



SIMPSON GUMPERTZ & HEGER



Engineering of Structures
and Building Enclosures

The Millennium Tower Settlement, Tilting and Upgrade

University of Kansas

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March 5, 2020



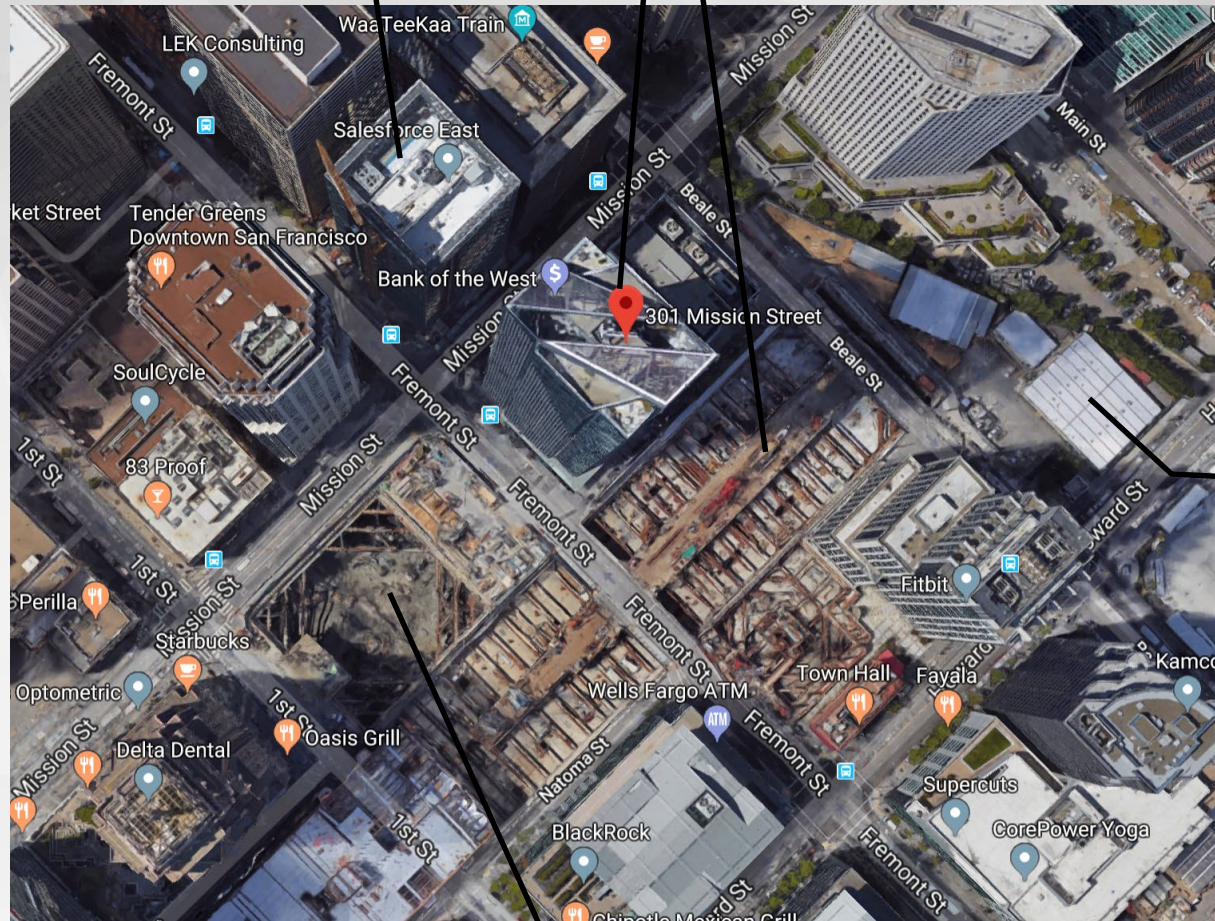
- **Constructed 2005-2009**
- **58 stories, 645 ft (197m) tall**
- **Tallest & most expensive residential tower in San Francisco**
- **Views from the Sierra to the Cascades to the Farallon Islands**
- **Most expensive unit sold in 2013 for \$13.5 million**
- **Construction Cost - \$600 Million Sales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

The Site

350 Mission
2012

301 Mission

Transbay terminal and track tube
2009



Salesforce Tower
2014

200
Beale
2017



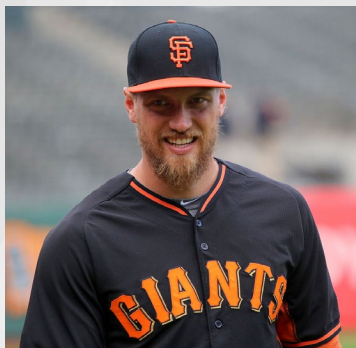
History of the Problem

- **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



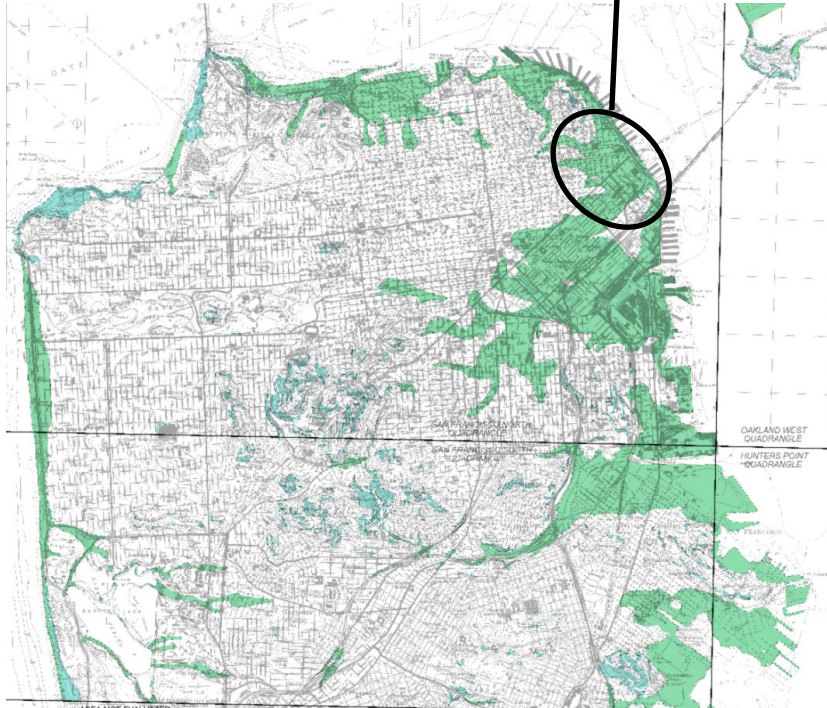
Laurence Kornfield
Retired Chief Deputy Building
Inspector, City of SF



Jerry Dodson
Personal Injury Attorney

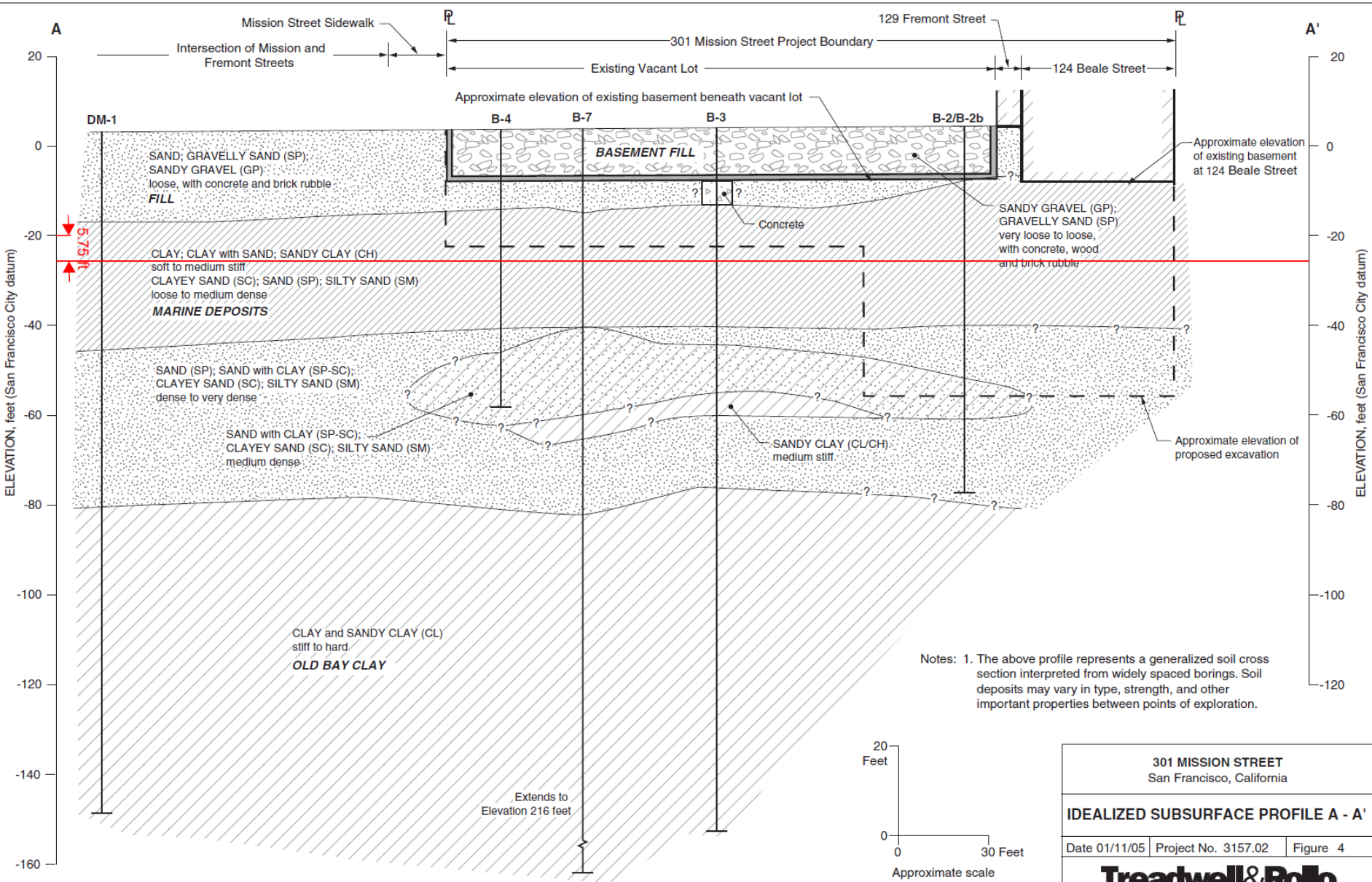
Why did this happen?

