SIMPSON GUMPERTZ & HEGER

Engineering of Structures and Building Enclosures

The Millennium Tower Settlement, Tilting and Upgrade

University of Kansas

Ronald O. Hamburger, S.E., SECB

March 5, 2020

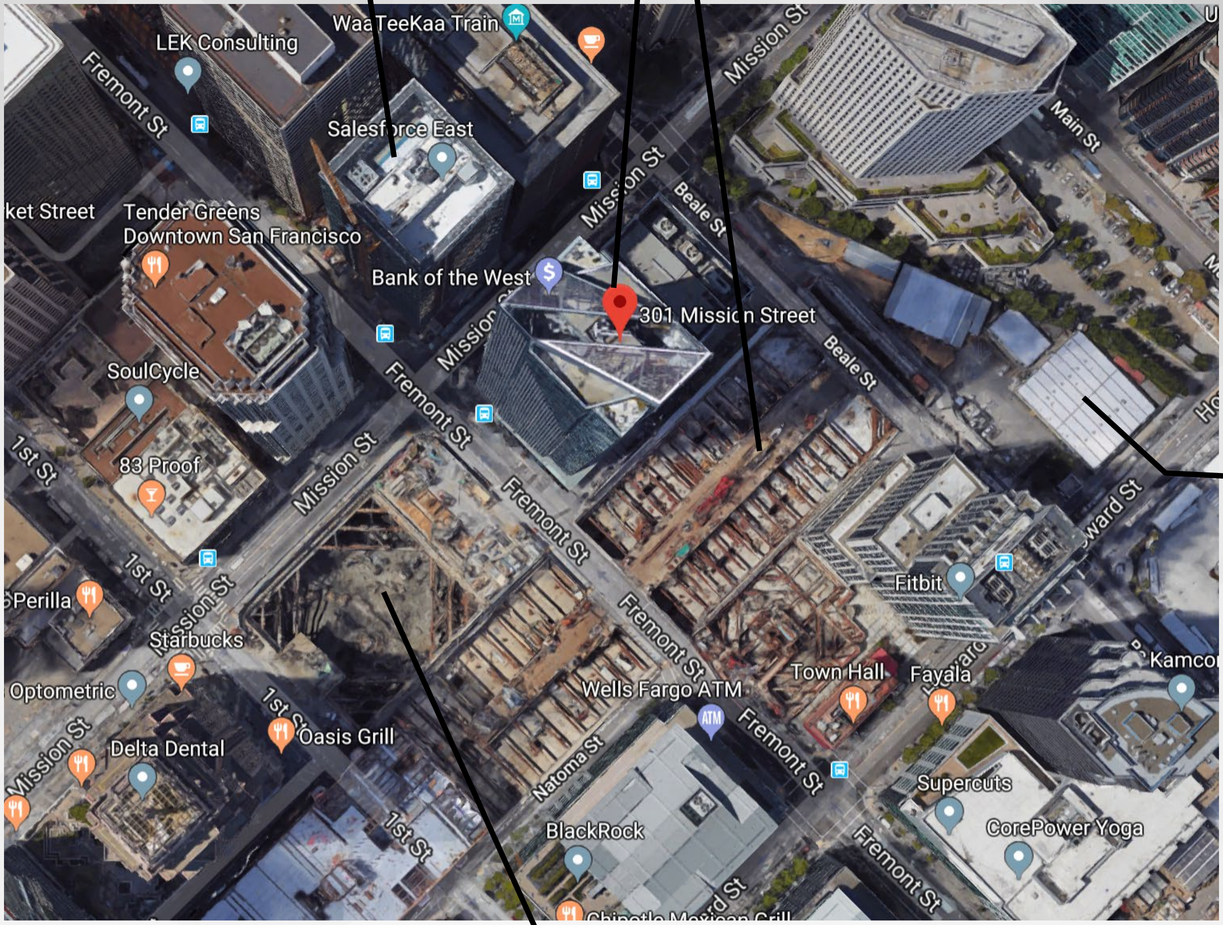
- Constructed 2005-2009
- 58 stories, 645 ft (197m) tall
- Tallest & most expensive residential tower in San Francisco
- Views from the Sierra to the Cascades to the Farallon Islands
- Most expensive unit sold in 2013 for $13.5 million
- Construction Cost - $600 Million Sales Cost - $750 Million

The Site

301 Mission

350 Mission
2012

Transbay terminal and track tube
2009



200
Beale
2017

Salesforce Tower
2014

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History of the Problem

- **Ground breaking – 2005**
  - Settlement predicted 4”-6”
- **Construction completed 2009**
  - Settlement reached 10”
  - Transbay Terminal excavation starts
- **Last unit sold in 2013**
  - Settlement 13”
- **SGH retained in 2014**
  - Settlement 15”
- **Litigation initiated in 2016**
  - Settlement 17”
- **Adjacent construction complete 2017**
  - Settlement 18”, Tilt 17” to northwest

Some Homeowners

Joe Montana
Hall of Fame Quarterback

Hunter Pence
San Francisco Giants Superstar

Steph Curry
Golden State Warriors Icon

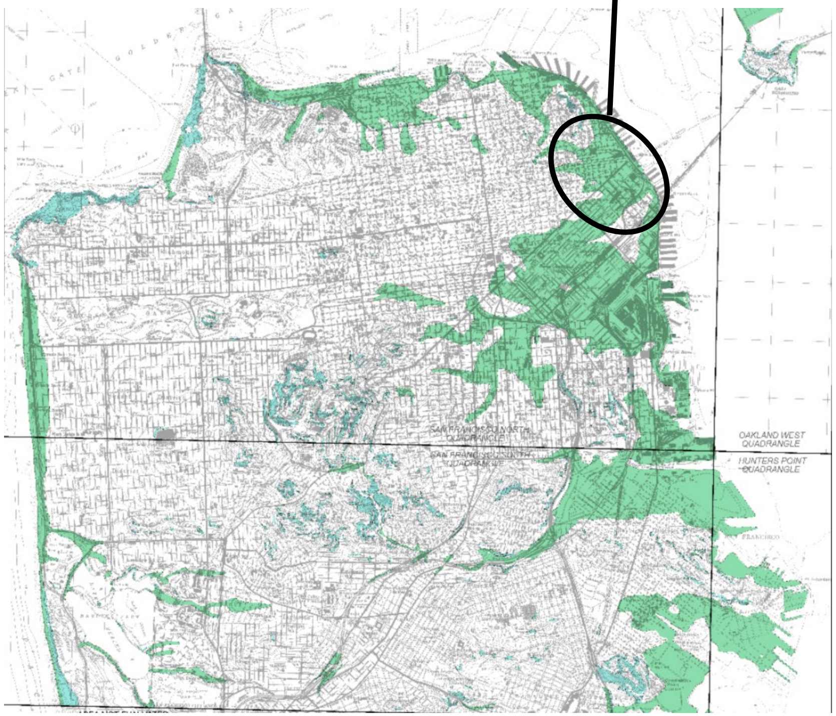
Some Homeowners

Laurence Kornfield
Retired Chief Deputy Building Inspector, City of SF

Jerry Dodson
Personal Injury Attorney

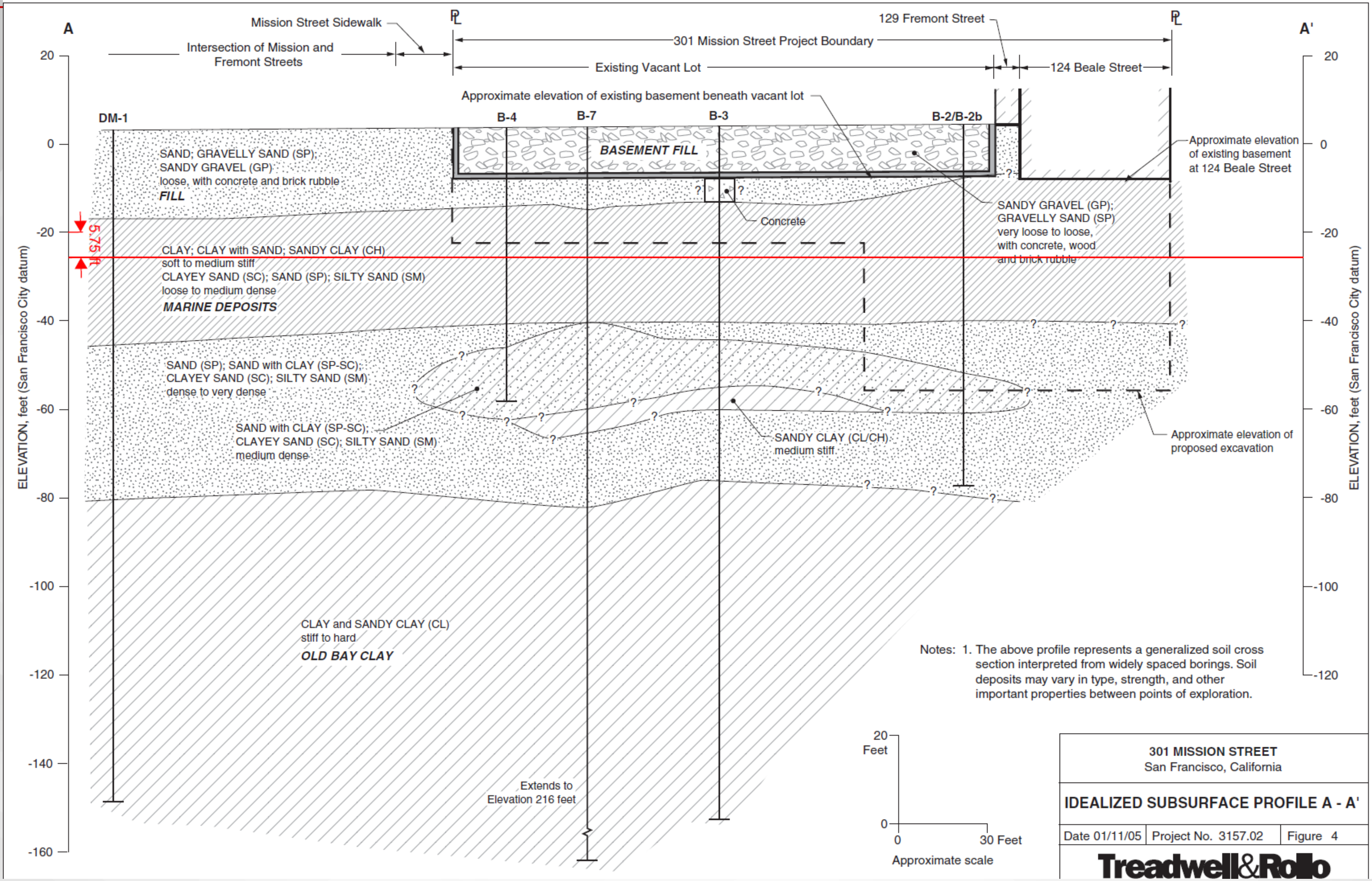
Why did this happen?

San Francisco Downtown



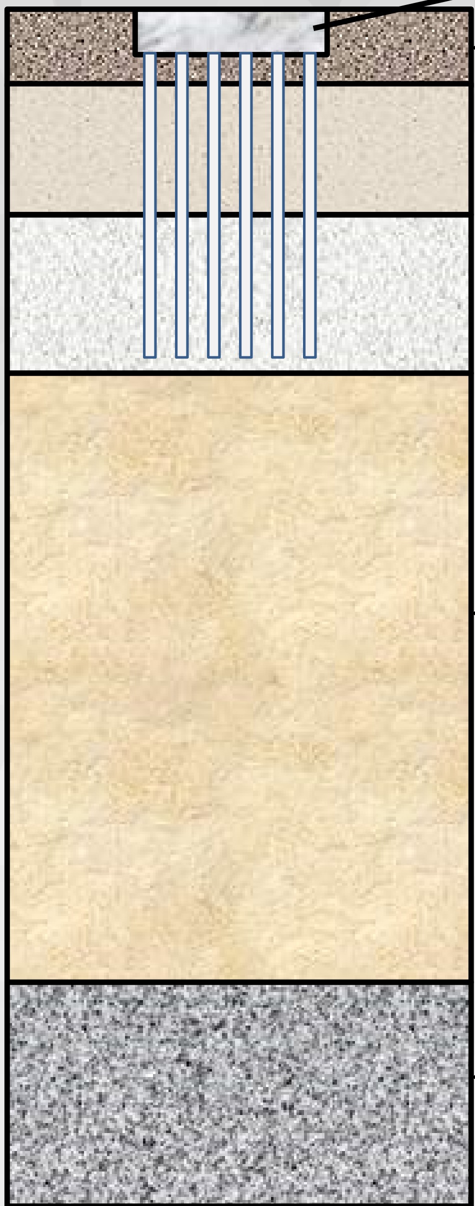
Area of “infirm” soils based on SF General Plan

Subsurface profile (from Treadwell & Rollo)



Subsurface conditions

10’ thick mat
75’ piles deep into Colma Sand



20’ (6m) – fill & rubble
loose sand, brick, concrete, gravel

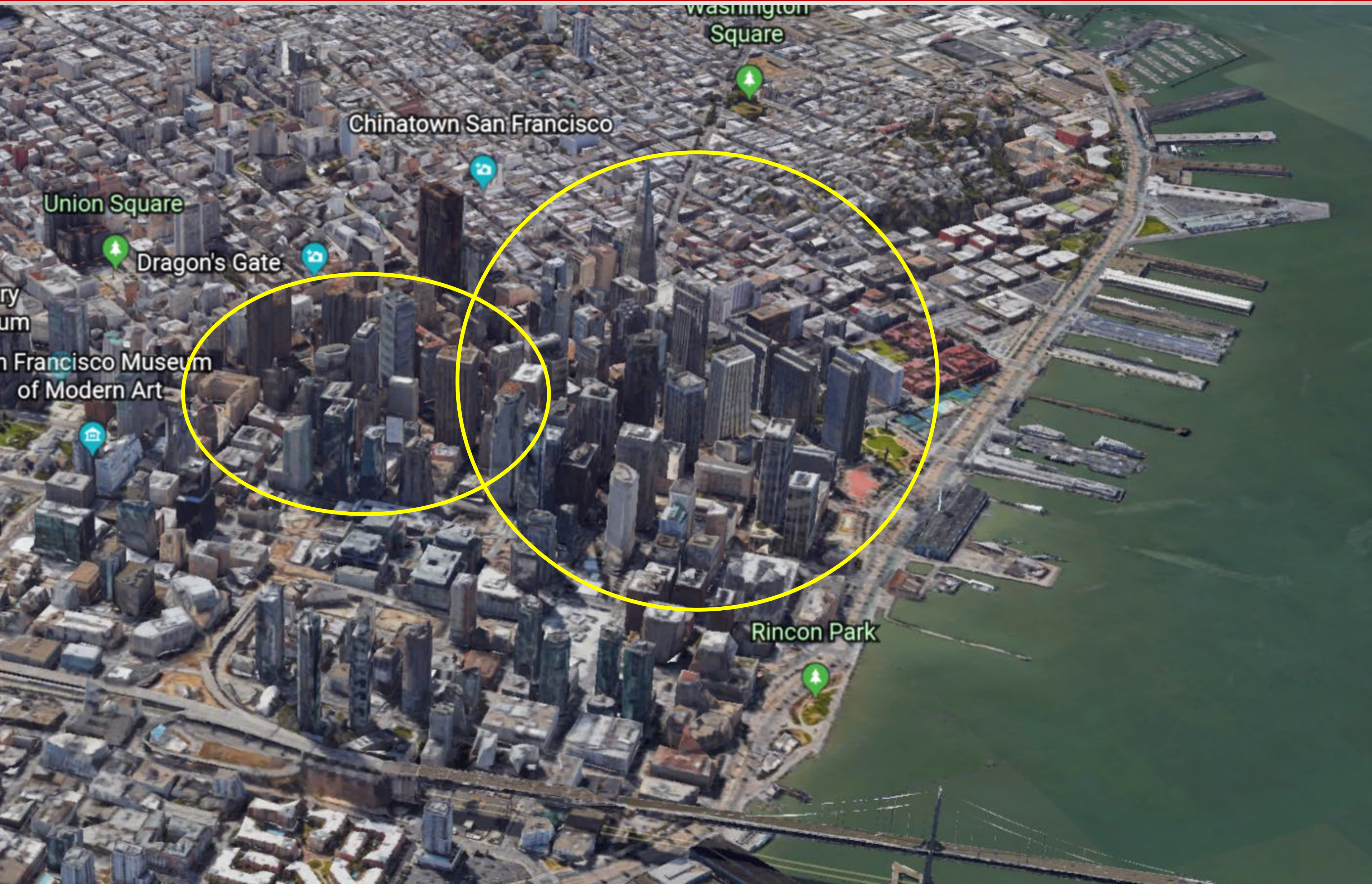
30’ (10m) – Young Bay Clay
marine deposits – last 12,000 years

35’ (12m) – Colma Sand
cemented sands with clay binder
(bearing pressures up to 6 -8 ksf)

140’ (45m) – Old Bay Clay
overconsolidated clays with
layers of silts and sands

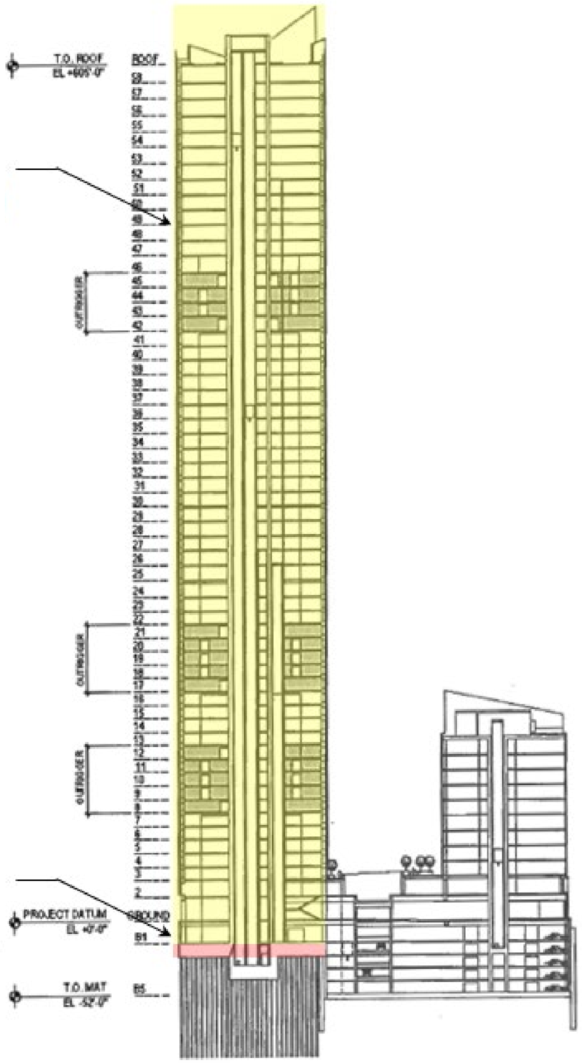
Franciscan formation
Sandstone, Siltstone, Claystone
Serptentine

