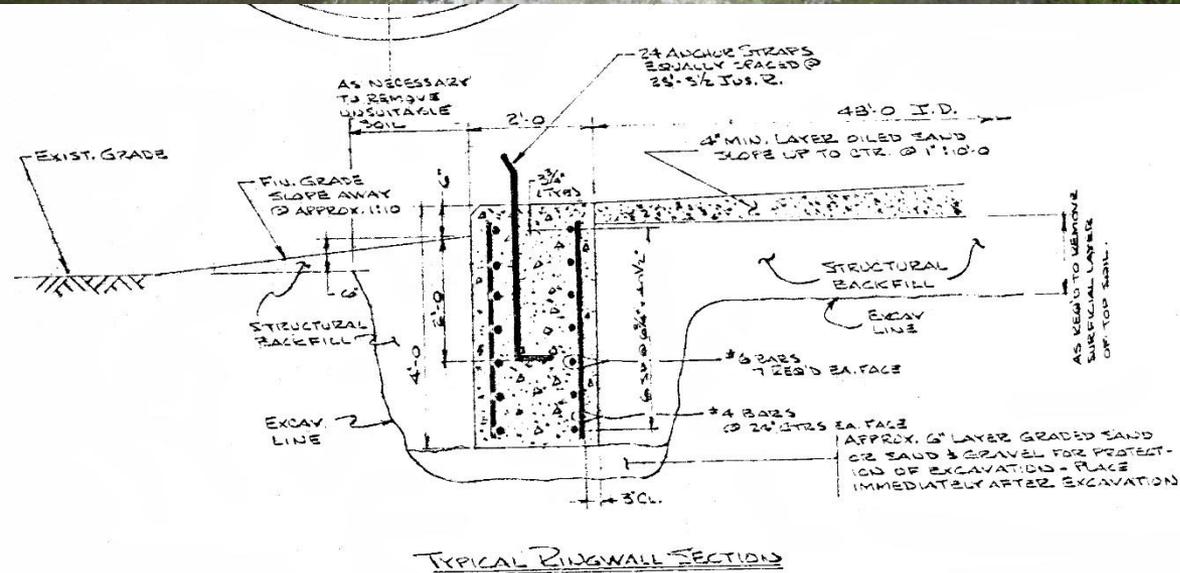


EAST RESERVOIR



SECTION A-A
SCALE: 1" = 1'-0"

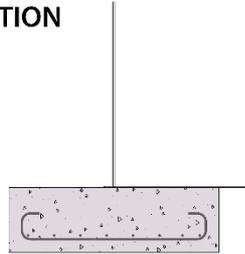
WEST RESERVOIR



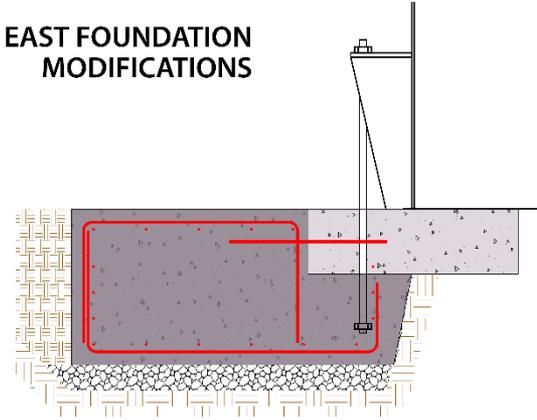
- Small Foundation = high bearing pressure
- Anchor Straps

RETROFIT SOLUTIONS

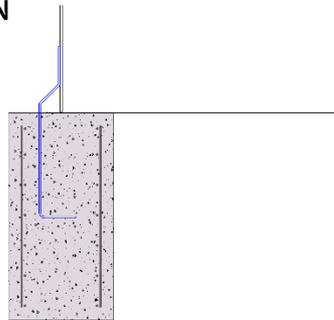
EAST FOUNDATION



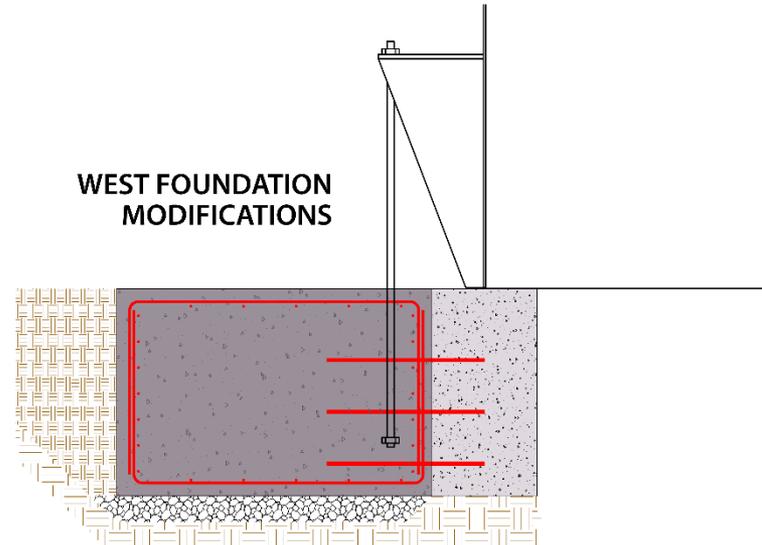
EAST FOUNDATION MODIFICATIONS



WEST FOUNDATION



WEST FOUNDATION MODIFICATIONS



EAST RESERVOIR ANCHORS



EAST RESERVOIR FOUNDATION



FOUNDATION CONSTRUCTION



WEST RESERVOIR ANCHORS



WEST RESERVOIR FOUNDATION



COMPLETED PROJECT



PIPING MODIFICATIONS

- Expansion joints on inlet, outlet, and drain
- New valves



SEISMIC VALVE



QUESTIONS?