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

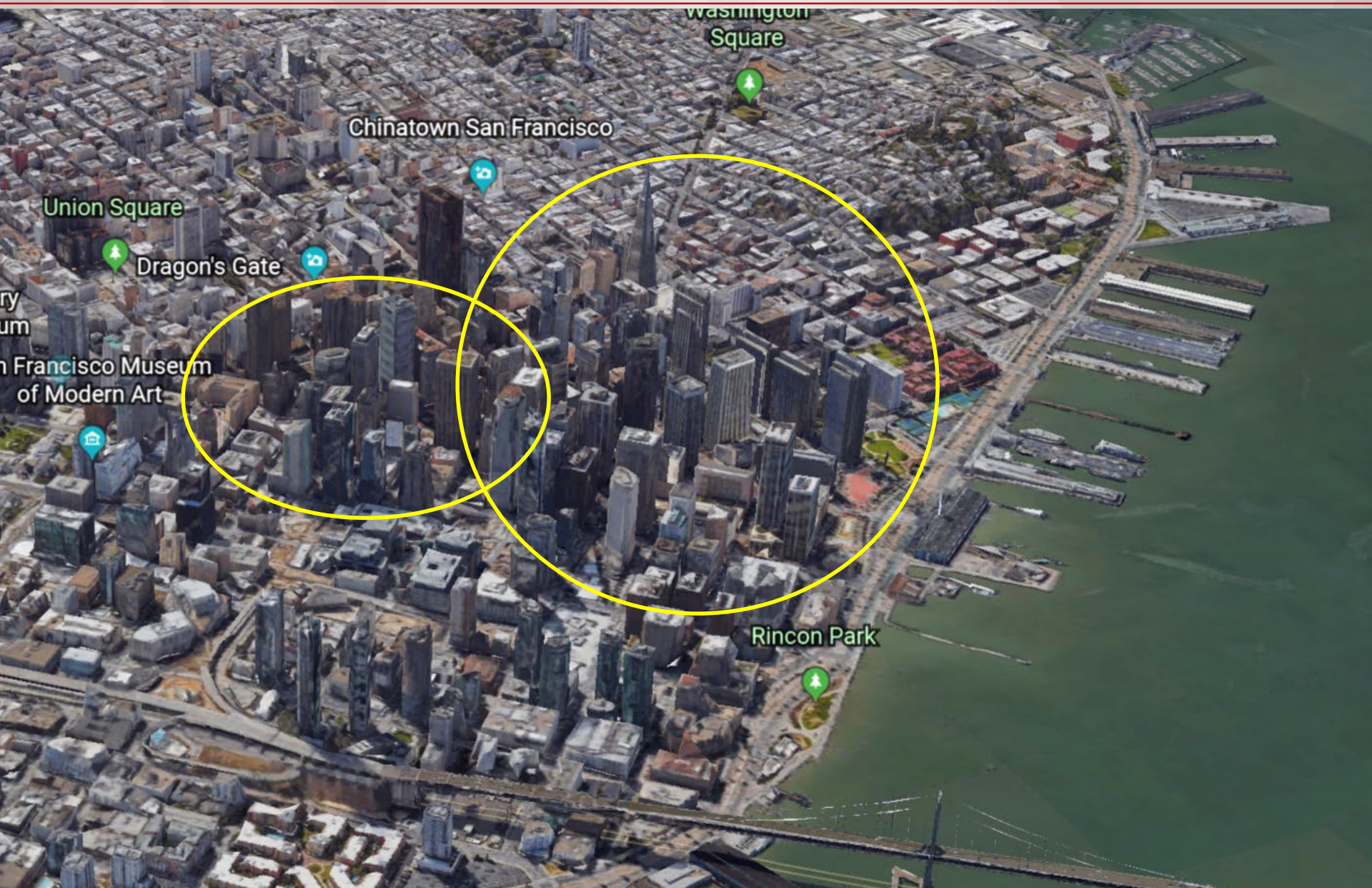
30' (10m) – Young Bay Clay
marine deposits – last 12,000 years