Other SF buildings with this foundation



The Millennium Tower

Superstructure
200,000 kips



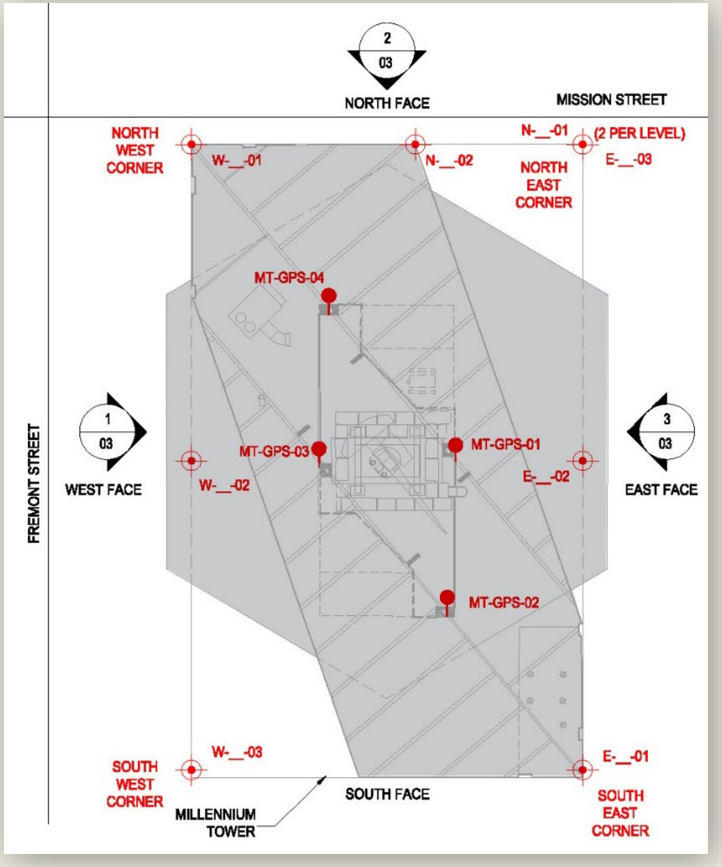
Substructure
24,000 kips

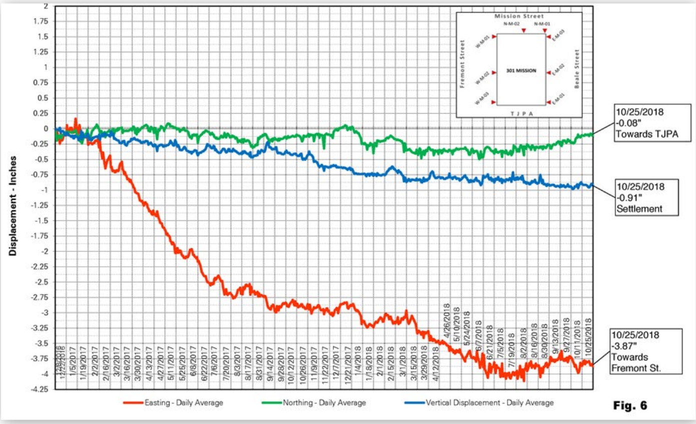
Imposed bearing pressure
224,000 kips
<u>100 x 200’</u> bearing area
11.2 ksf

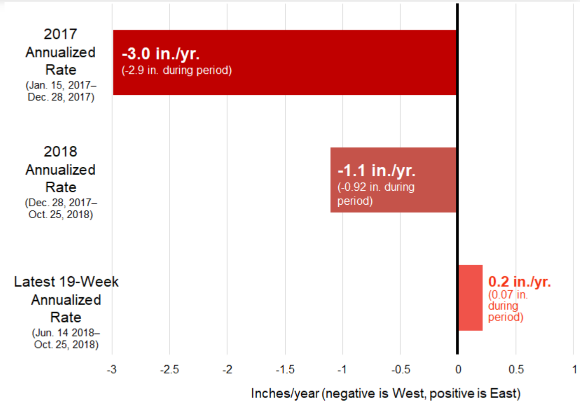
Why the settlement?

- **Consolidation of Old Bay Clays**
- **Prolonged dewatering due to construction of adjacent projects exacerbated the situation**
  - 2009-2014 – Transbay Terminal and Train Tube
  - 2013-2015 – 350 Mission Street
  - 2014-2016 – Sales Force Tower
- **Adjacent construction completed**
  - Water table rose
  - Effective stress on Old Bay Clays decreased
  - Old Bay Clays went into secondary compression (creep)
    - Left unchecked, over a period of 30 years, could double primary compression

How has tilt varied with time?







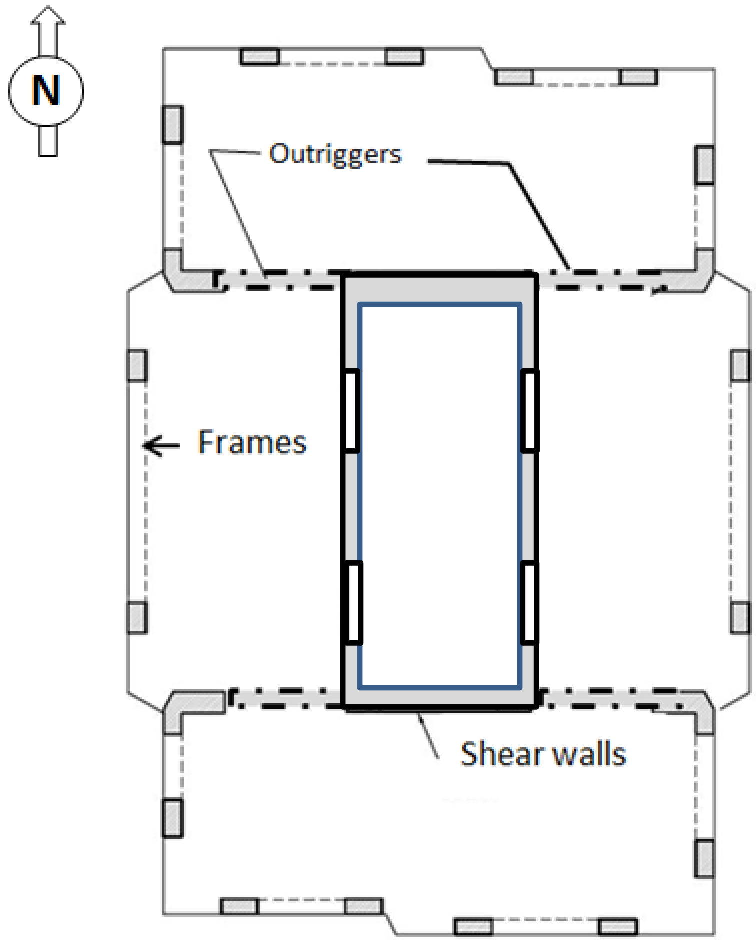
CONFIDENTIAL – MEDIATION PRIVILEGE

Our assignment

- **Determine if the settlement had significantly affected the building's structural and seismic safety**
  – Is it "safe"?

- **Determine if retrofit is necessary or feasible**

Structural System



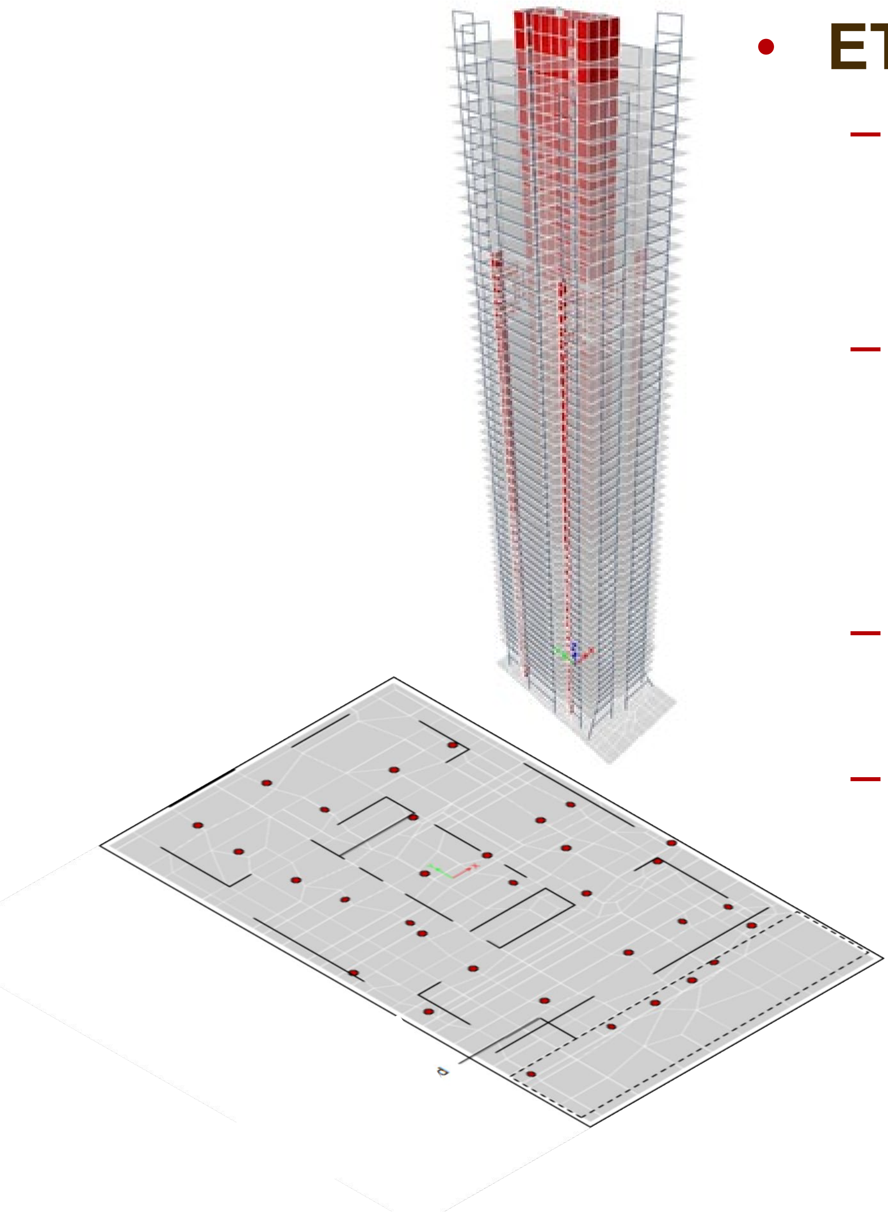
- 58 stories
- 1 basement
- 10’ thick mat with 960 piles
- Post-tensioned flat slab floors
- Central core wall with outriggers
- Perimeter moment frames

Investigation tasks

- **Review Drawings and Specifications**
- **Condition Survey**
- **Perform linear analysis**
- **Nonlinear evaluation**
  - Before Settlement
  - After Settlement
- **Develop Retrofit Solution**
  - Reanalyze
  - Demonstrate code compliance

Linear Analyses

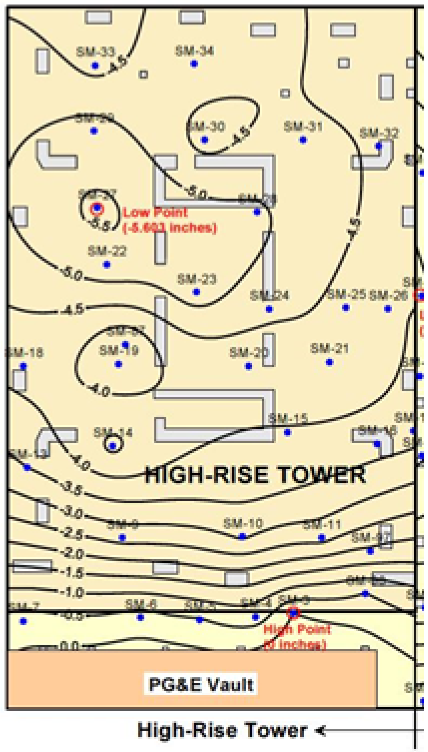
Modeling



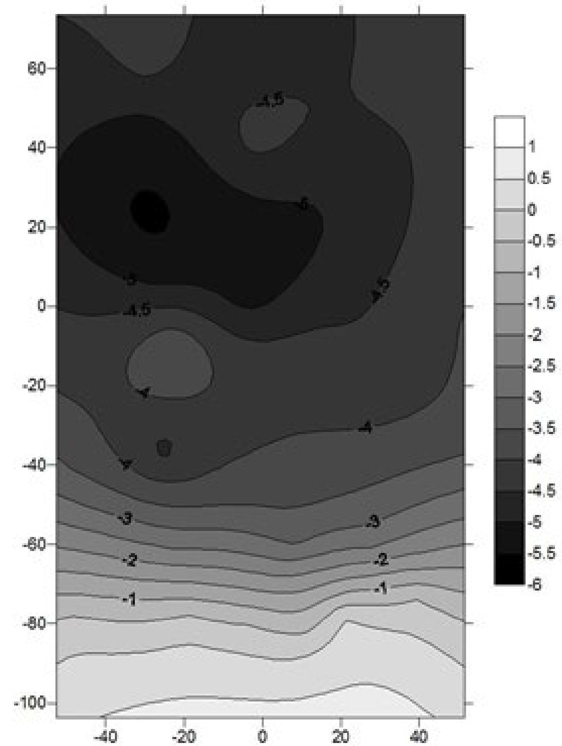
- **ETABs software**
  - Frame elements
    - Beams
    - Columns
  - Wall (panel) elements
    - Walls
    - Coupling beams
    - Outriggers
  - Shell elements
    - Foundation mat
  - Piles modeled as fixed translation points at shell nodes

Settlement Representation

Measured Settlement 6/14

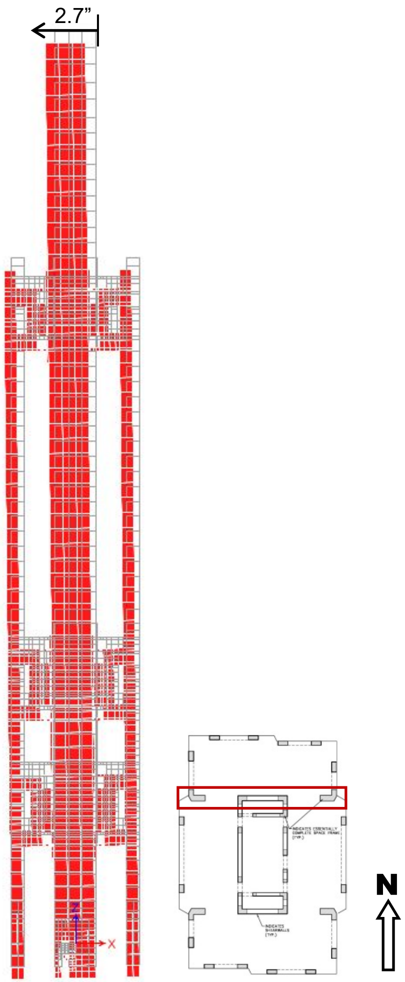


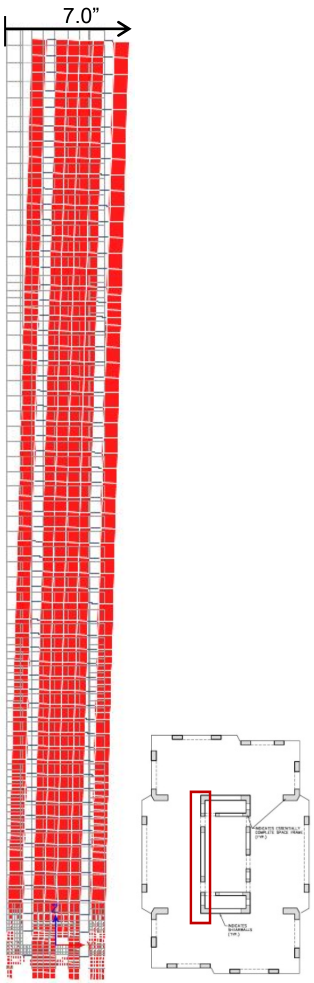
Enforced Displacement



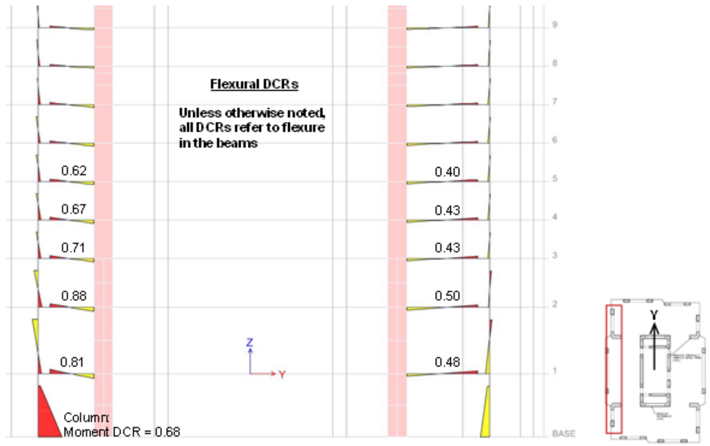
- **Input 38 points into Surfer 8 software**
  – Provides smooth contours matching discrete points
- **Imposed enforced displacements on mat**