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
Serpentine

Other SF buildings with this foundation

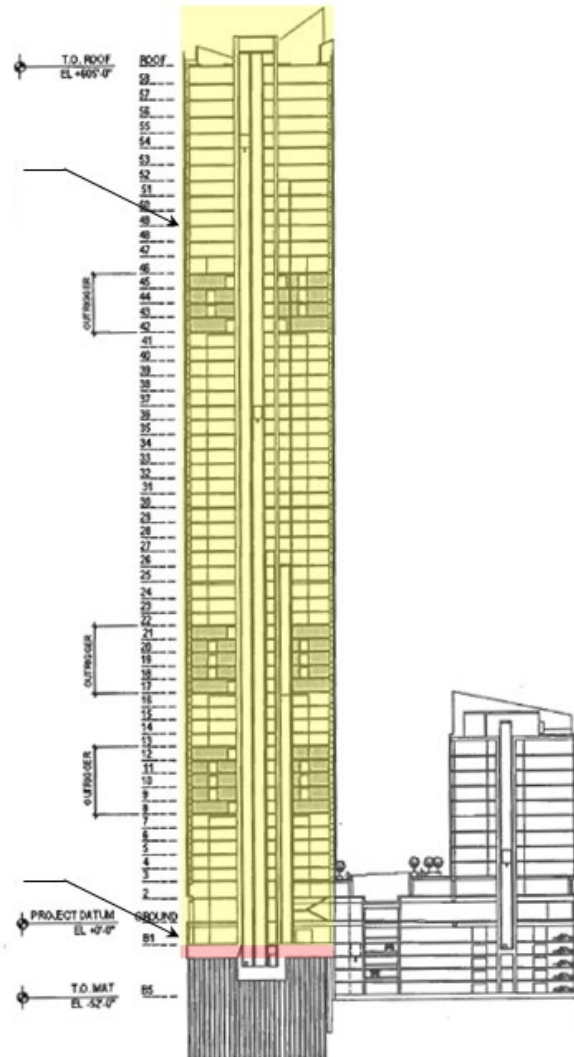


The Millennium Tower

Superstructure
200,000 kips

Imposed bearing pressure
224,000 kips
100 x 200' bearing area
11.2 ksf

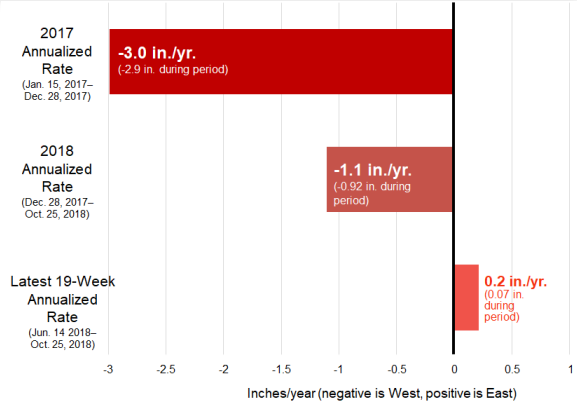
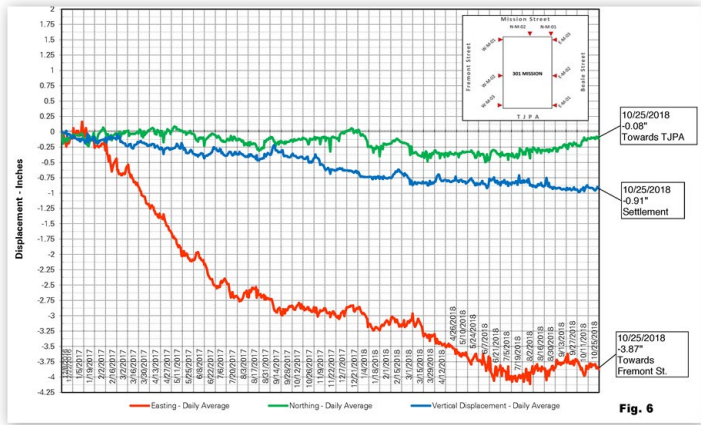
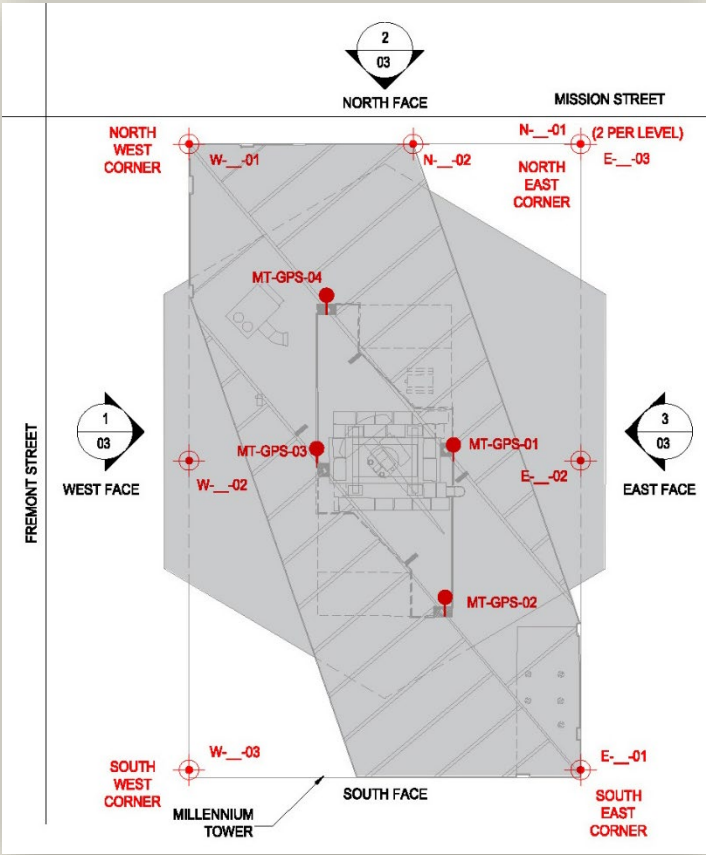
Substructure
24,000 kips



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?

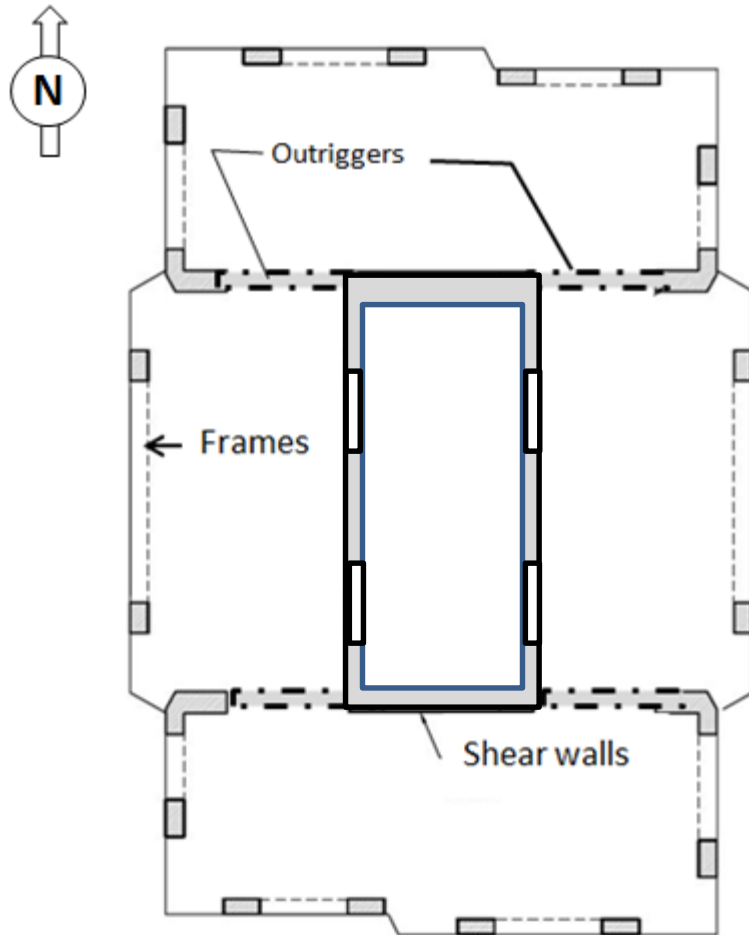


CONFIDENTIAL – MEDIATION PRIVILEGE

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**

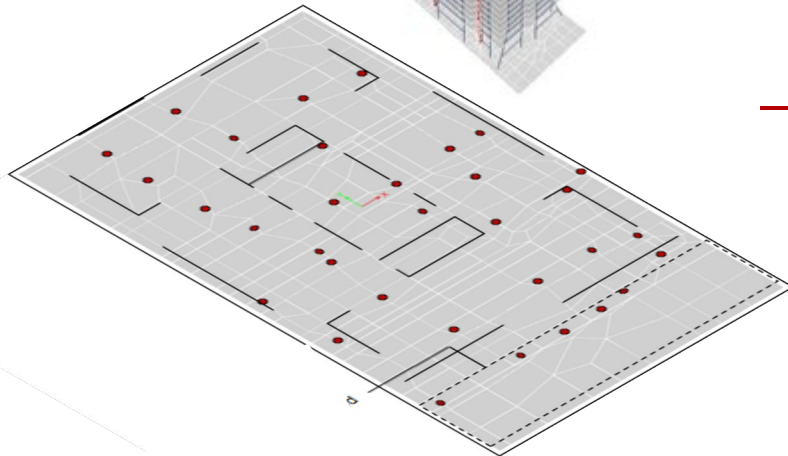
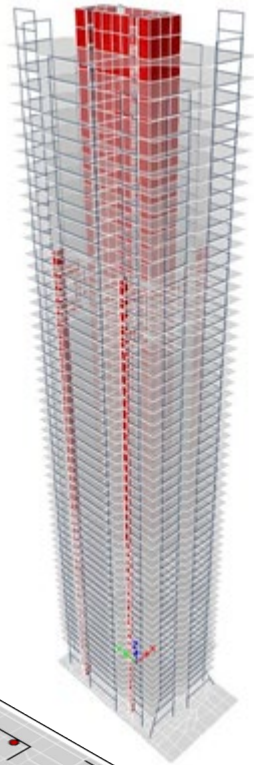
Investigation tasks

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



Linear Analyses

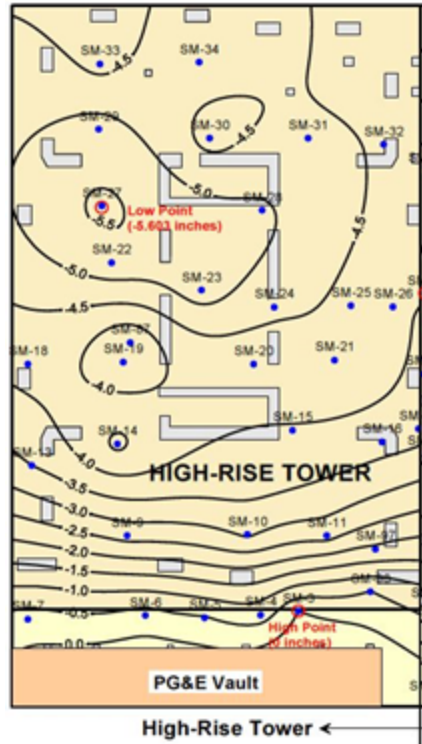
Modeling



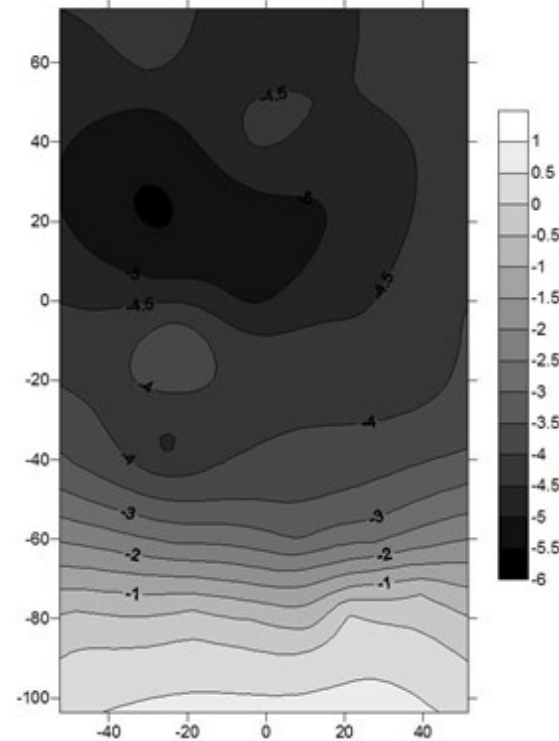
- **ETABs software**
 - Frame elements
 - Beams
 - Columns
 - Wall (panel) elements
 - Walls
 - Coupling beams
 - Outriggers
 - Shell elements
 - Foundation mat
 - Piles modeled as fixed translation points at shell nodes

Settlement Representation

Measured Settlement 6/14

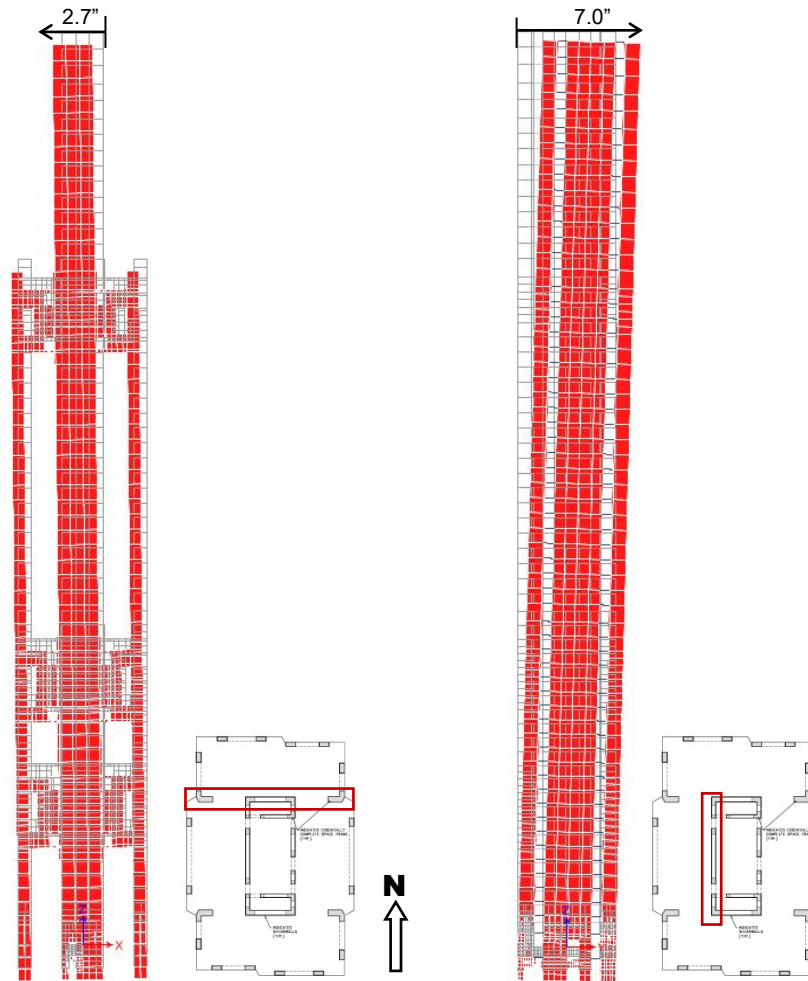


Enforced Displacement

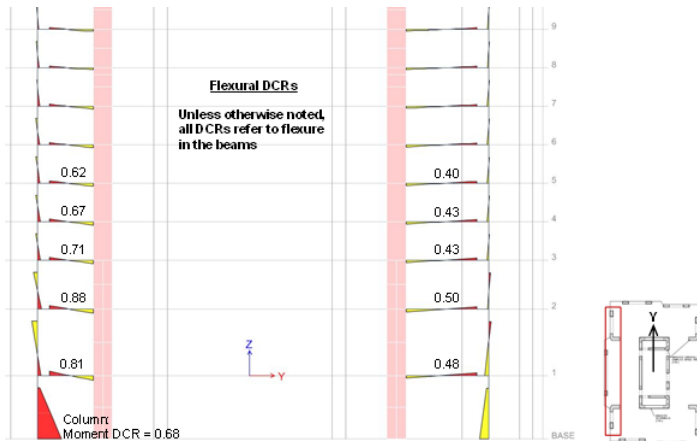


- **Input 38 points into Surfer 8 software**
 - Provides smooth contours matching discrete points
- **Imposed enforced displacements on mat**

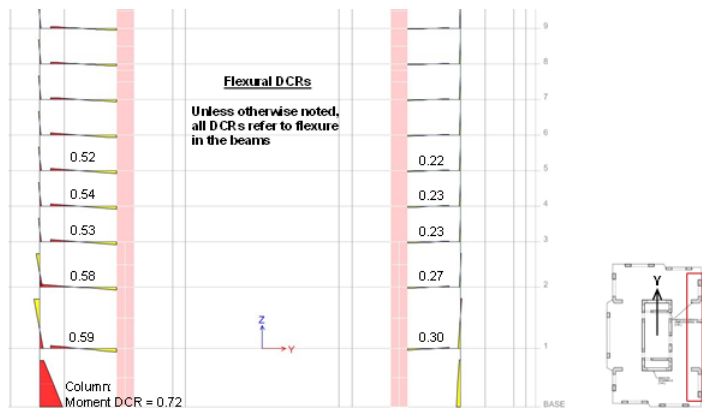
Effect of Settlement



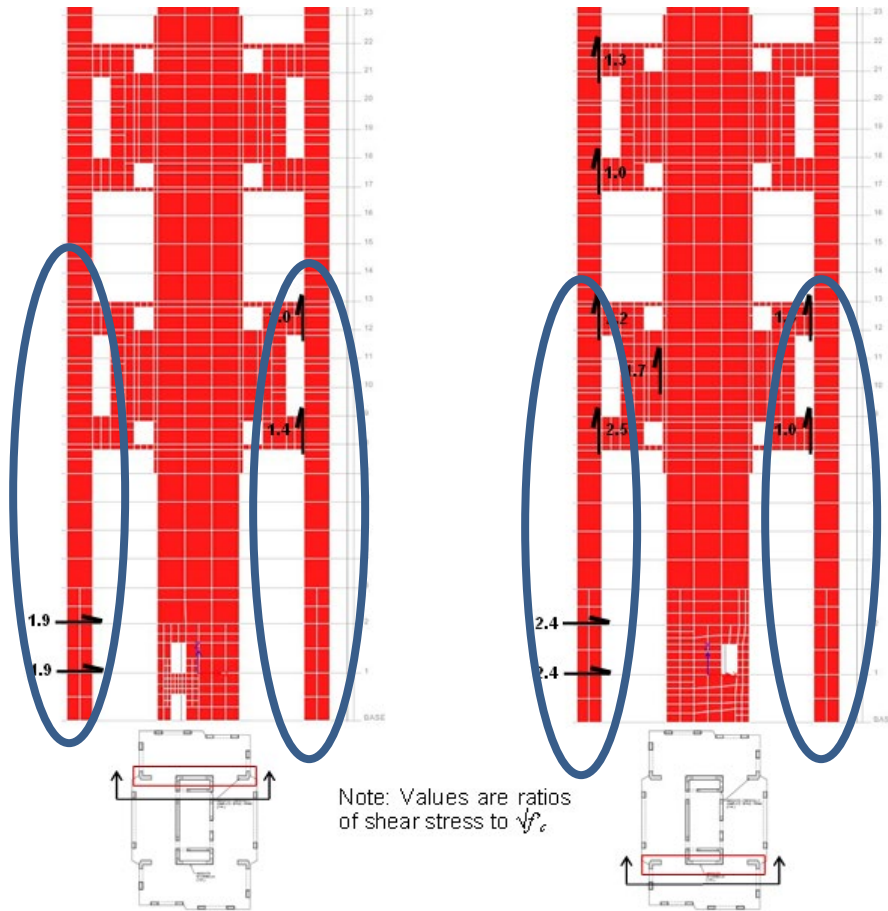
Linear Results (Settlement)– Moment Frames