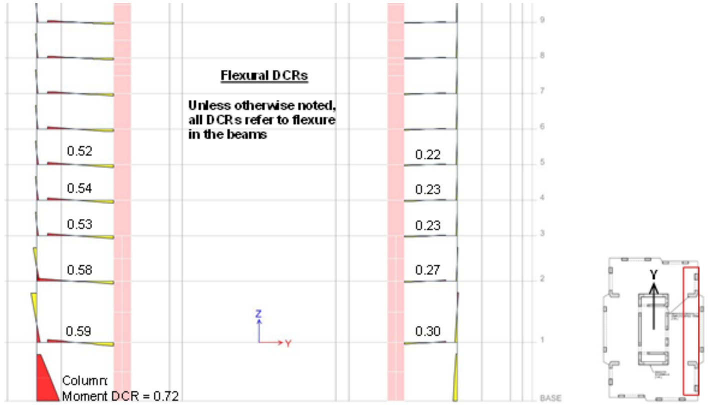
Effect of Settlement





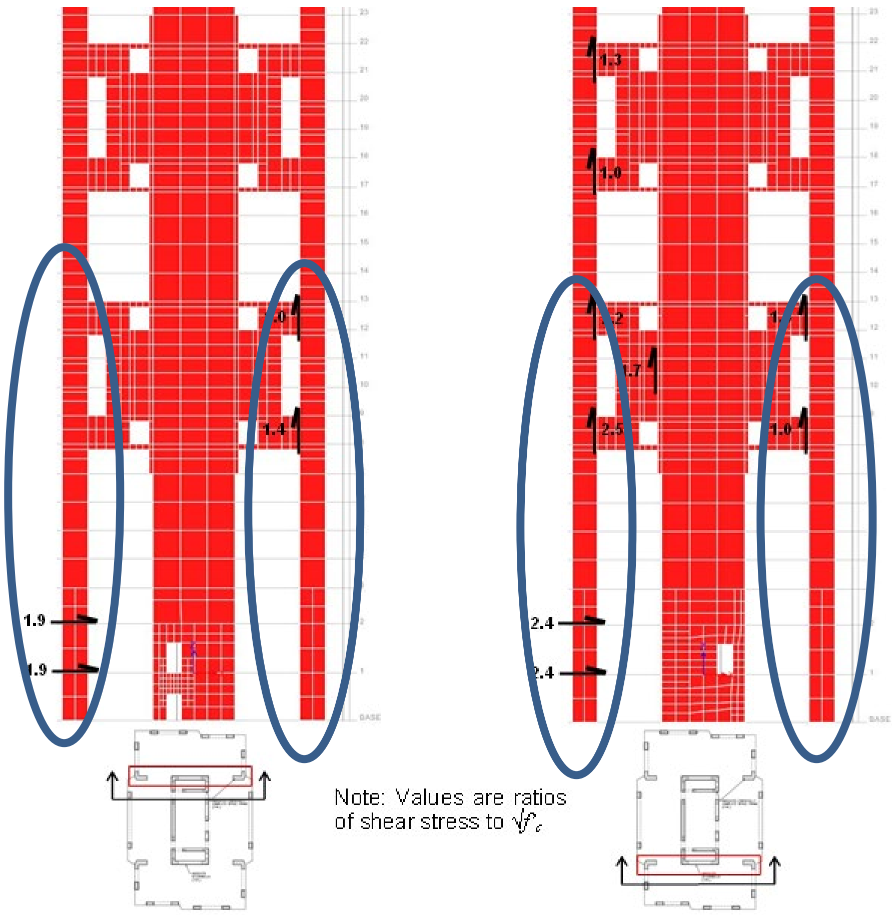
Linear Results (Settlement)– Moment Frames





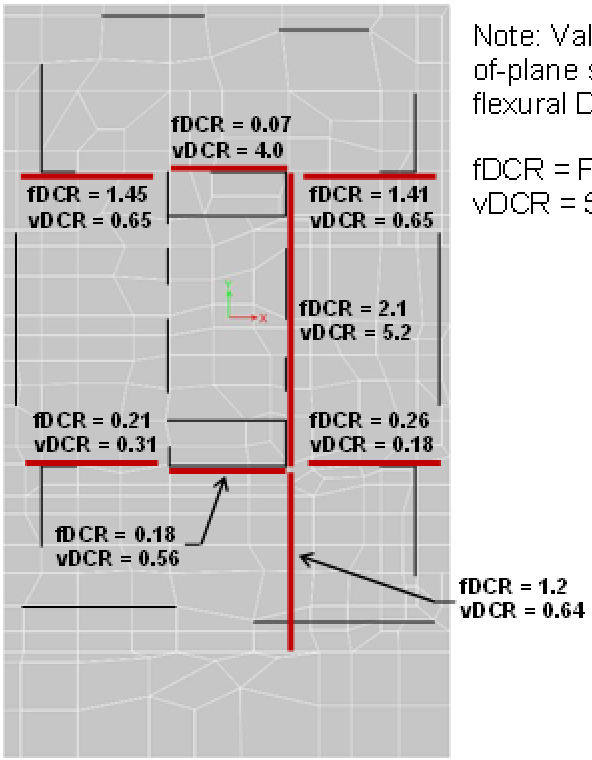
- DCRs under settlement are generally less than 30%
- Columns at base DCR~0.9

Linear Results (Settlement)
Shear Core and Outriggers



- Shear walls have low DCRs
- Outriggers, and outrigger columns have DCRs in range of 1 to 3
- No observable damage in these areas

Linear Analysis (Settlement) – Mat Foundation



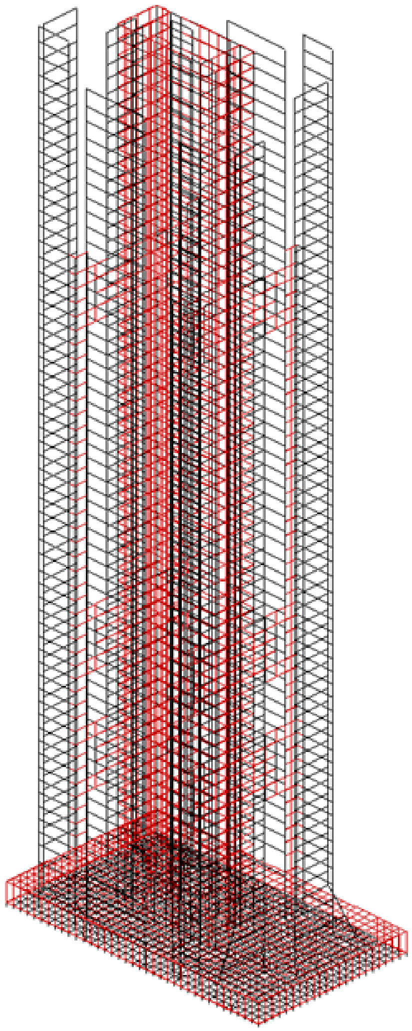
Note: Values are out-of-plane shear and flexural DCRs

fDCR = Flexural DCR
vDCR = Shear DCR

- Flexural DCRs limited, but high shear DCRs along boundary of core
- Conclusion, linear analysis was not predicting the behavior well
- Use Nonlinear Analysis

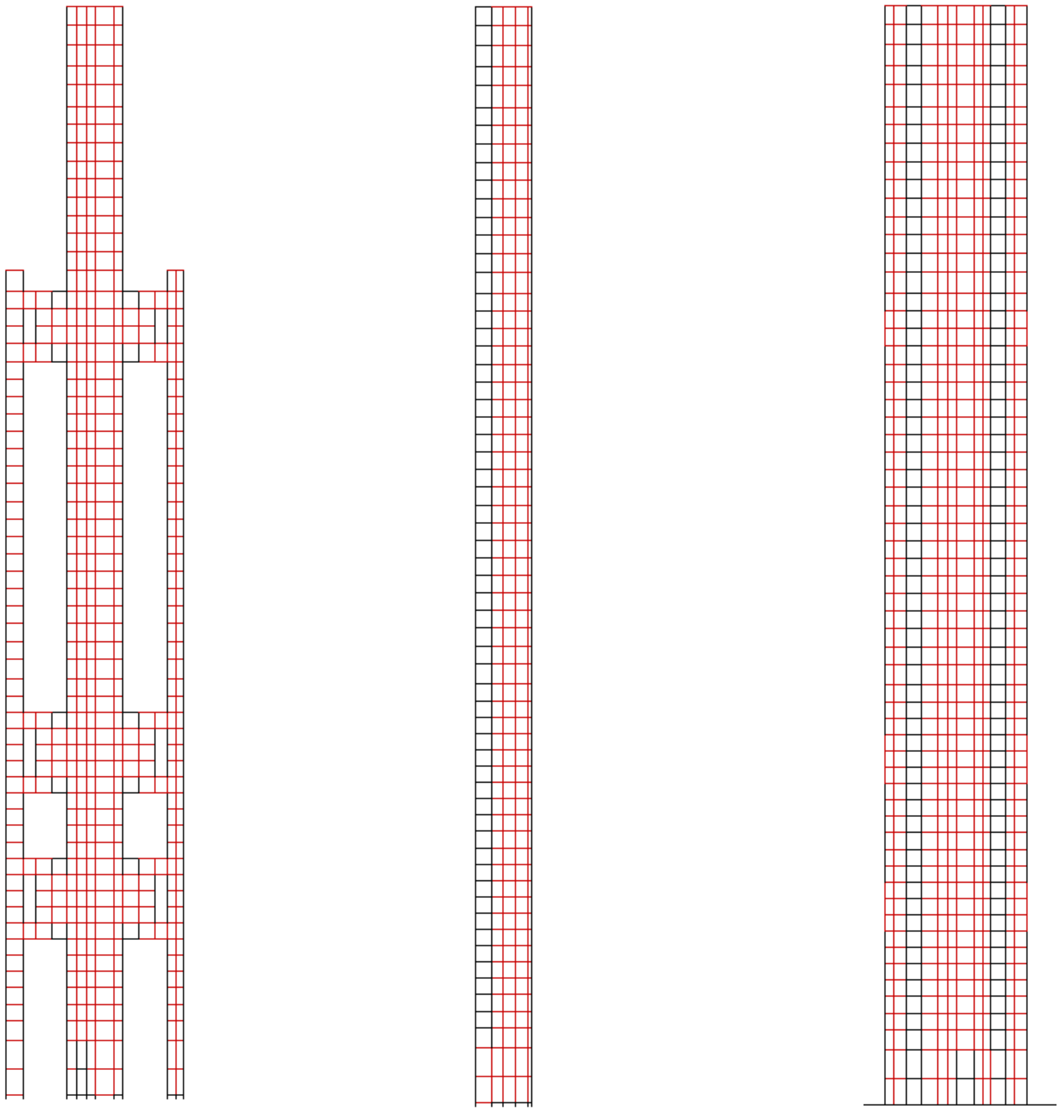
Non-Linear Analyses

Nonlinear Analysis

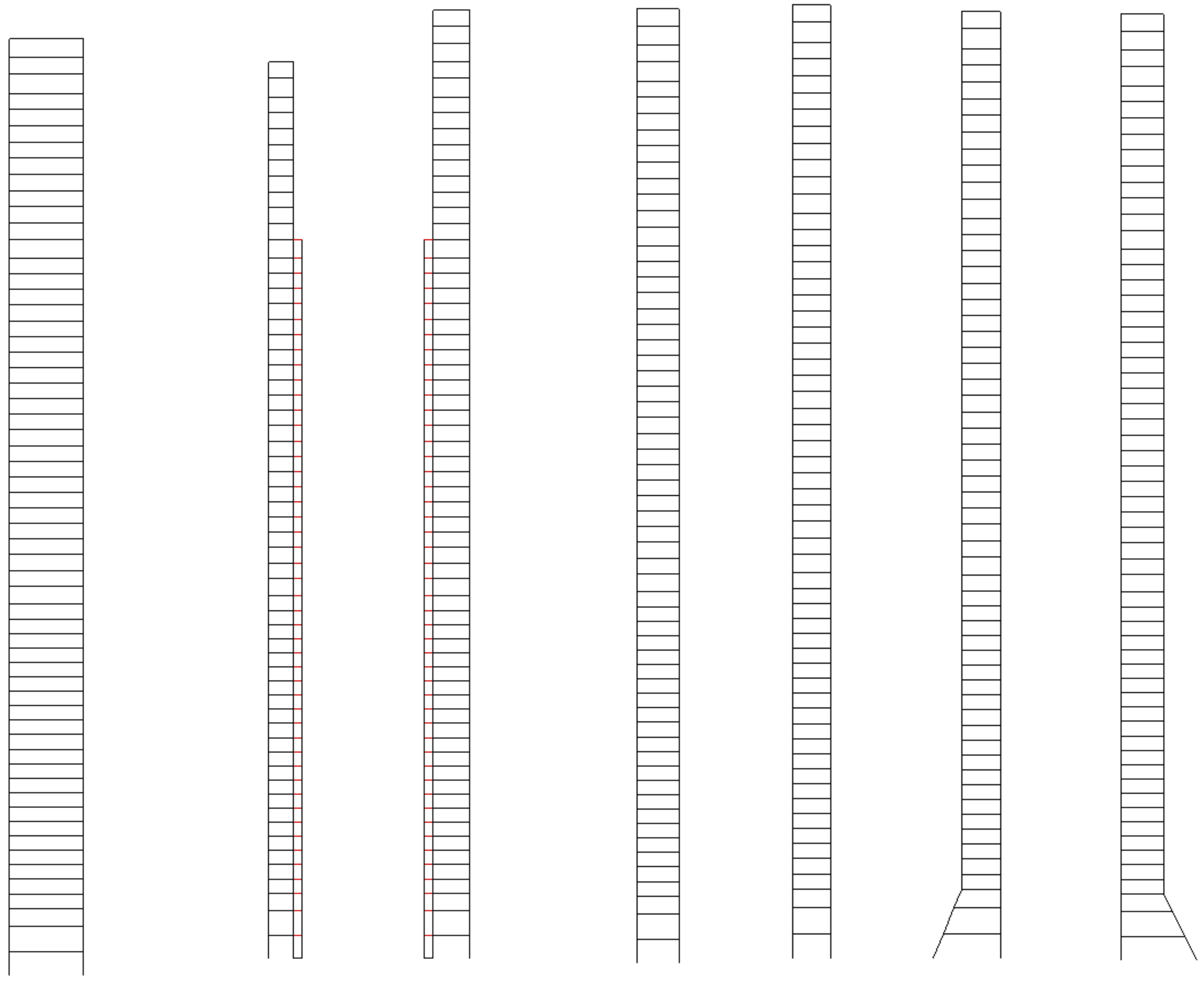


- Perform 3D software
- Frames modeled using nonlinear 2D elements
- Walls and outriggers modeled using fiber elements
- Foundation
  - 2D grid frame nonlinear beam elements
  - Nonlinear springs (piles)