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

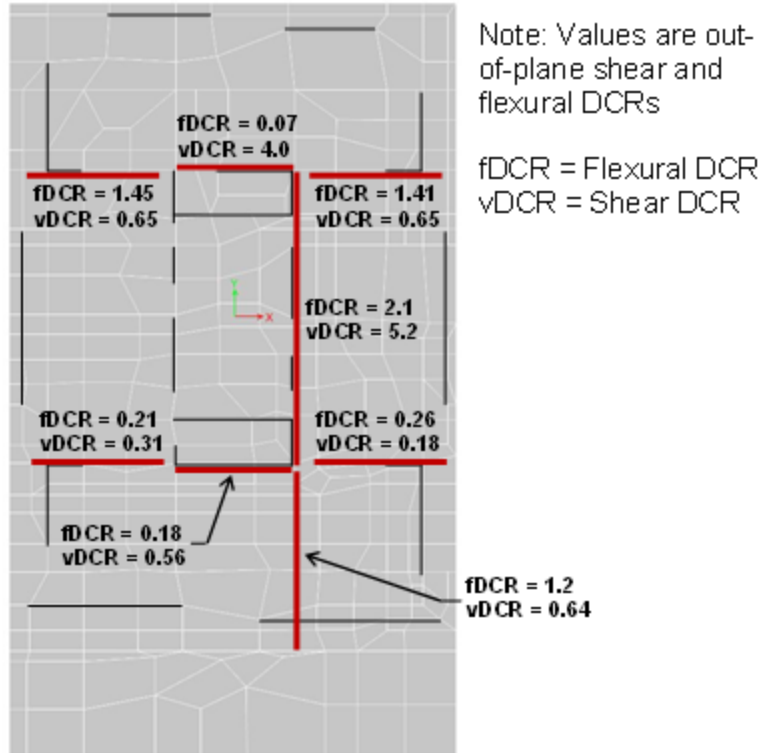


Linear Results (Settlement) Shear Core and Outriggers



- 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

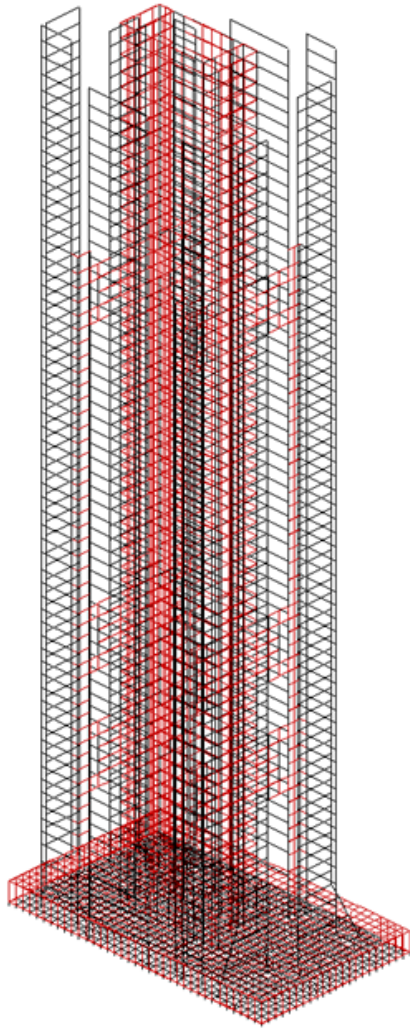


- Flexural DCRs limited, but high shear DCRs along boundary of core
- Conclusion, linear analysis was not predicting the behavior well
- Use Nonlinear Analysis



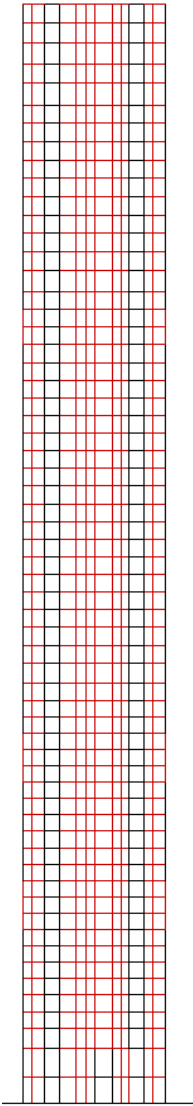
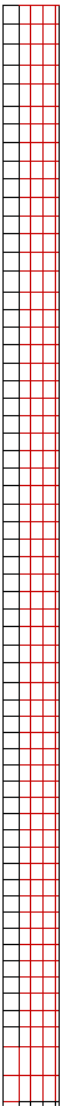
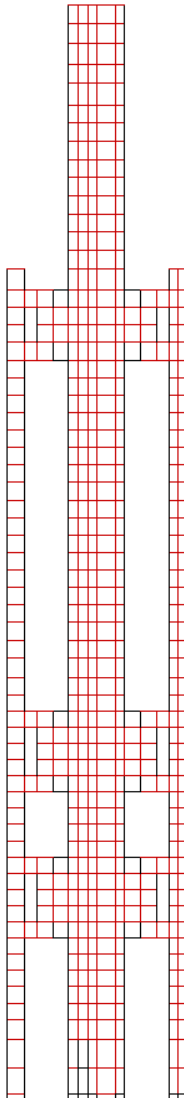
Non-Linear Analyses

Nonlinear Analysis

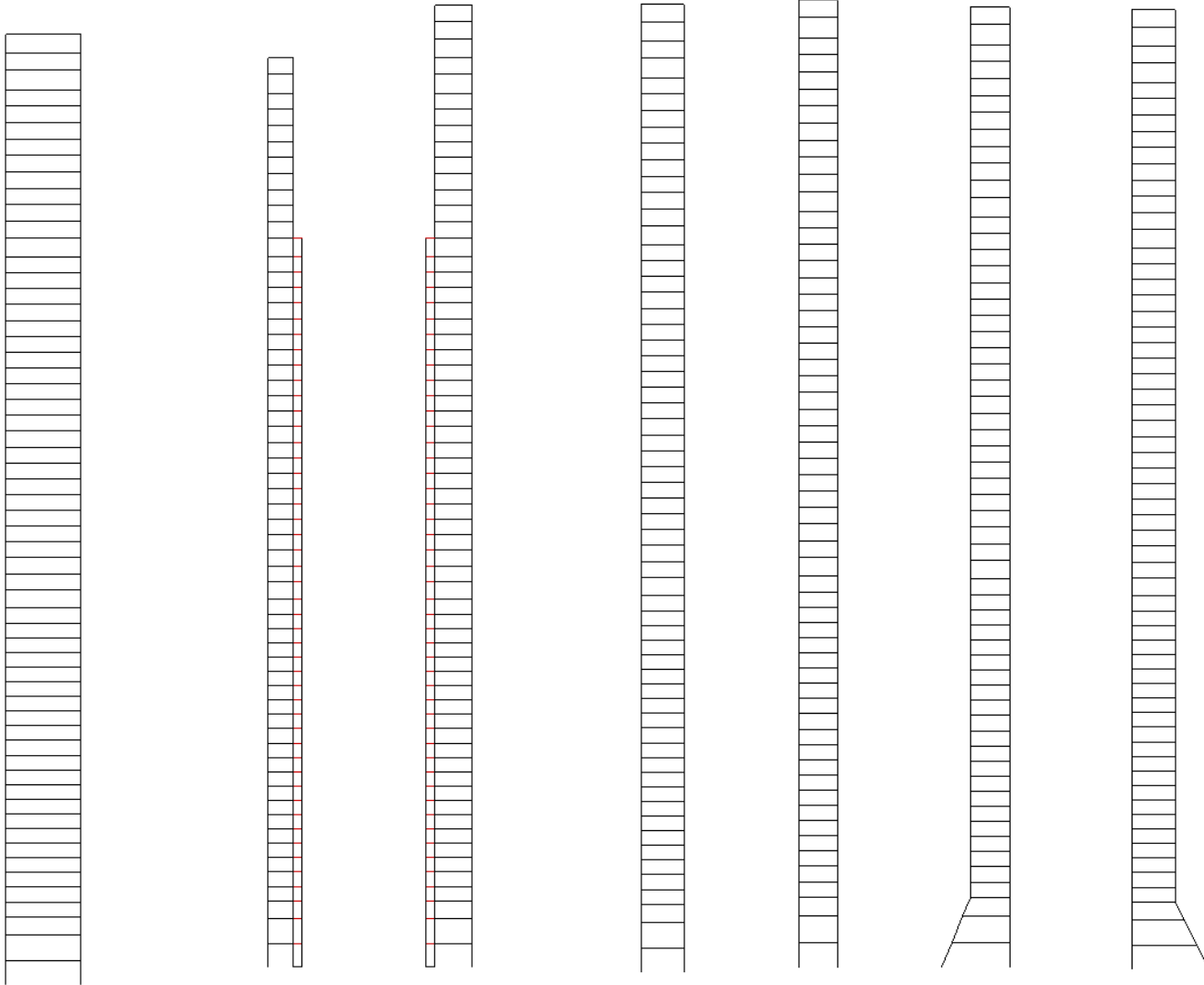


- Perform 3D software
- Frames modeled using nonlinear 2D elements
- Walls and outriggers modeled using fiber elements
- Foundation
 - 2D grid frame nonlinear beam elements
 - Nonlinear springs (piles)

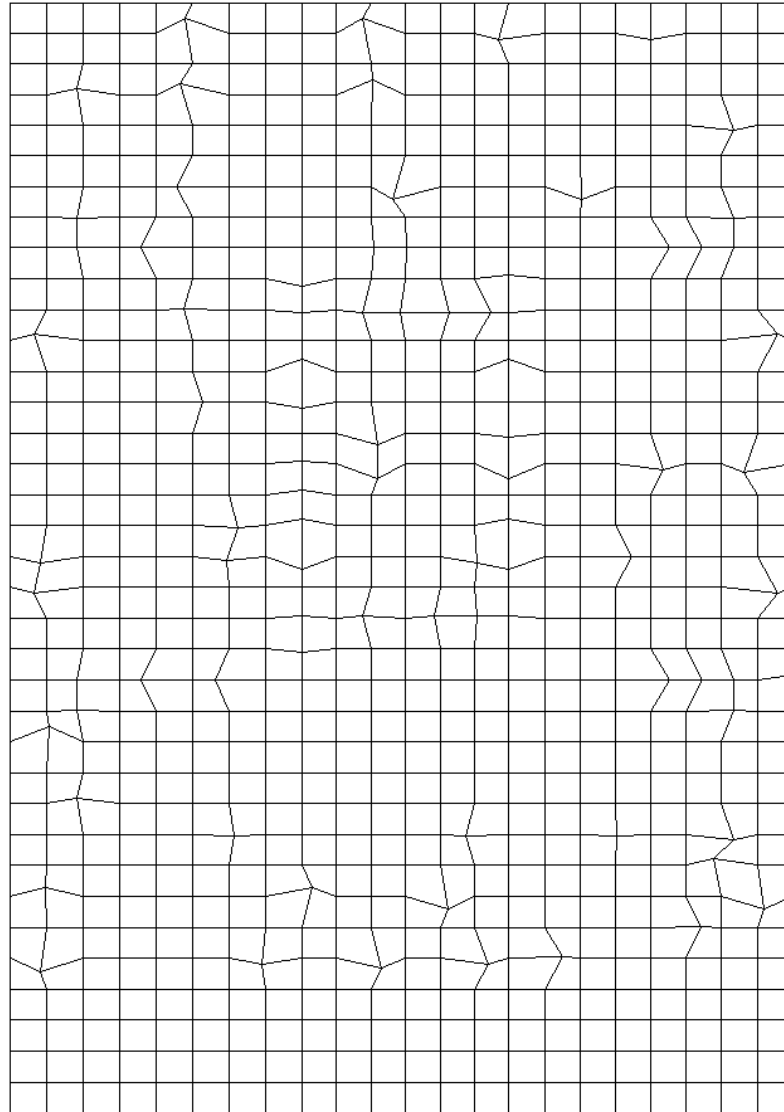
Wall Elements



Frame Elements

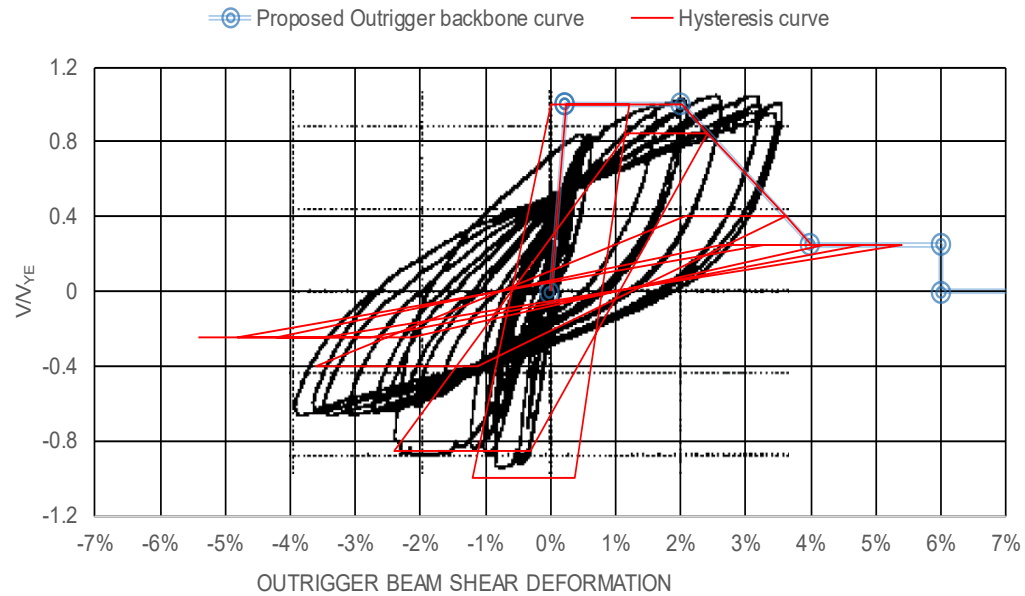
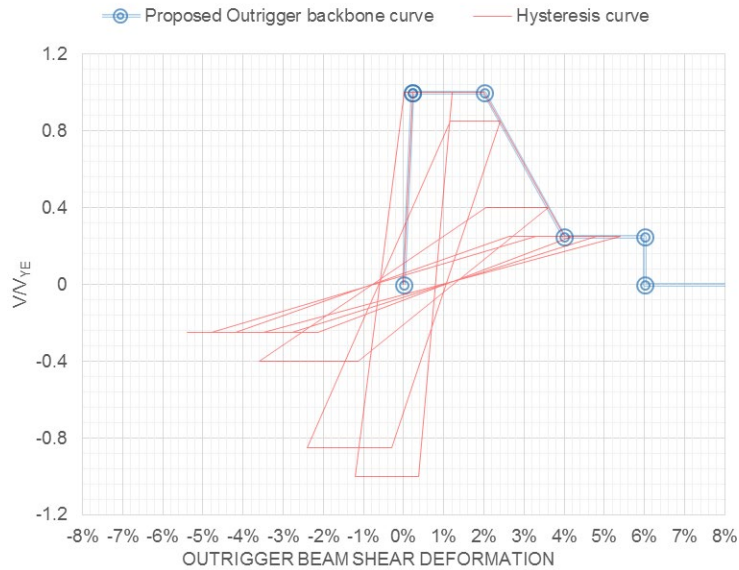


Mat



Nonlinear modeling

Outrigger coupling beams

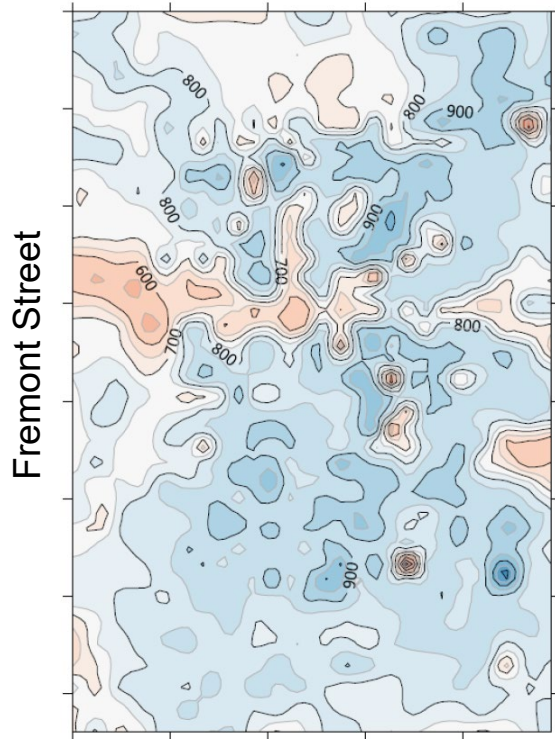


Perform-3d Outrigger coupling beam, $A/R = 0.5$

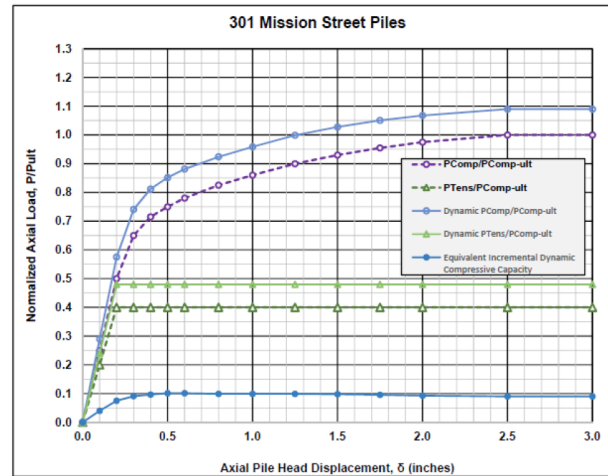
Compared to $A/R = 1.0$ from a 2005 test by Canbolat et. al.