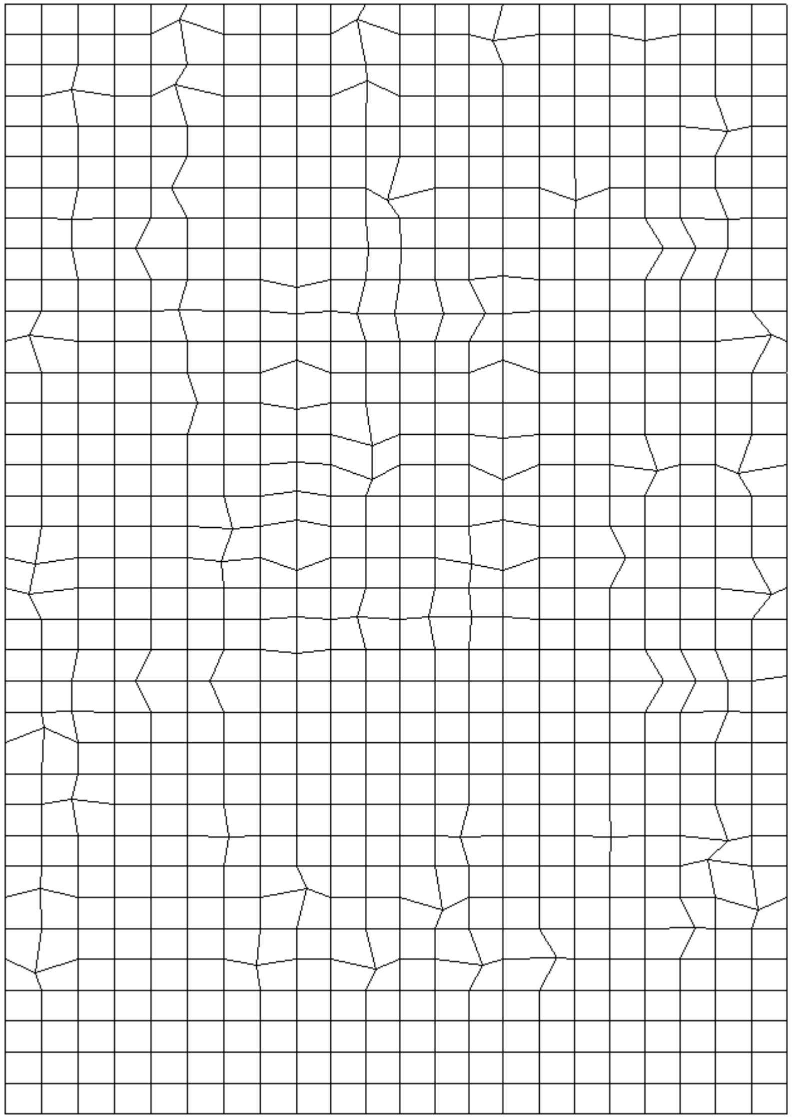
Wall Elements



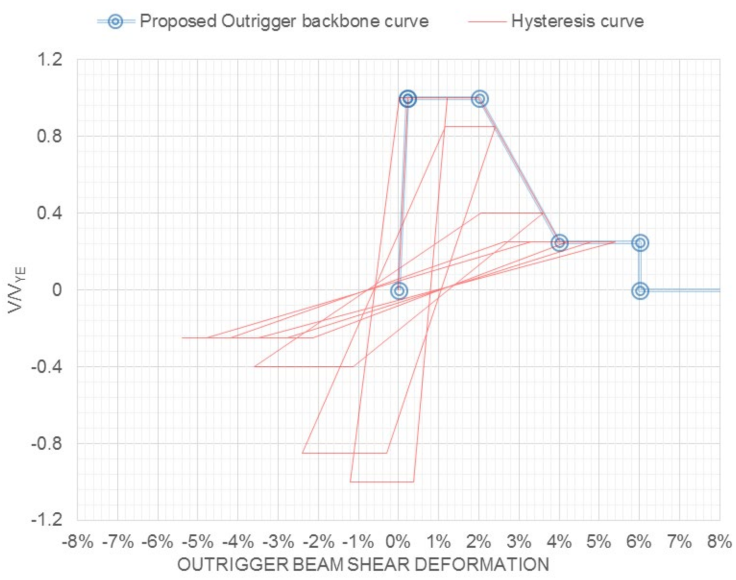
Frame Elements



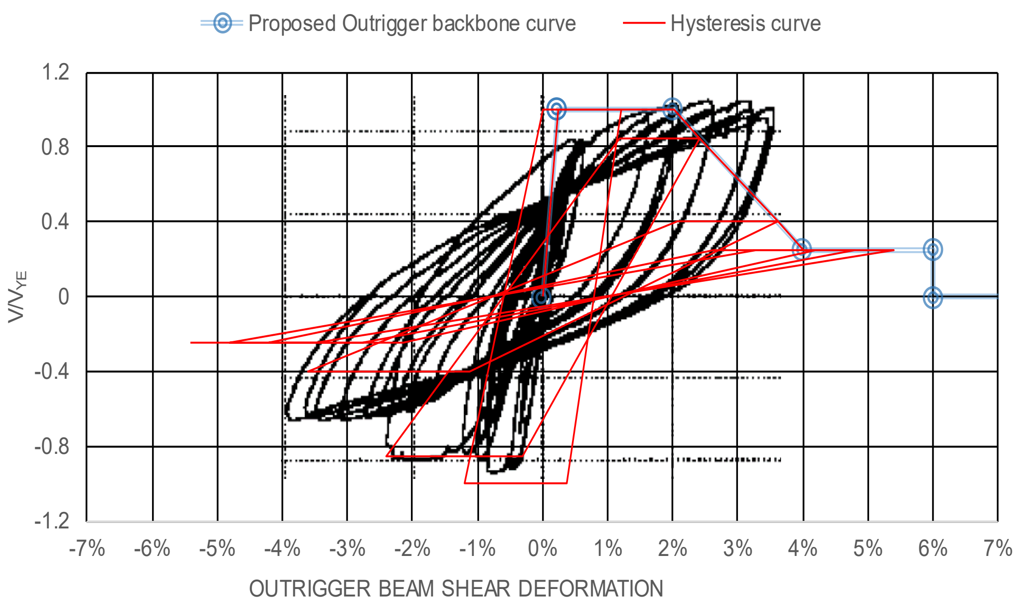
Mat



Nonlinear modeling
Outrigger coupling beams



Perform-3d Outrigger coupling beam, A/R = 0.5

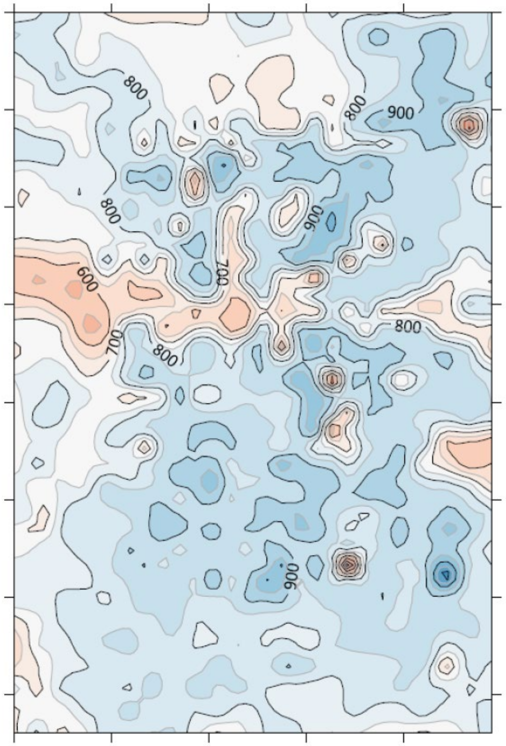


Compared to A/R = 1.0 from a 2005 test by Canbolat et. al.

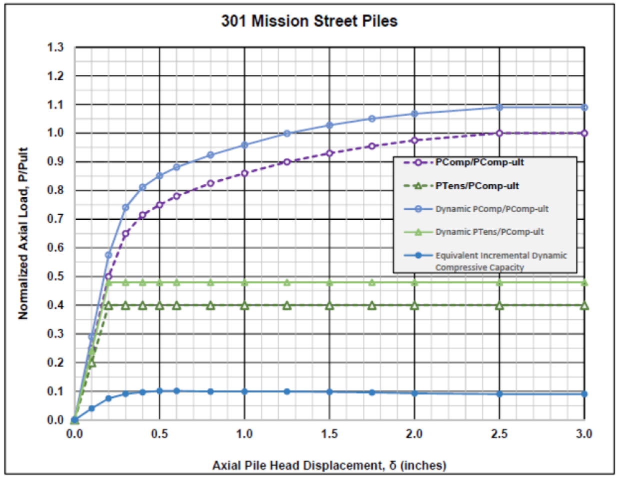
Pile Representation
Geotechnical Capacities

Mission Street

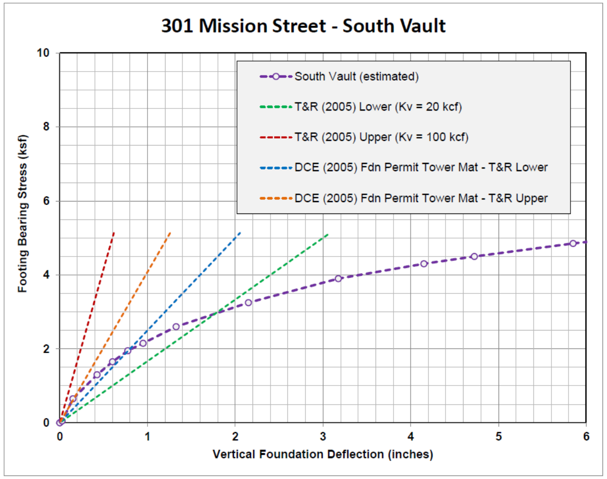
Fremont Street



Normalized Pile P-Z

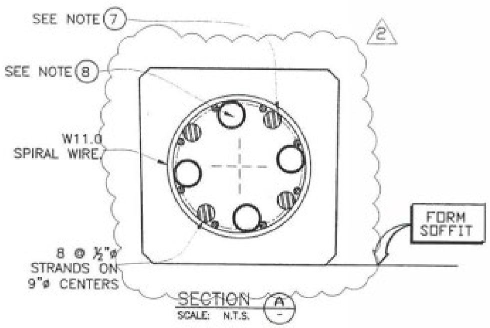


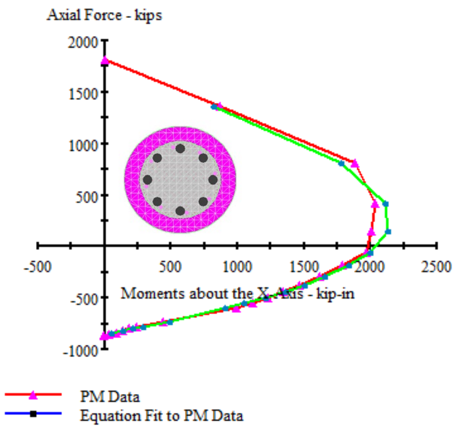
Soil springs at vault



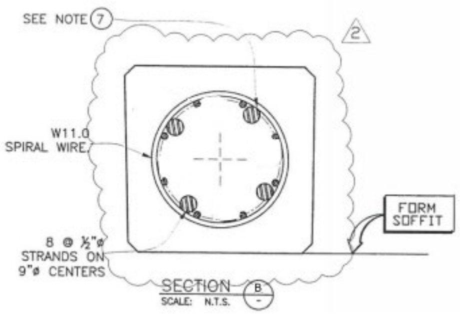
Production Pile—XTRACT

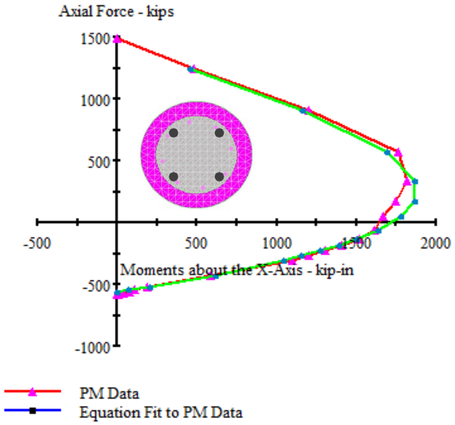
Top of Pile



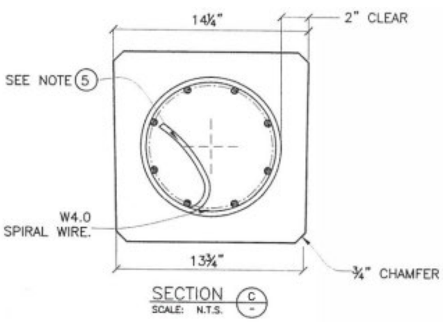


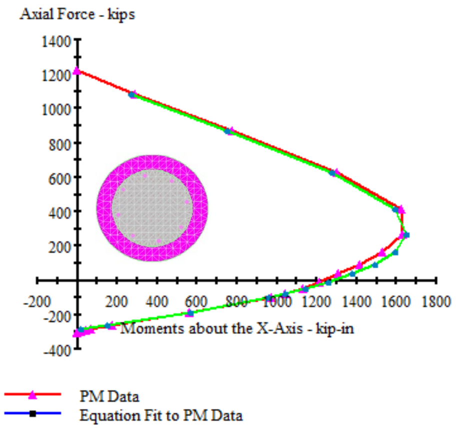
@ 2.5



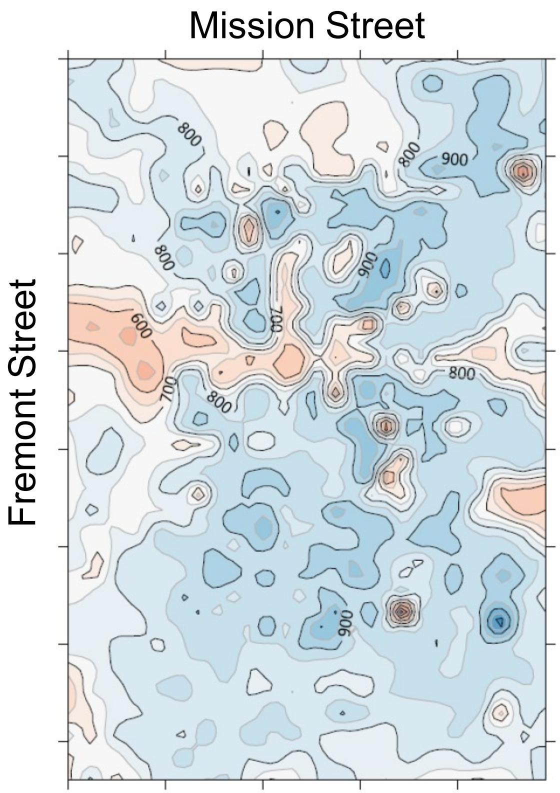


@ 7 ft



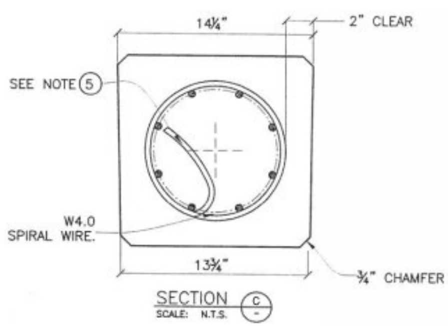


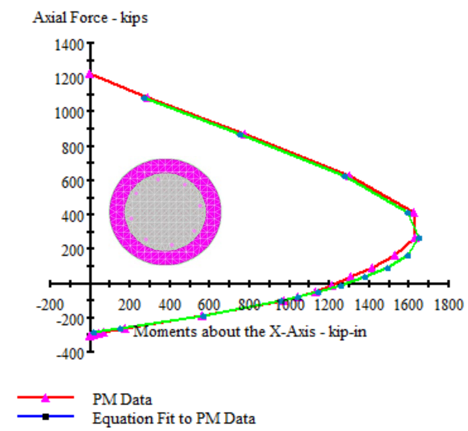
Geotech vs Structural capacity



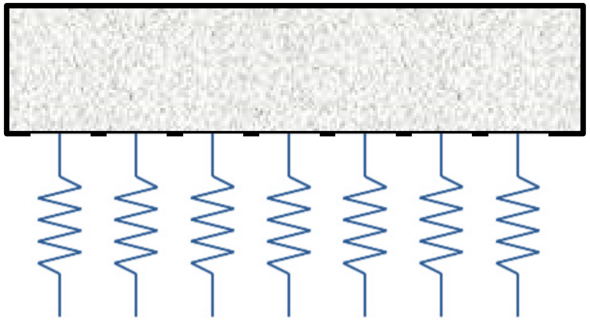
Maximum Geotechnical Compressive Capacity = 1175 kips

Pile Compressive Capacity @ Weakest section = 1227 kips





Simulation of Settlement



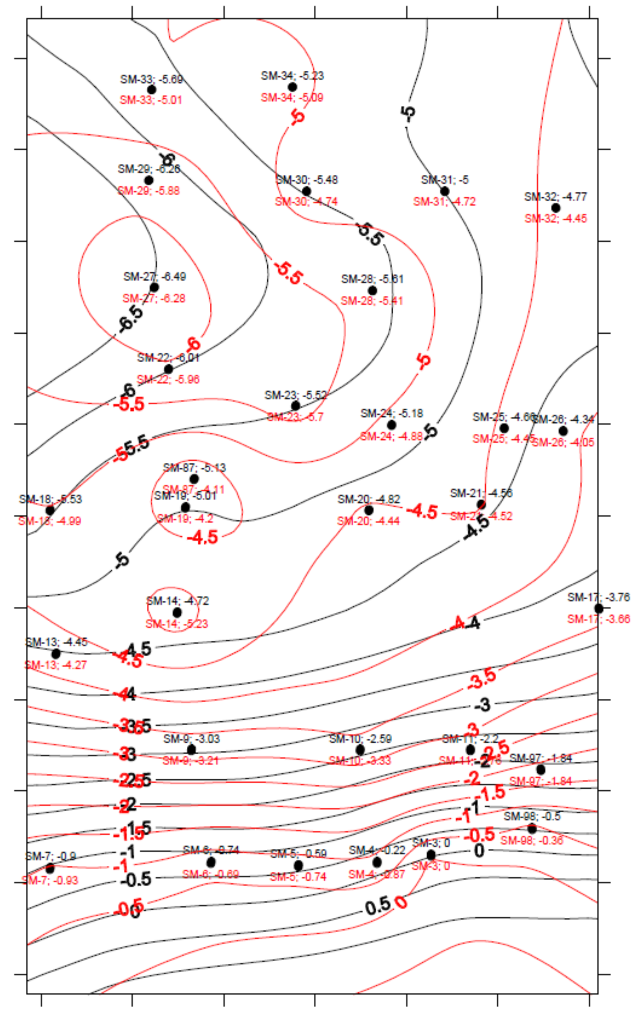
1. Apply compression only springs to mat
2. Apply Gravity Loads
3. Impose negative thermal loading on piles to produce dished shape
4. Iterate to produce desired shape
5. Adjust spring tops flush with the mat and reattach

Gravity + Settlement Displacements

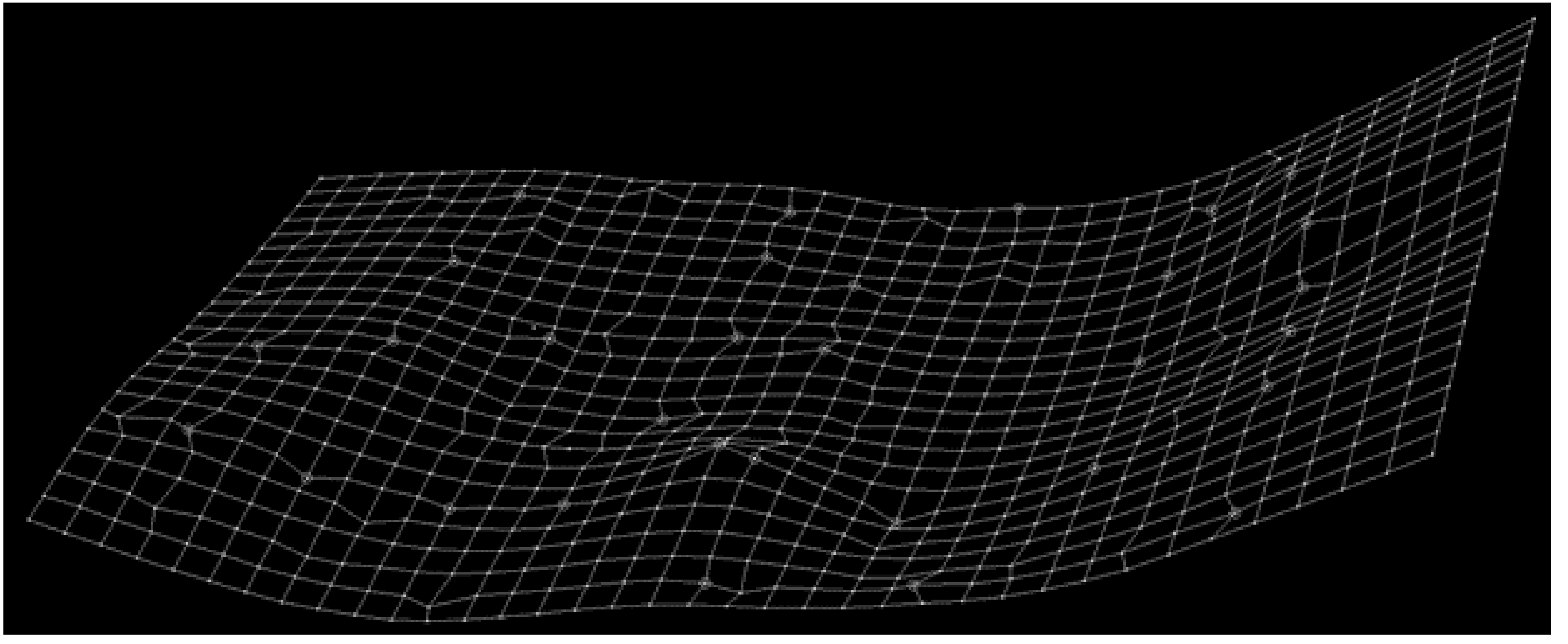
SM#	Nonlinear Model	Survey		Difference	%
3	0.00	0.00		0.00	
4	-0.22	-0.87		0.65	-75%
5	-0.59	-0.74		0.15	-21%
6	-0.74	-0.69		-0.06	8%
7	-0.90	-0.93		0.04	-4%
9	-3.03	-3.21		0.17	-5%
10	-2.59	-3.33		0.75	-22%
11	-2.20	-2.76		0.56	-20%
13	-4.45	-4.27		-0.18	4%
14	-4.72	-5.23		0.51	-10%
17	-3.76	-3.66		-0.10	3%
18	-5.53	-4.99		-0.54	11%
19	-5.01	-4.20		-0.81	19%
20	-4.82	-4.44		-0.38	9%
21	-4.56	-4.52		-0.04	1%
22	-6.01	-5.96		-0.05	1%
23	-5.52	-5.70		0.18	-3%
24	-5.18	-4.88		-0.30	6%
25	-4.66	-4.45		-0.20	5%
26	-4.34	-4.05		-0.29	7%
27	-6.49	-6.28		-0.21	3%
28	-5.61	-5.41		-0.20	4%
29	-6.26	-5.88		-0.38	6%
30	-5.48	-4.74		-0.74	16%
31	-5.00	-4.72		-0.28	6%
32	-4.77	-4.45		-0.32	7%
33	-5.69	-5.01		-0.68	14%
34	-5.23	-5.09		-0.13	3%
87	-5.13	-4.11		-1.02	25%
97	-1.84	-1.84		0.00	0%
98	-0.50	-0.36		-0.14	37%