Pile Representation Geotechnical Capacities

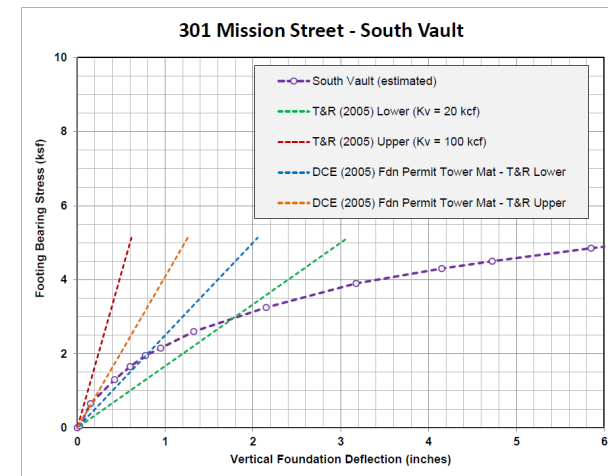
Mission Street



Normalized Pile P-Z

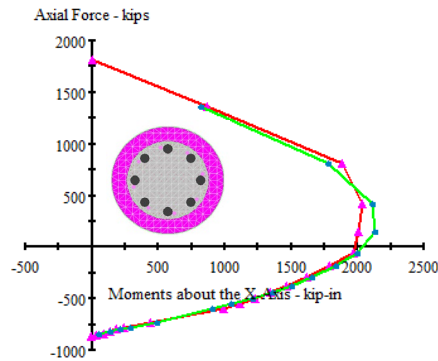
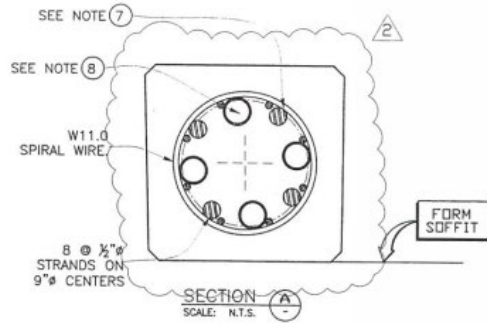


Soil springs at vault



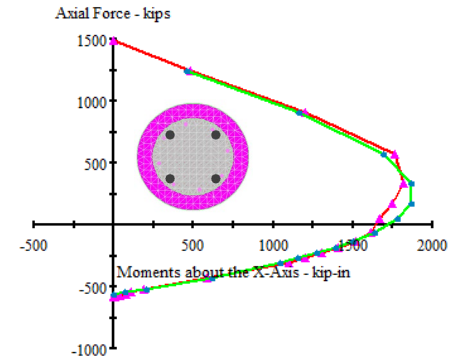
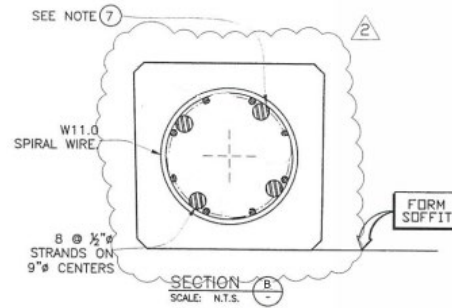
Production Pile—XTRACT

Top of Pile



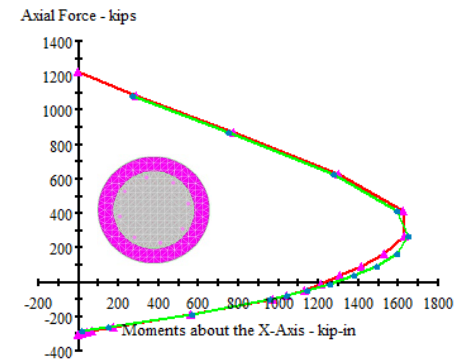
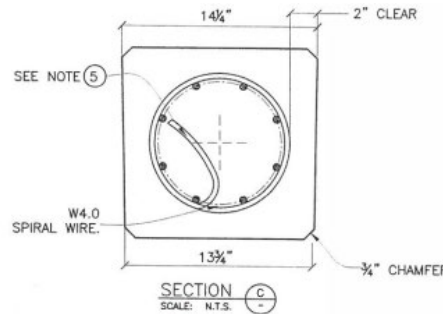
—▲— PM Data
—■— Equation Fit to PM Data

@ 2.5



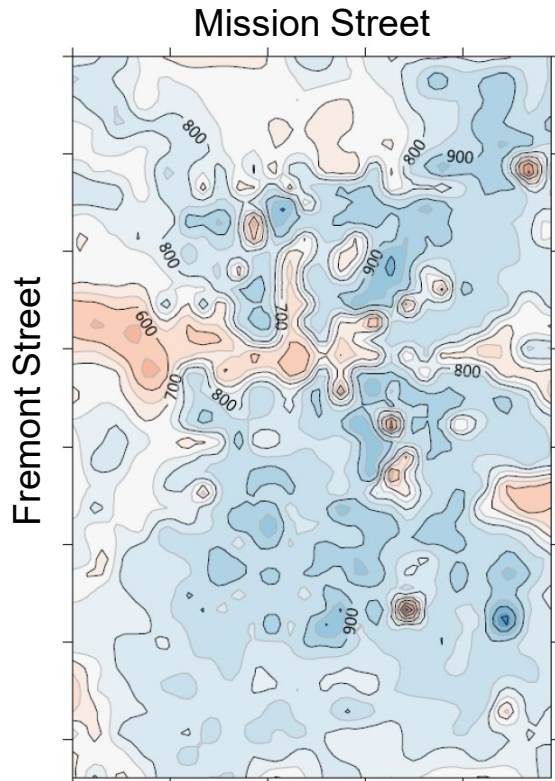
—▲— PM Data
—■— Equation Fit to PM Data

@ 7 ft



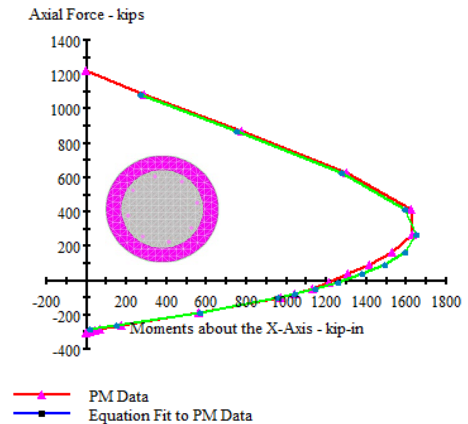
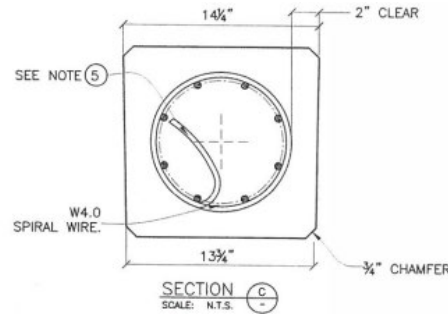
—▲— PM Data
—■— Equation Fit to PM Data