Nonlinear Model (Perform-3d)

10 June 2016 Survey



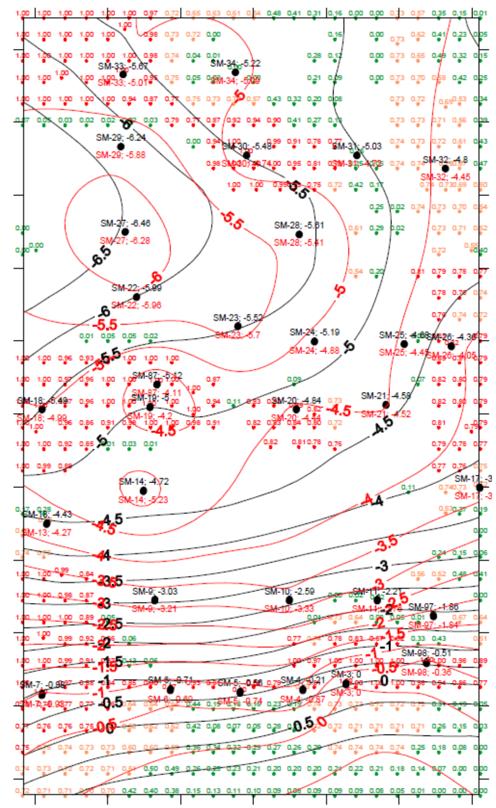
Mat Settlement



Pile Compression—Geotech DCR

Gravity

- DCR>0
- DCR>0.50
- DCR>0.75

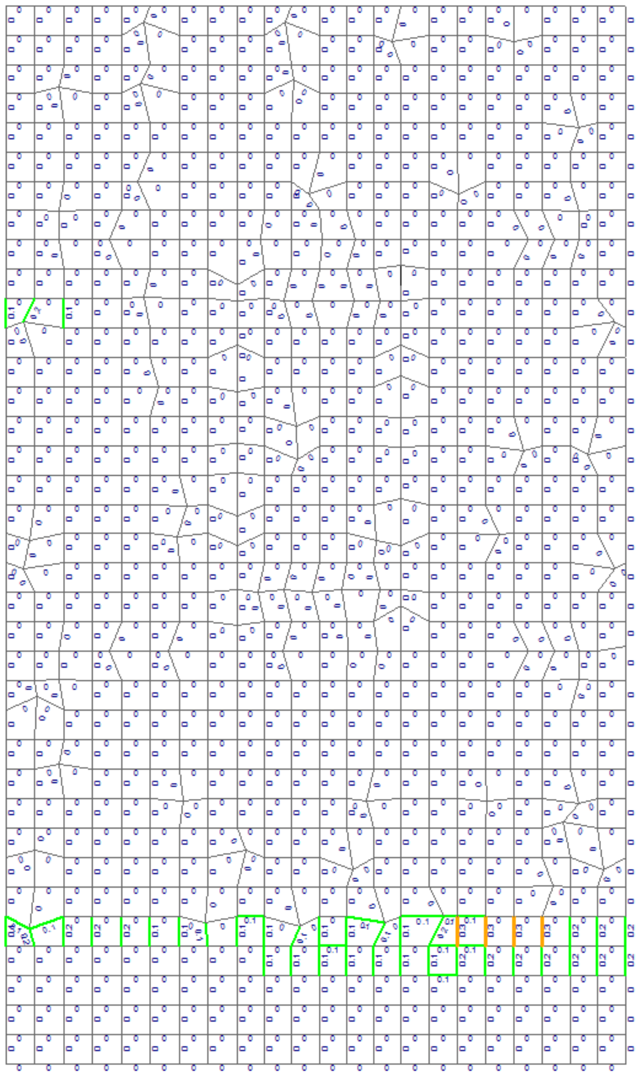


Max = 1.0

May 2017

Mat Grillage Inelastic Rotations

Gravity



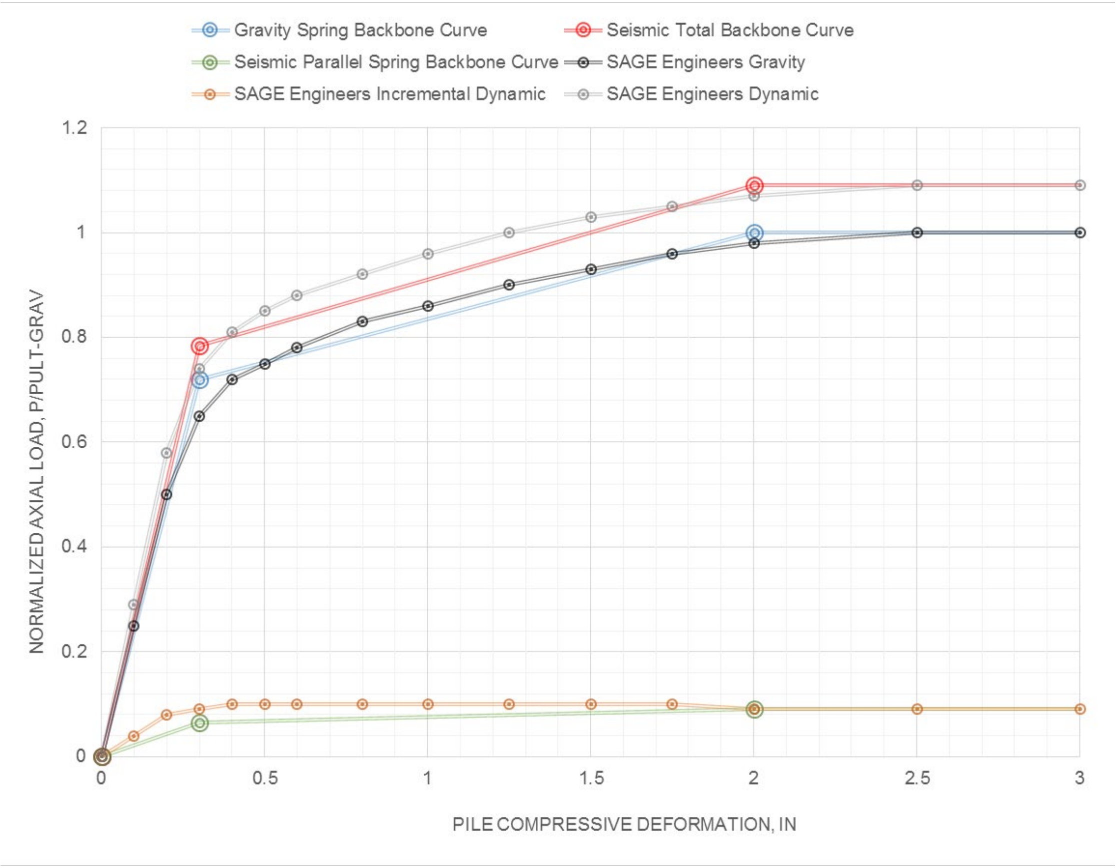
DCR>0

DCR>0.25

DCR>0.50

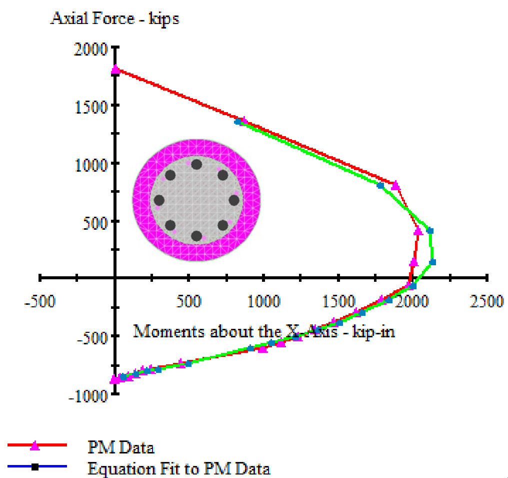
Max = 0.4%

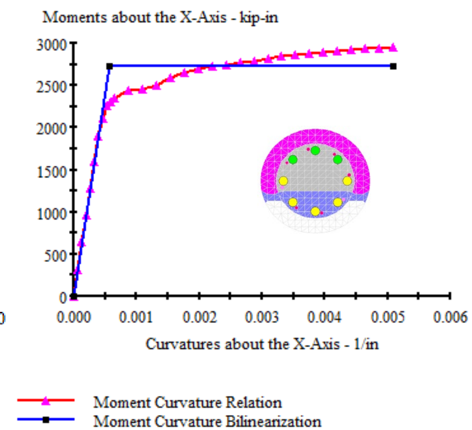
Pile Dynamic Compressive Capacity



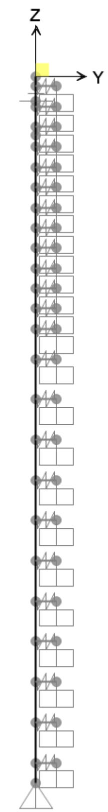
Pile Lateral Response

XTRA
CT

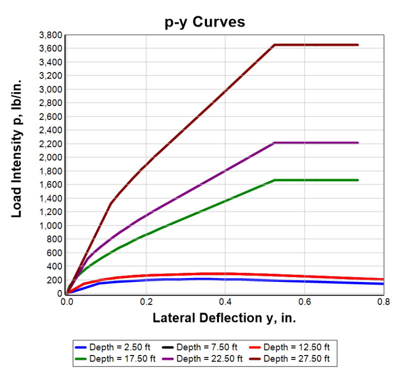




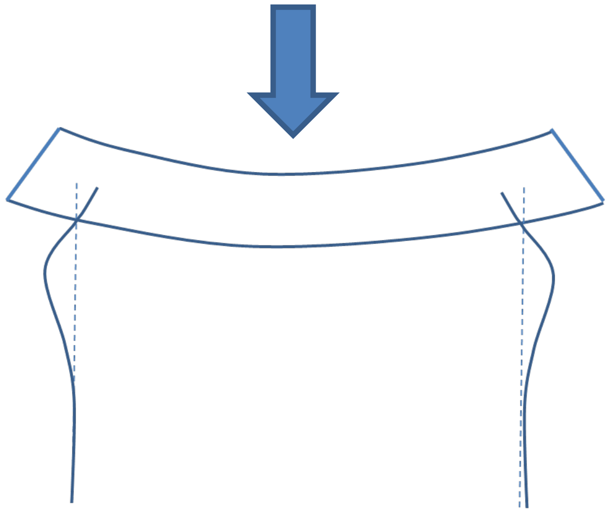
SAP20
00

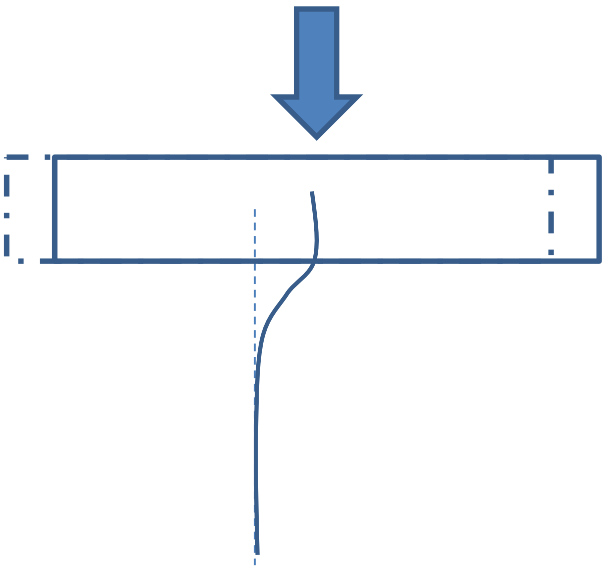


LPile



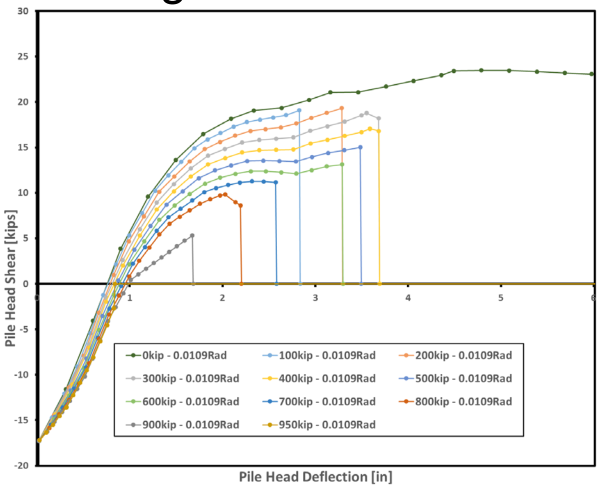
Pushover Conditions



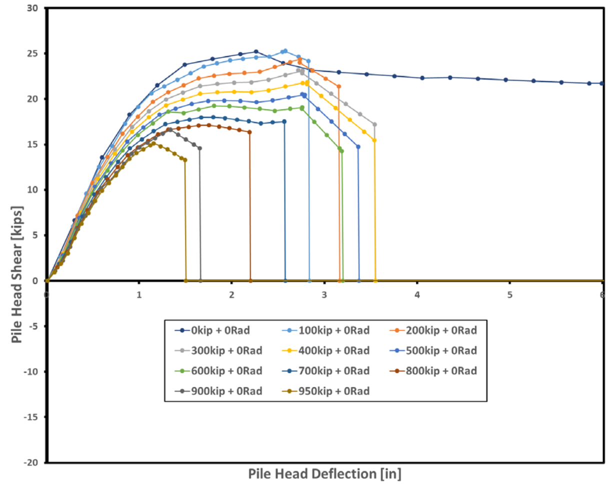


Pushover Analyses

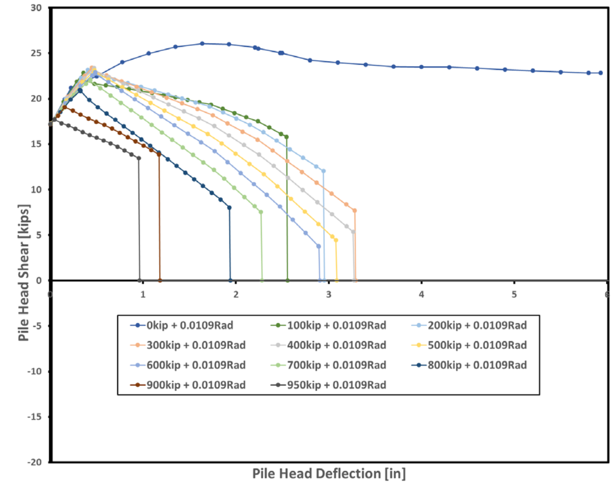
Negative 1% rotation



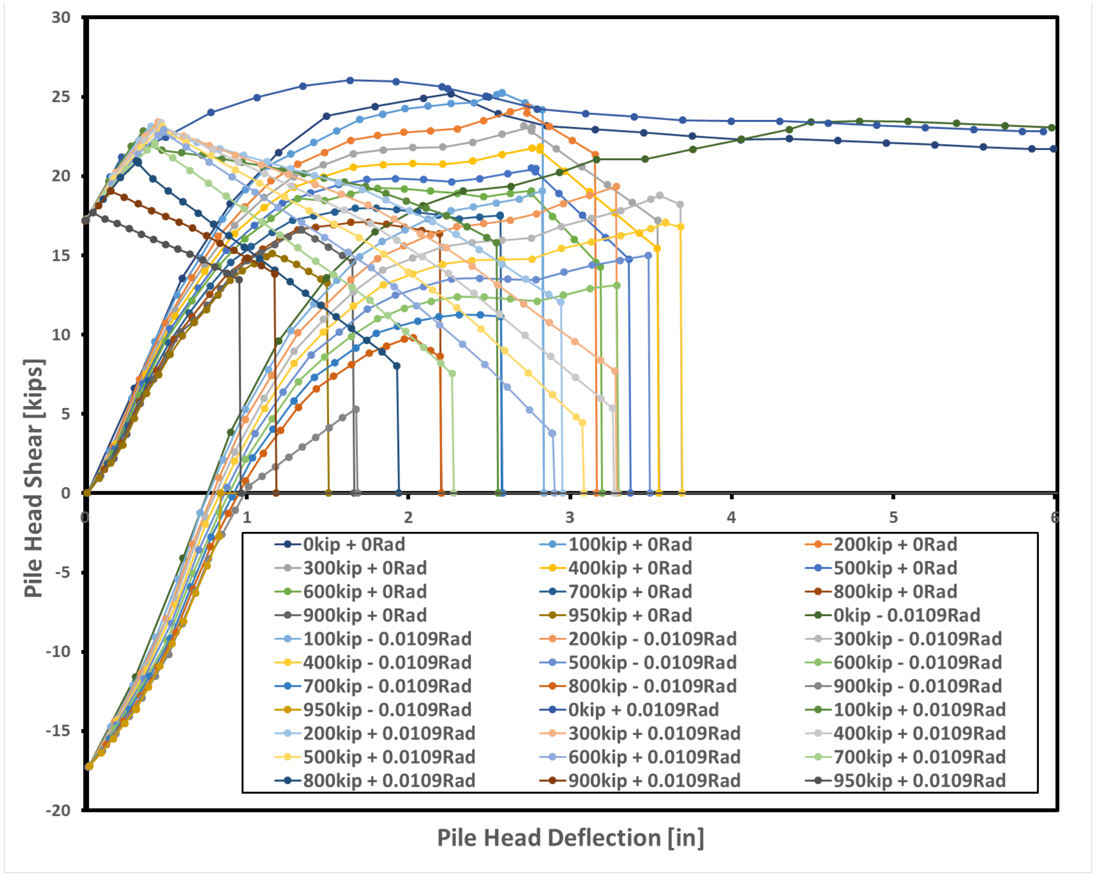
Nil rotation



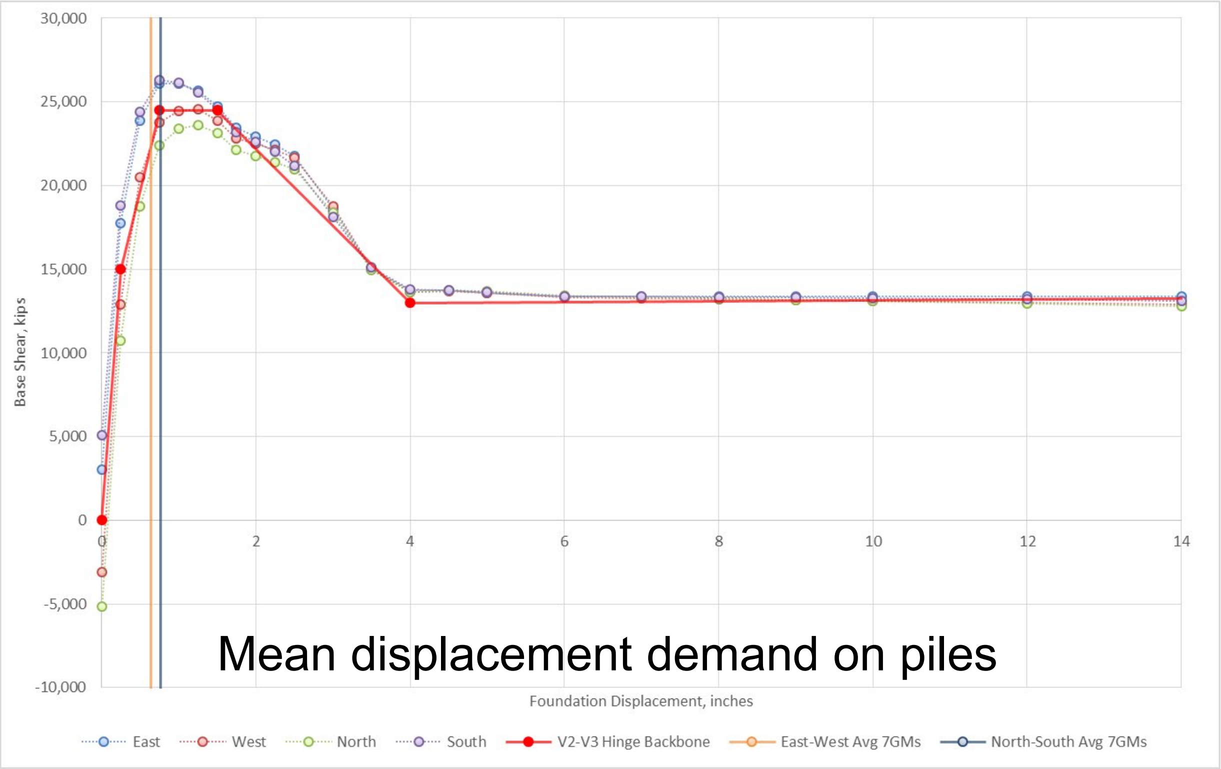
Positive 1% rotation



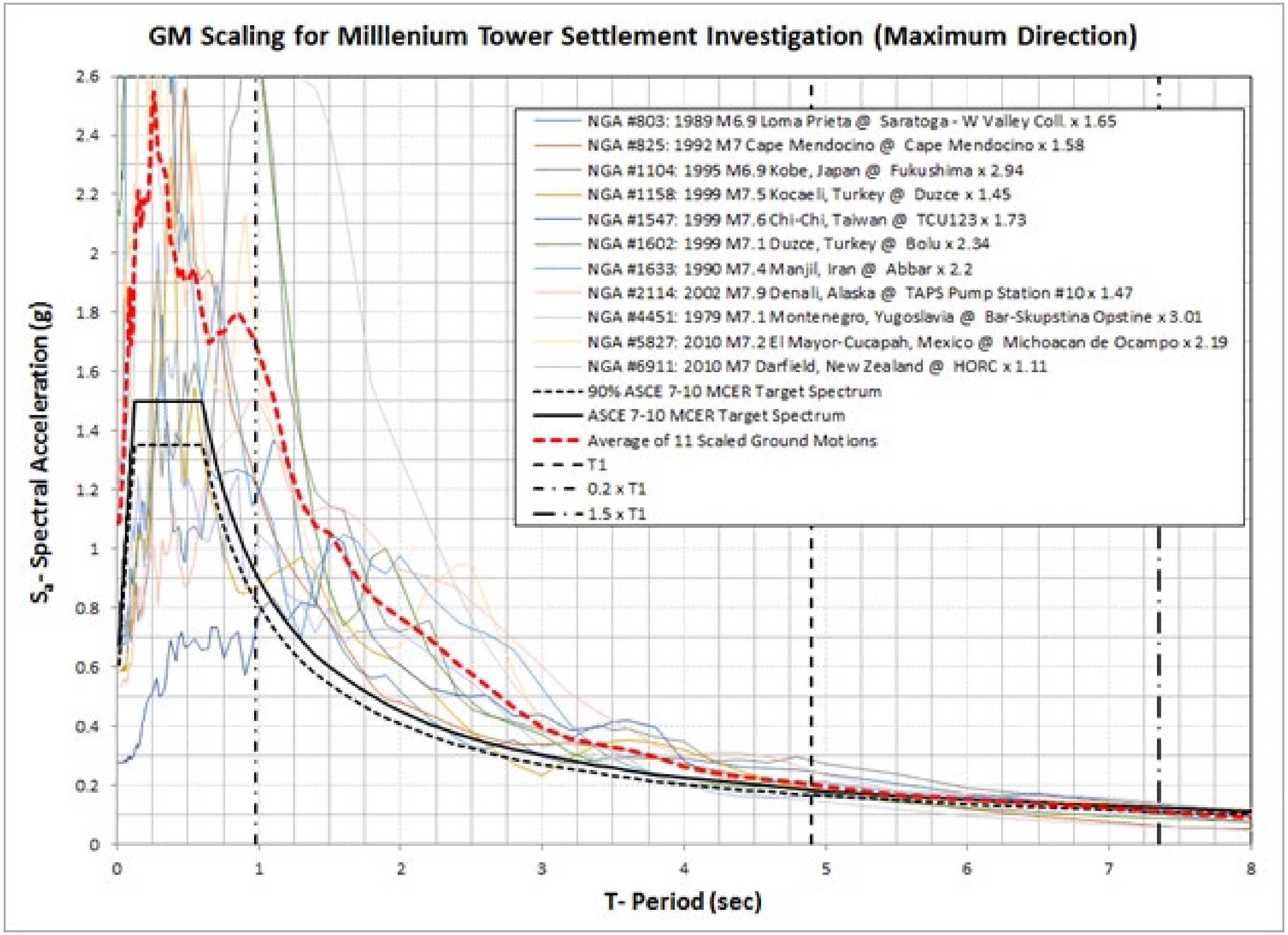
Pile Pushover Analyses



Cumulative pushover—Base Shear

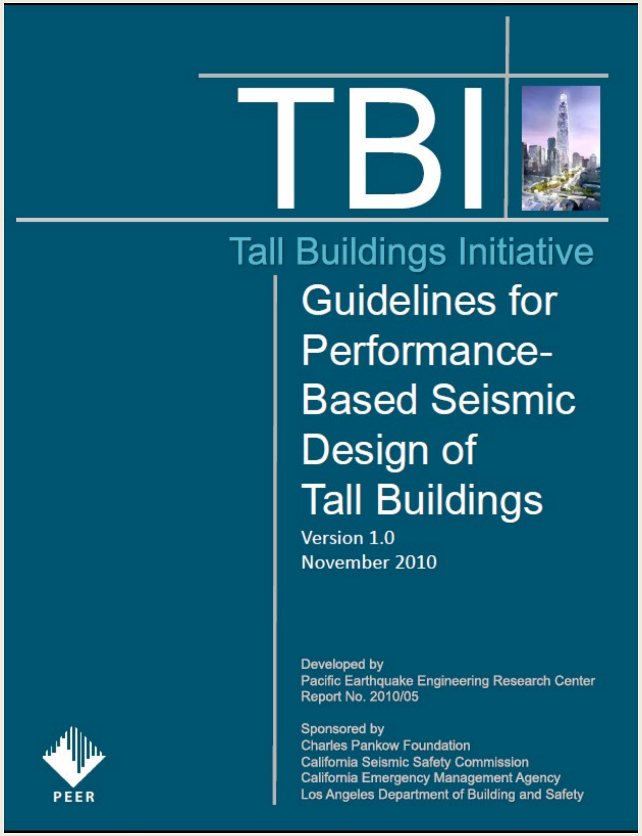


Ground Motions



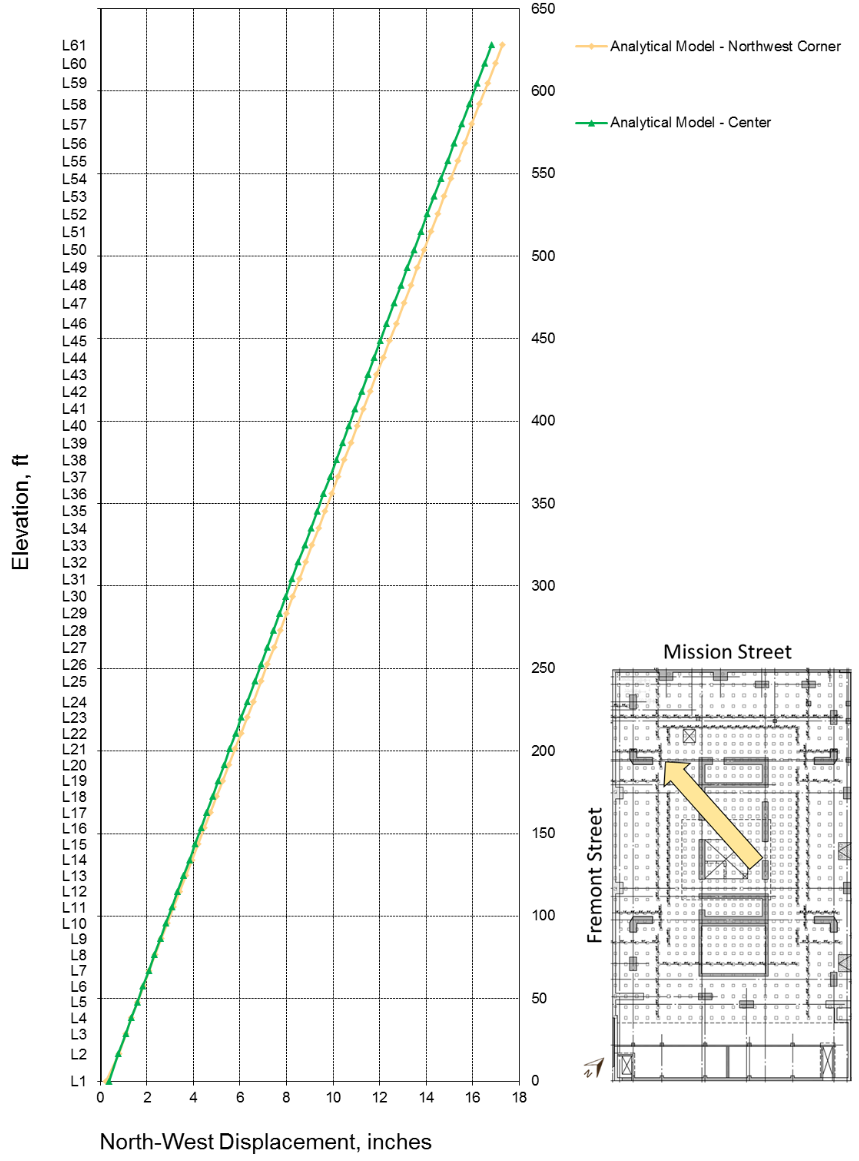
Results

Acceptance Evaluation

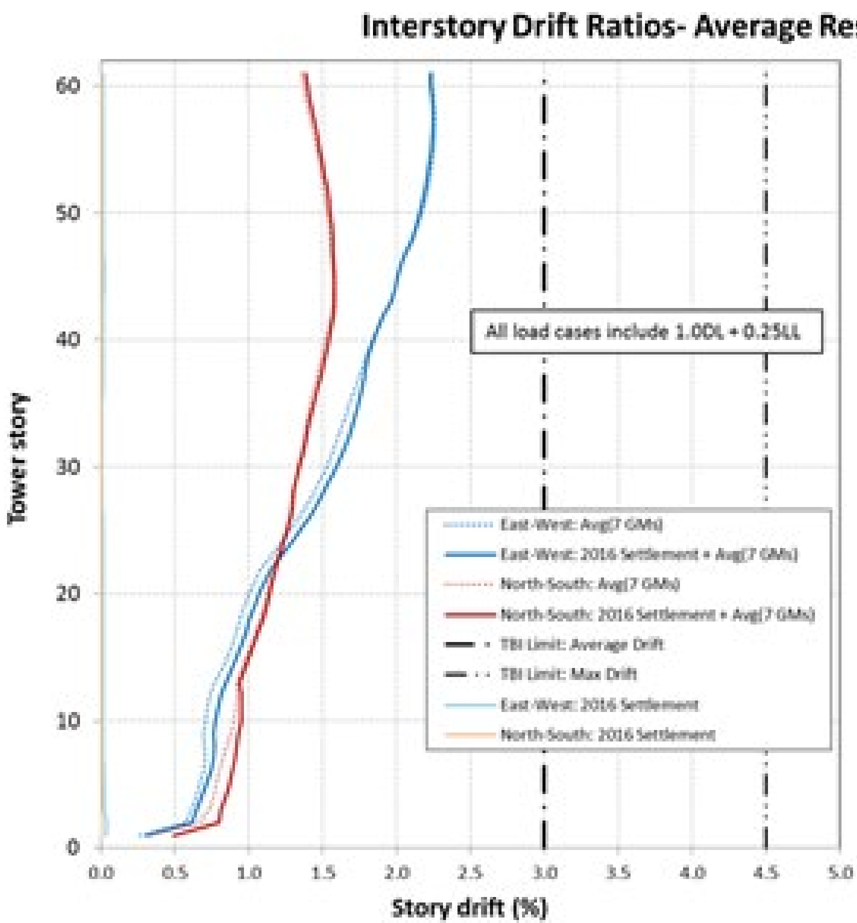


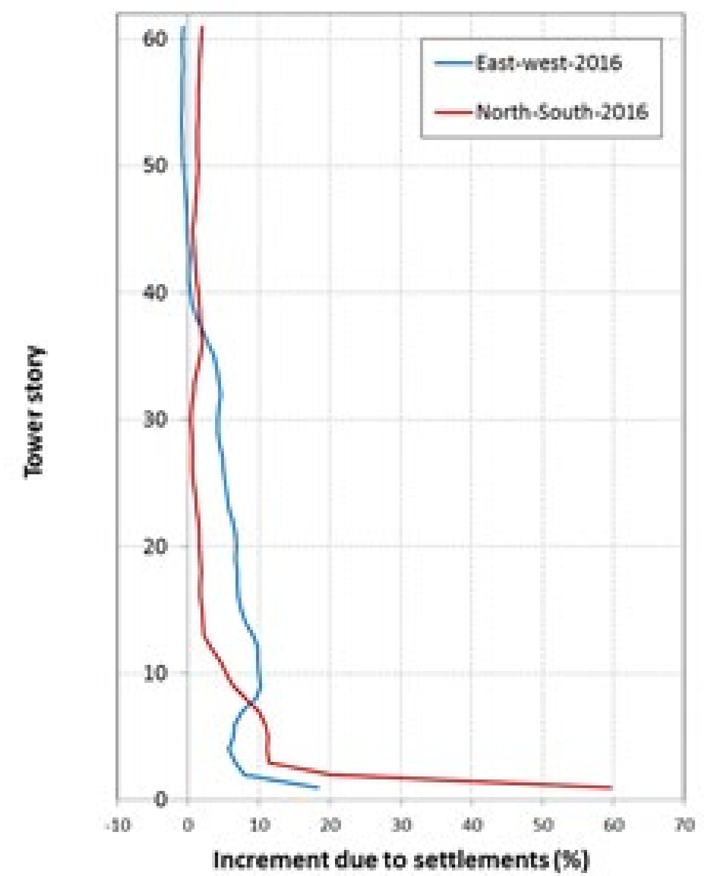
- **Acceptance evaluation used PEER TBI - Tall Building Guidelines**
  - Performance-based design procedure
  - Global performance
    - Residual and permanent drift
    - Unacceptable response limited
  - Element Performance
    - Response does not exceed valid range of modeling
    - Force-controlled elements provide acceptable margin against failure

Building Tilt - Gravity + Settlement

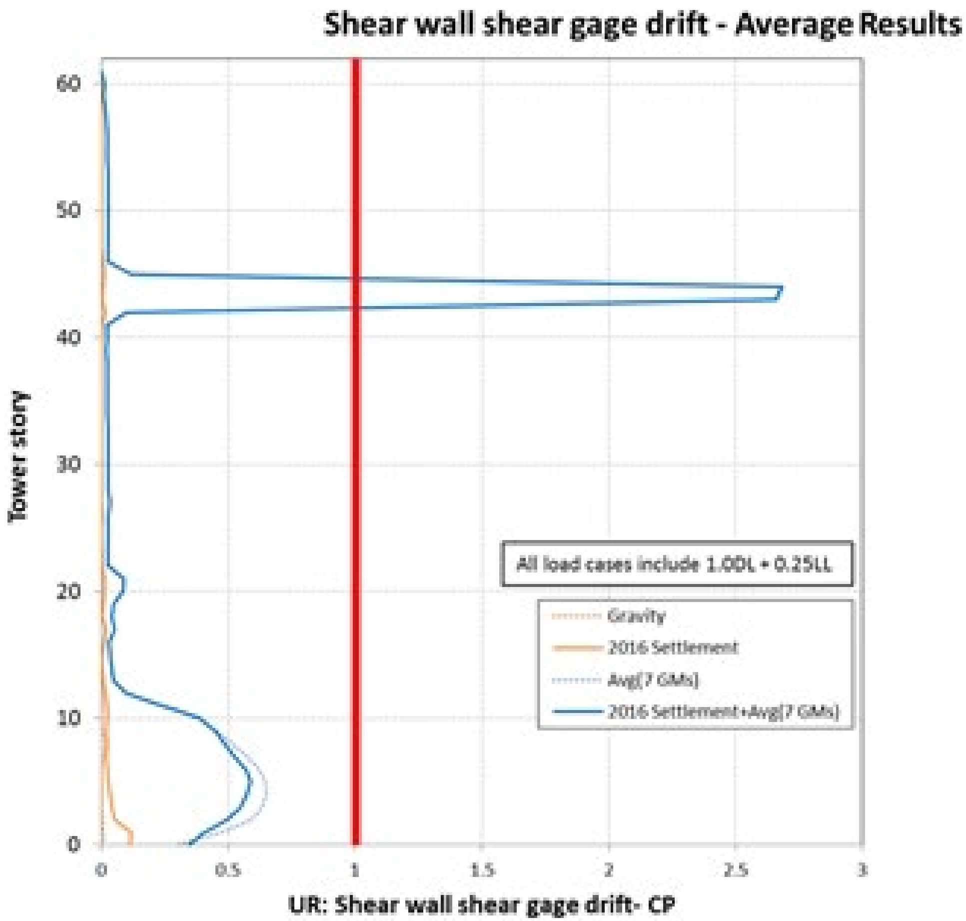


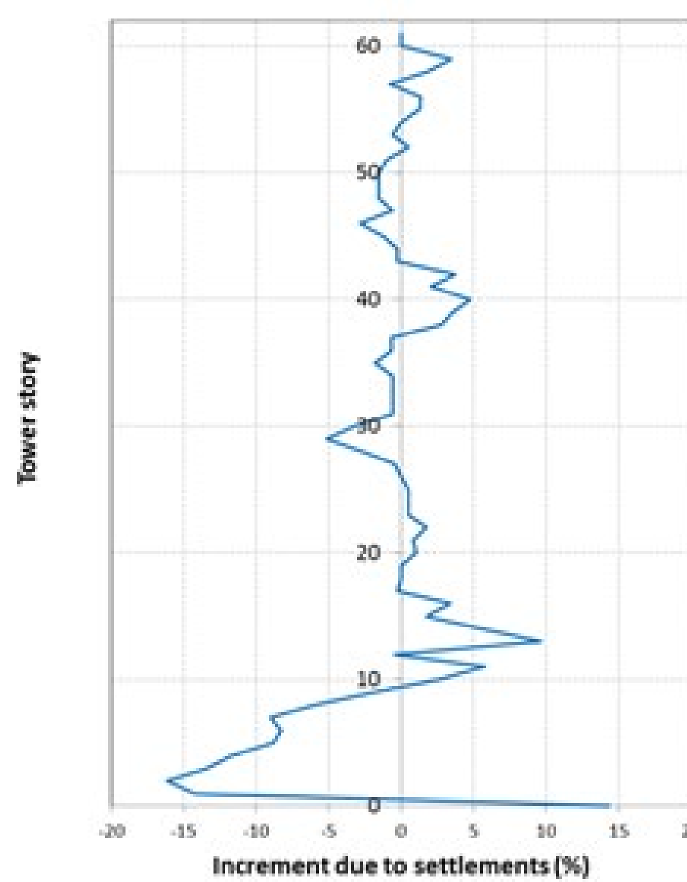
Story Drift – Gravity + Settlement + Seismic



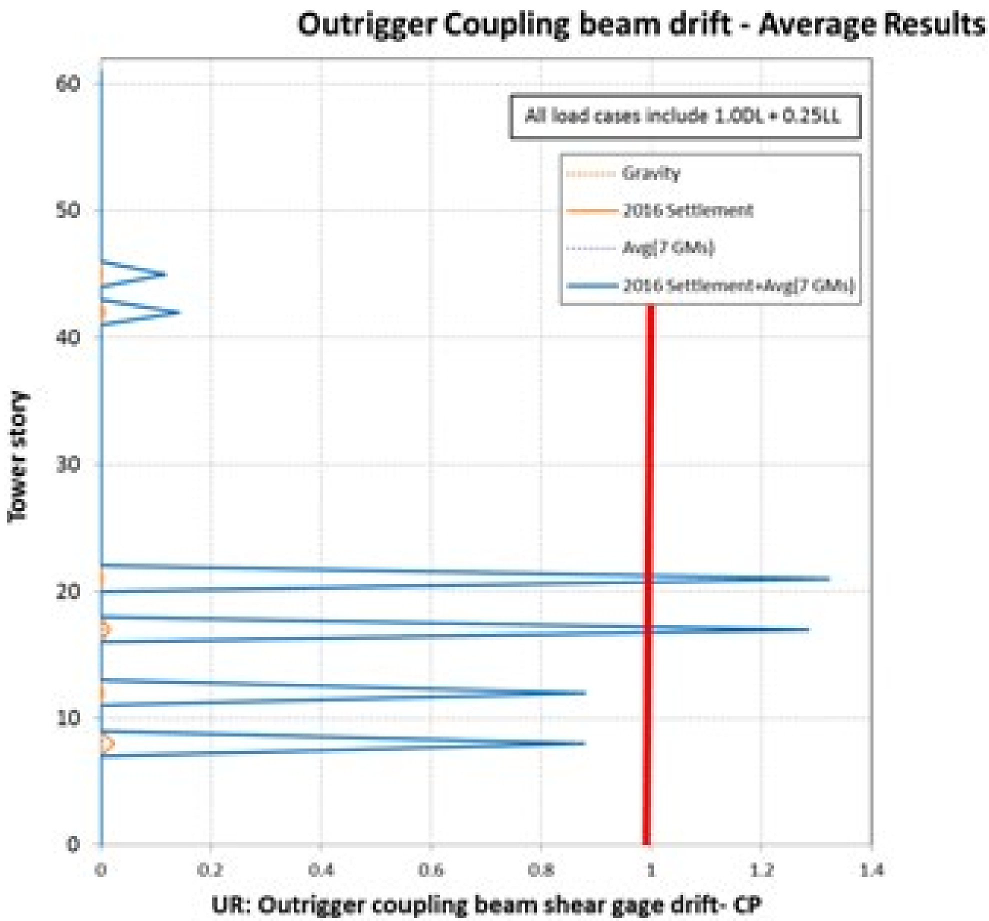


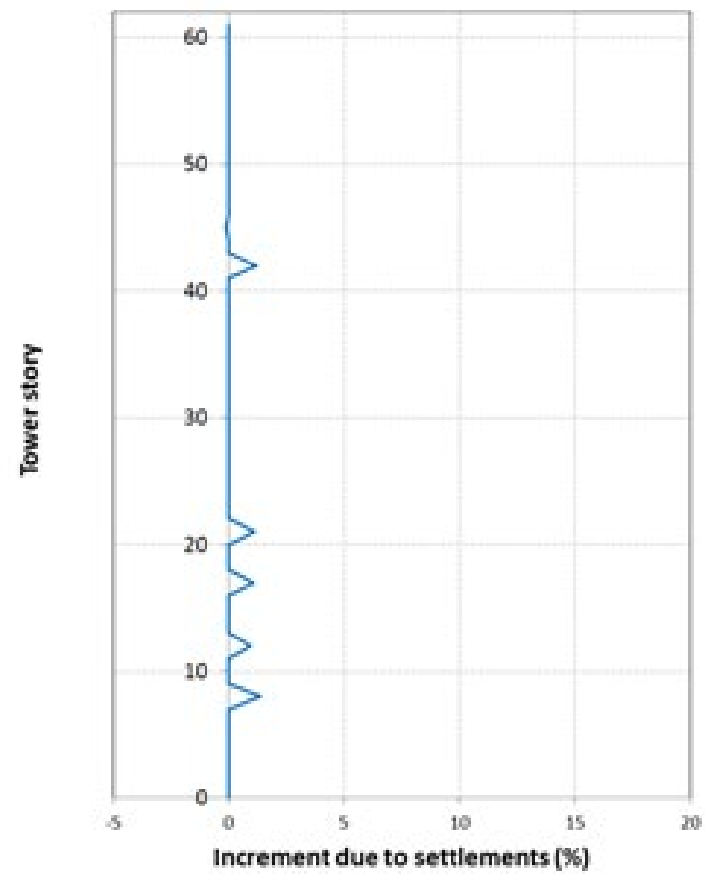
Shear Wall Shear Drift



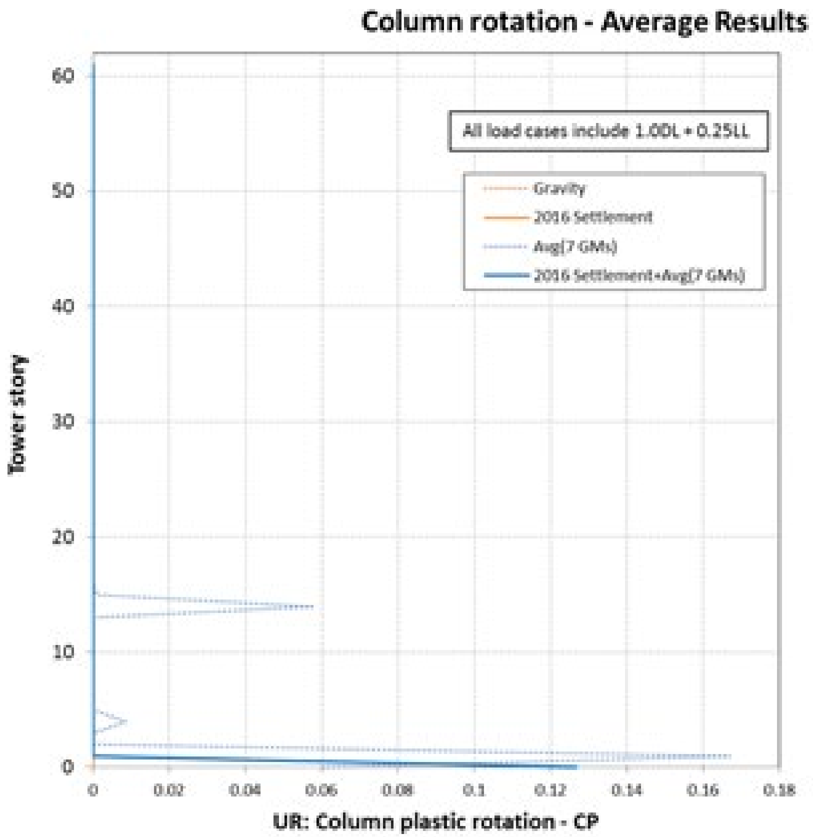


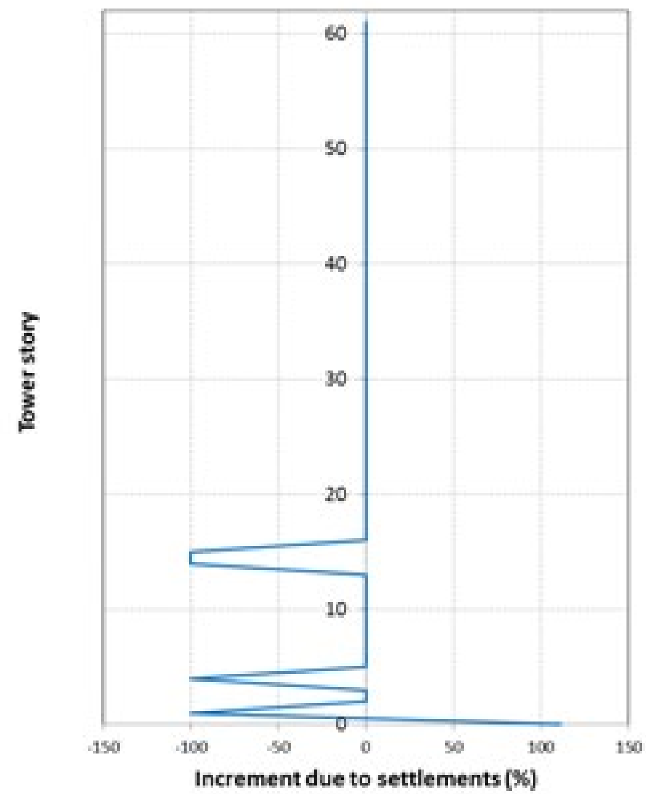
Outrigger Coupling Beams



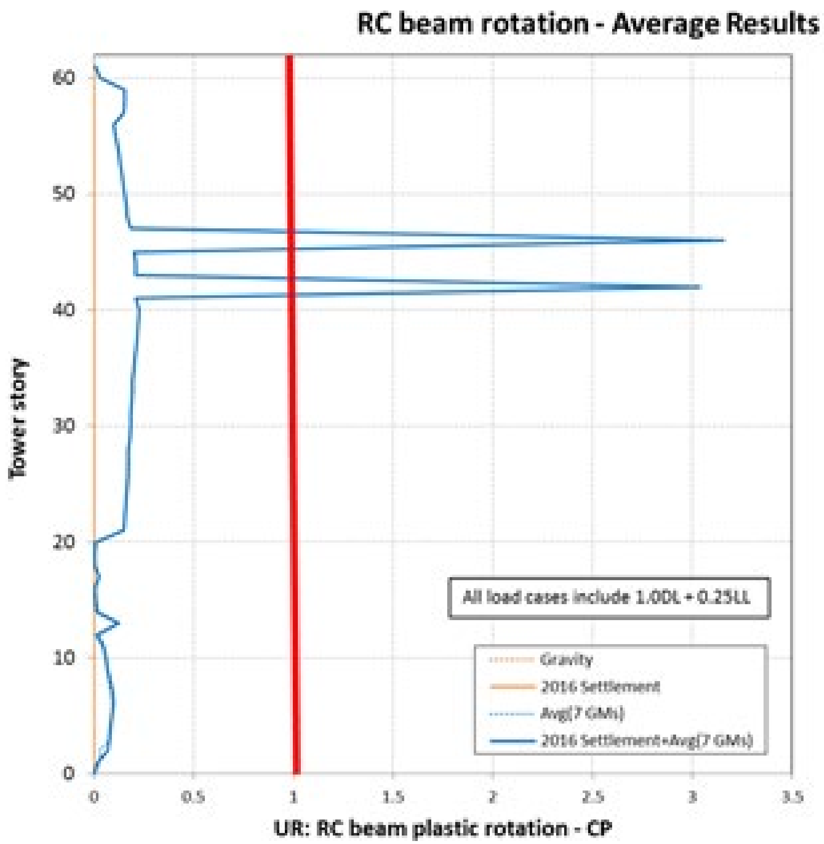


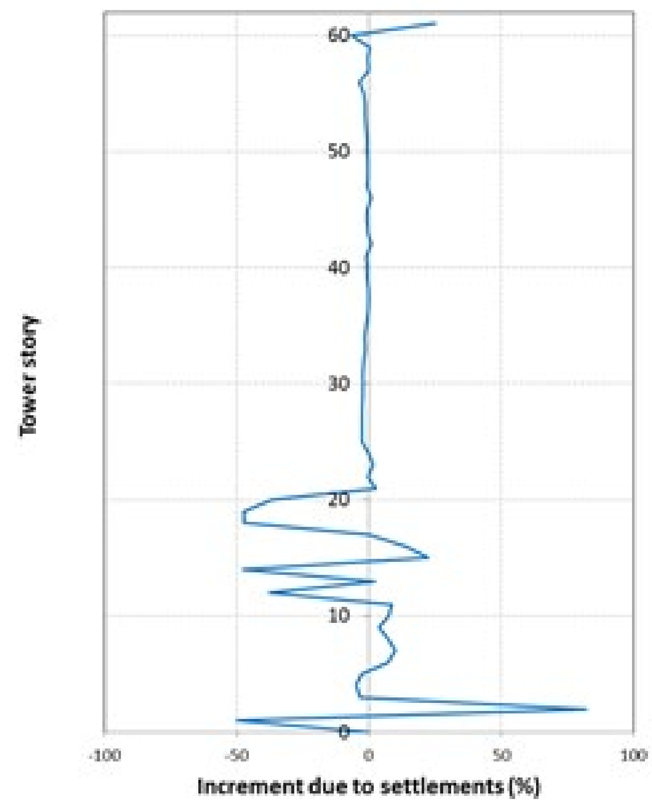
Column Plastic Rotation





Frame Beam Plastic Rotation





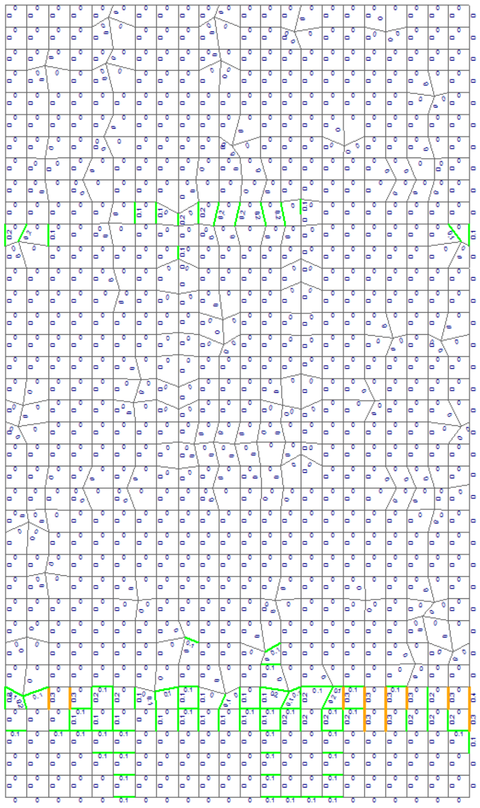
Mat Grillage Inelastic Rotations

Avg 7 GMs

DCR>0

DCR>0.25

DCR>0.50



Max = 0.4%

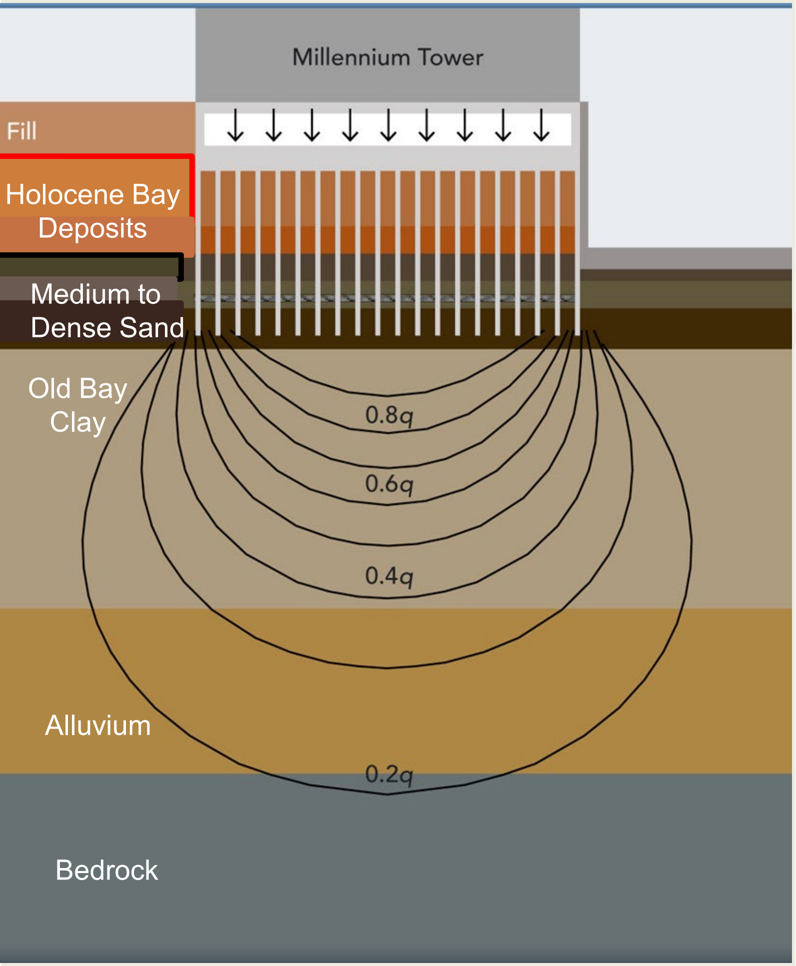
May 2017

Conclusions

- Building seismic response considering settlement is essentially the same as that neglecting it.
- Building essentially meets criteria for new buildings designed using performance-based procedures
- The settlement has not substantially affected the building's adequacy

Perimeter Pile Upgrade

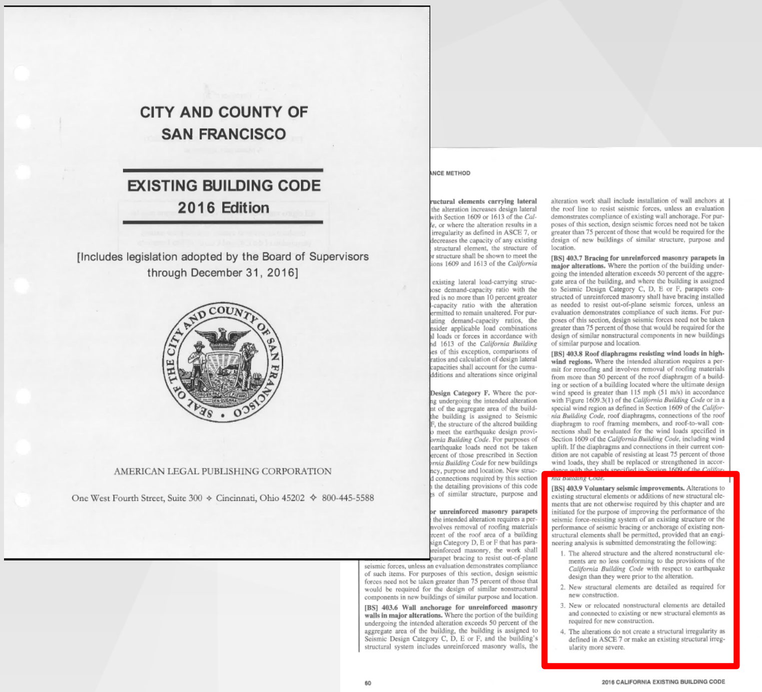
Perimeter Pile Upgrade



Design Objectives

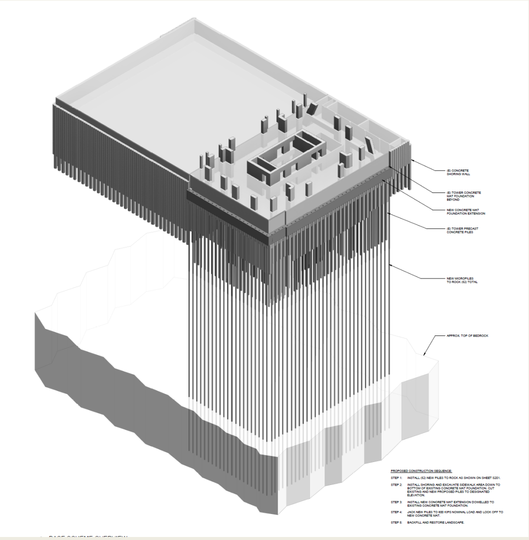
- Arrest Settlement
- Recover a portion of tilt
- Remove sufficient stress from the consolidating Old Bay Clays to:
  - Take the OBC layer out of primary compression
  - Upgrade the building's seismic performance (secondary benefit)
- Demonstrate the building continues to meet applicable City of San Francisco requirements

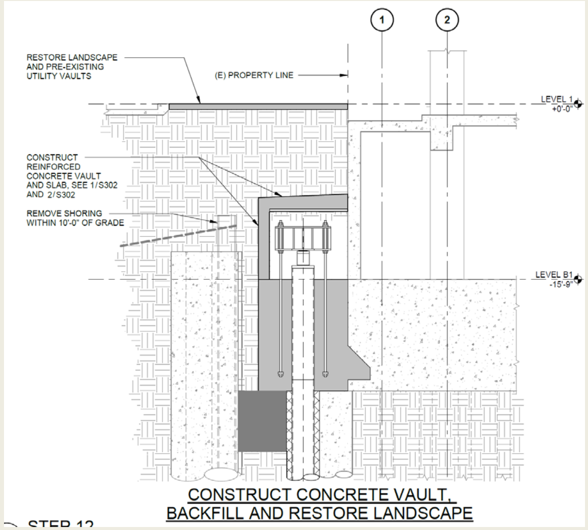
Design Criteria



[BS] 403.9 Voluntary seismic improvements. Alterations to existing structural elements or additions of new structural elements that are not otherwise required by this chapter and are initiated for the purpose of improving the performance of the seismic force-resisting system of an existing structure or the performance of seismic bracing or anchorage of existing nonstructural elements shall be permitted, provided that an engineering analysis is submitted demonstrating the following:

1. The altered structure and the altered nonstructural elements are no less conforming to the provisions of the *California Building Code* with respect to earthquake design than they were prior to the alteration.
2. New structural elements are detailed as required for new construction.
3. New or relocated nonstructural elements are detailed and connected to existing or new structural elements as required for new construction.
4. The alterations do not create a structural irregularity as defined in ASCE 7 or make an existing structural irregularity more severe.

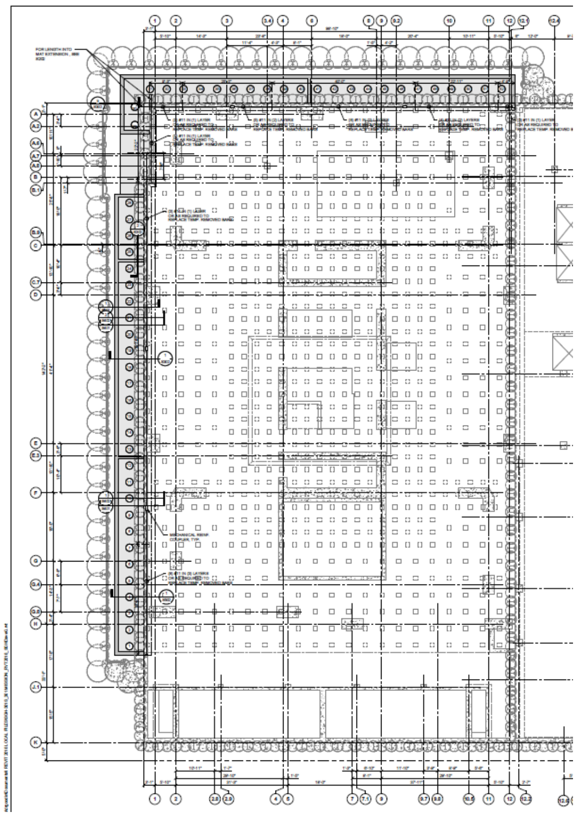




Design Concept

- Install 52 new piles to rock along north and west building edges
- Construct extension of 10'-thick mat
- Jack piles to remove 41,000 kips (18%) of the building weight
- Pile to Cap connection detailed to limit load transmitted to new piles under long term residual settlement

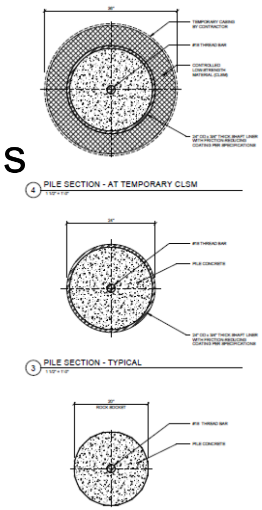
Retrofit Piles

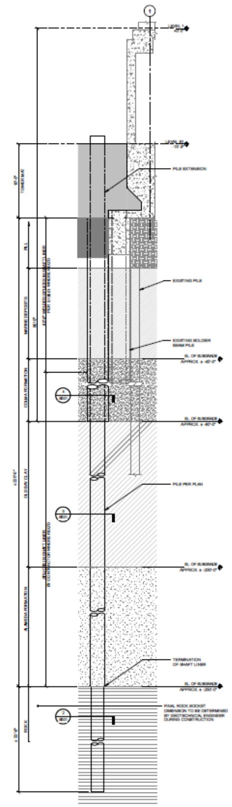


36 inch through Colma sands

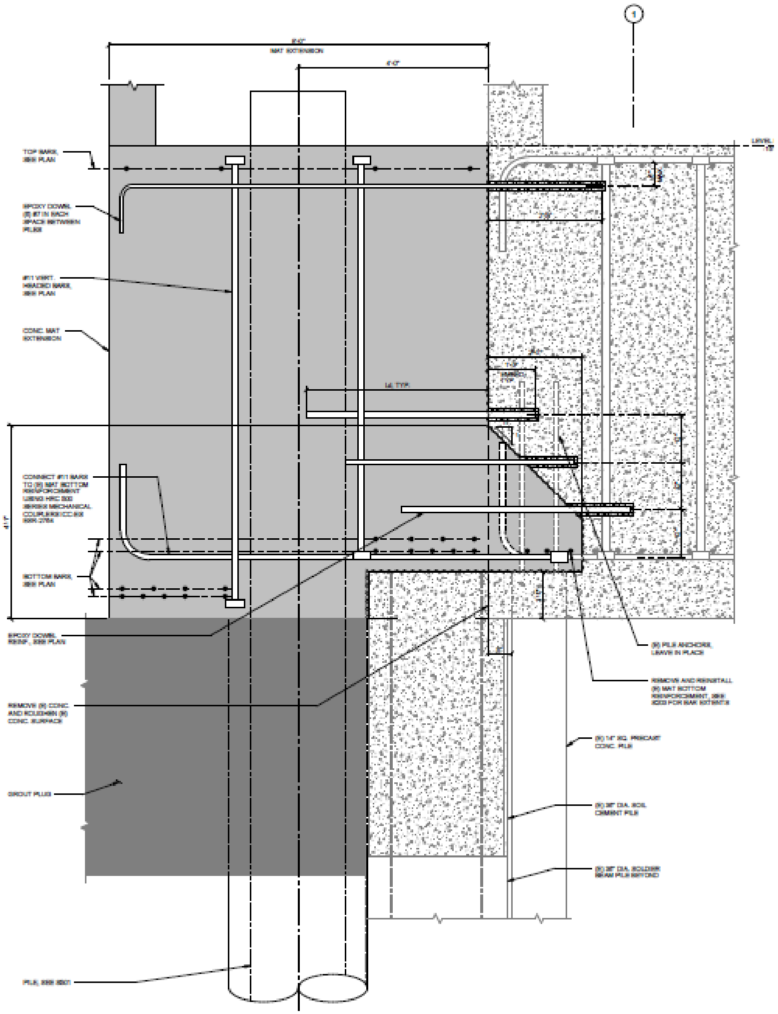
24 inch to Franciscan

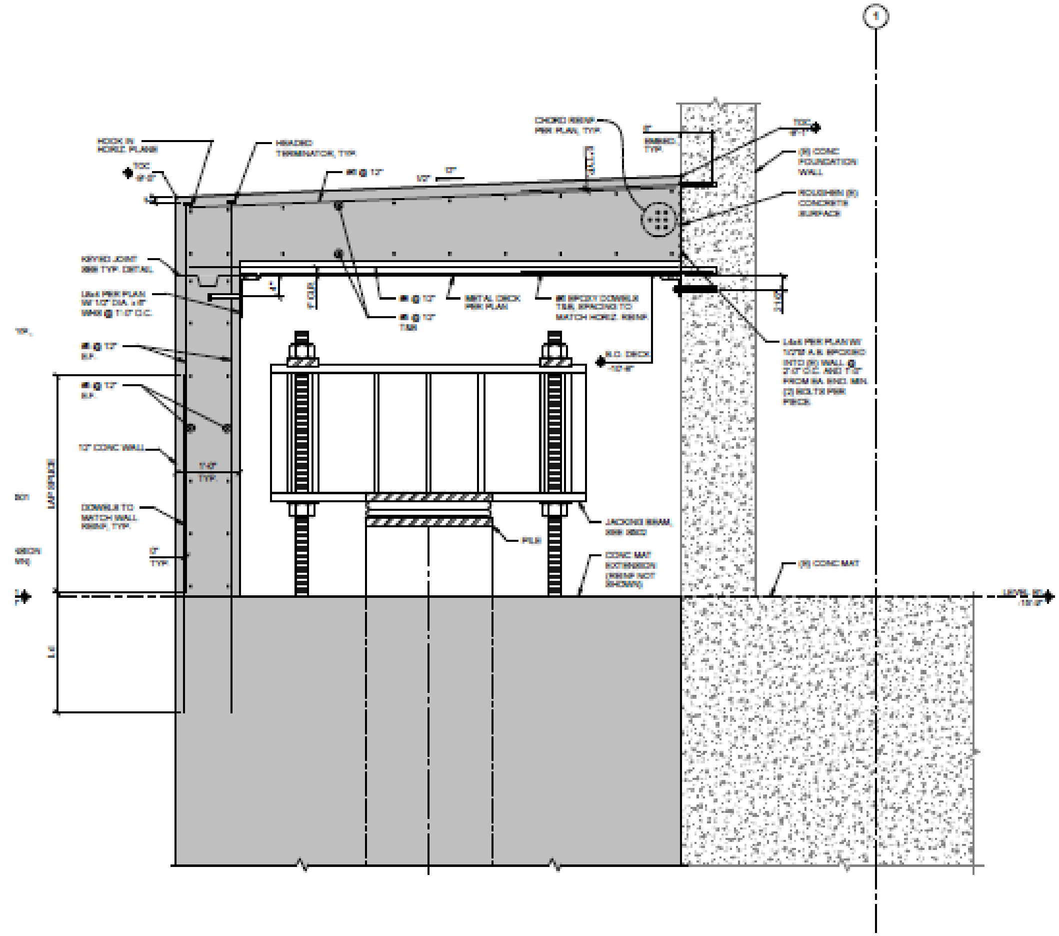
20 inch in Franciscan



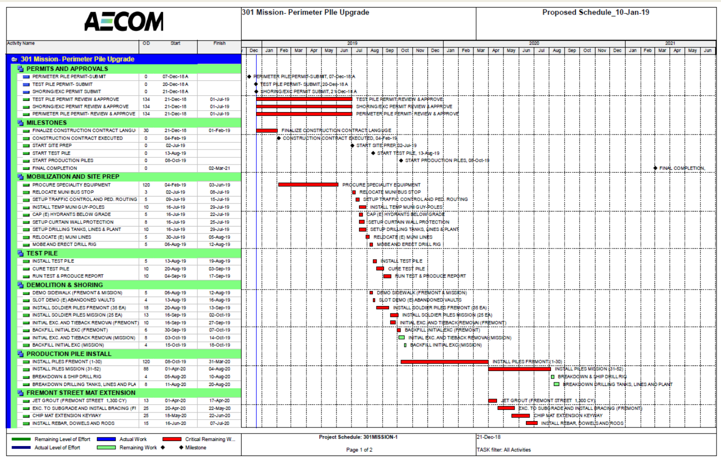


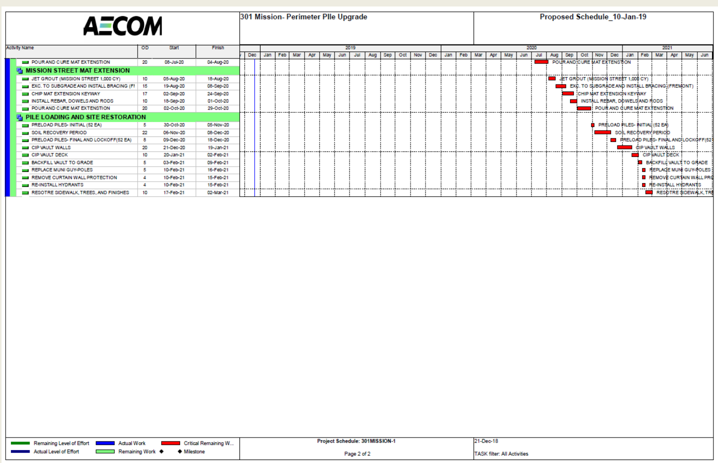
Foundation Upgrade Details





Project Schedule





- City-appointed peer review approved retrofit on 4 December 2018
- Parties have been engaging in terms and condition of legal settlement
- Construction start projected 1 May 2020
- 22 month duration
- Monitoring of pile loads, settlement and piezometric head in soils for 10 years

Conclusions

& Summary

Conclusions

- Settlement has not impacted the building’s seismic resistance
- There is no reason, structurally that the building needs to be upgraded
- Homeowners need a major retrofit to “revalue” their units
- Perimeter pile upgrade will have a cost of approximately $100 million
- Construction completion forecast for Spring 2022

Aftermath

- **All new high rises in San Francisco “infirm soil” areas now use piles extending to rock**
- **City of San Francisco now requires geotechnical peer review of all high rise buildings**
- **City is developing an Administrative Bulletin governing the criteria for foundation review**

Questions?