Geotech vs Structural capacity

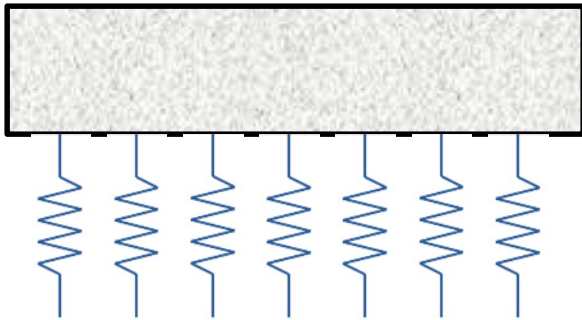


Maximum Geotechnical Compressive Capacity = 1175 kips

Pile Compressive Capacity @ Weakest section = 1227 kips



Simulation of Settlement

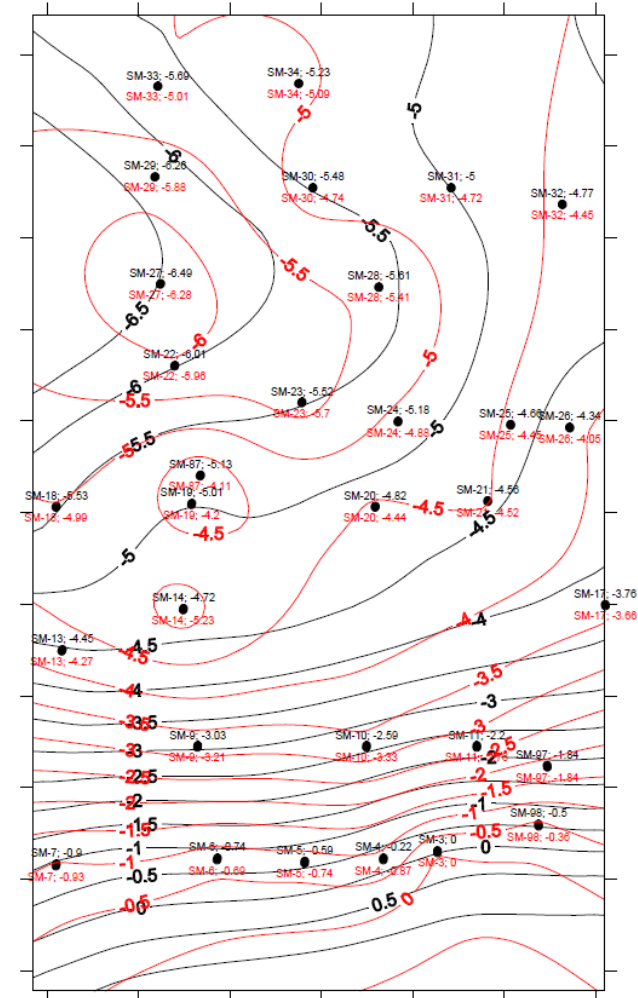


1. Apply compression only springs to mat
2. Apply Gravity Loads
3. Impose negative thermal loading on piles to produce dished shape
4. Iterate to produce desired shape
5. Adjust spring tops flush with the mat and reattach

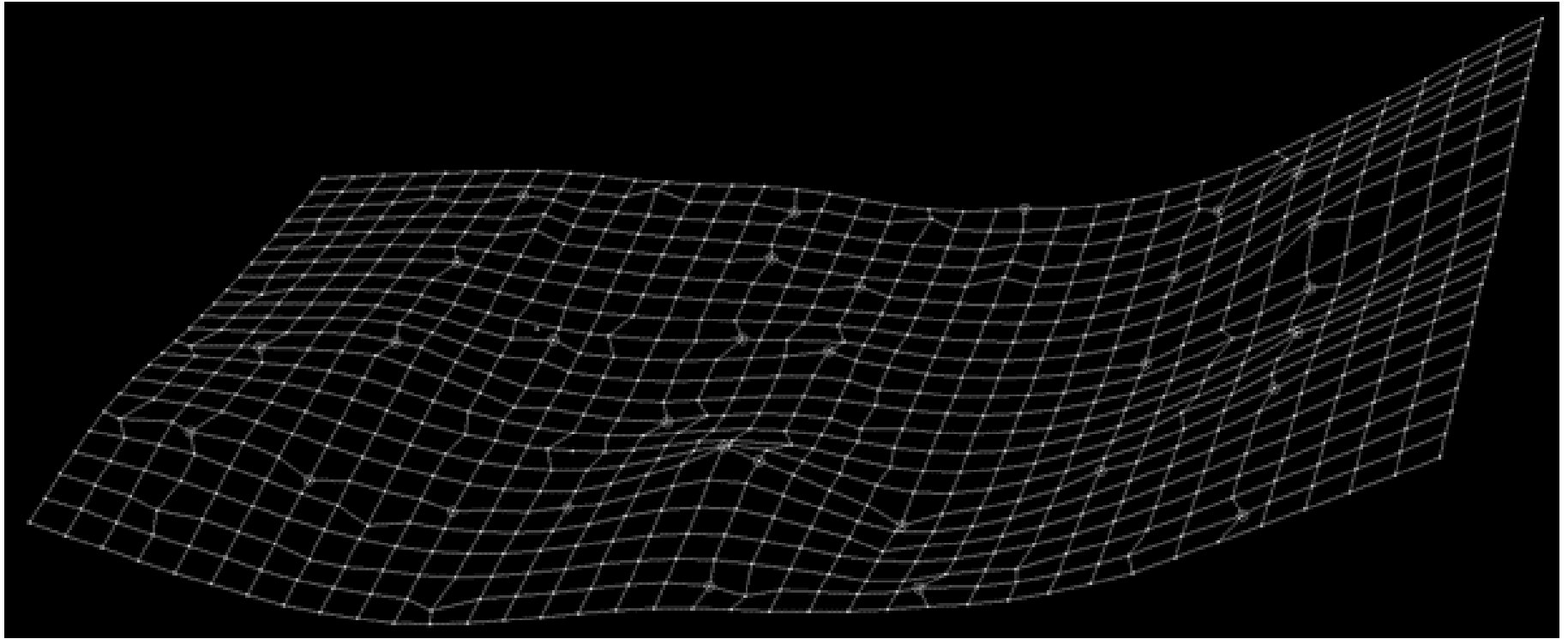
Gravity + Settlement Displacements

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



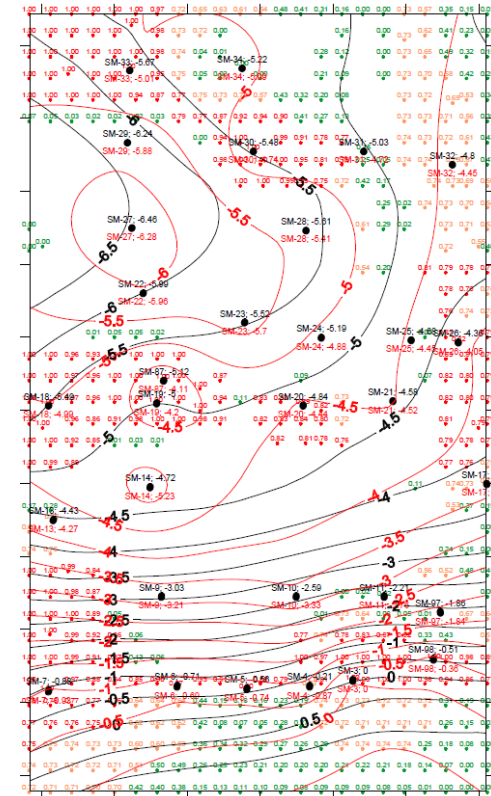
Mat Settlement



Pile Compression—Geotech DCR

Gravity

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



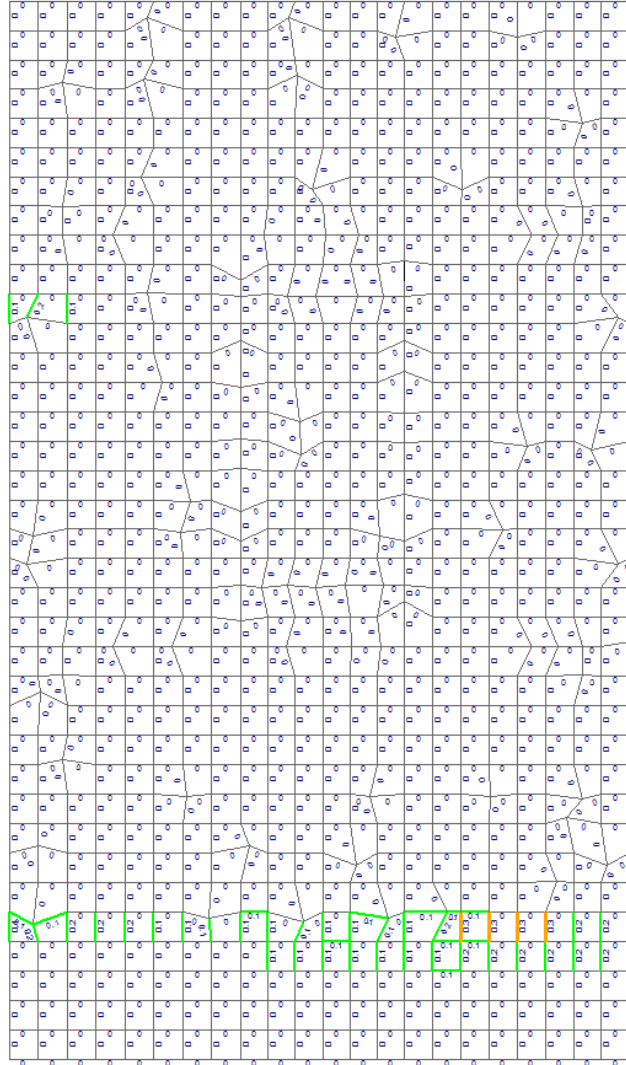
Max = 1.0

May 2017

Mat Grillage Inelastic Rotations

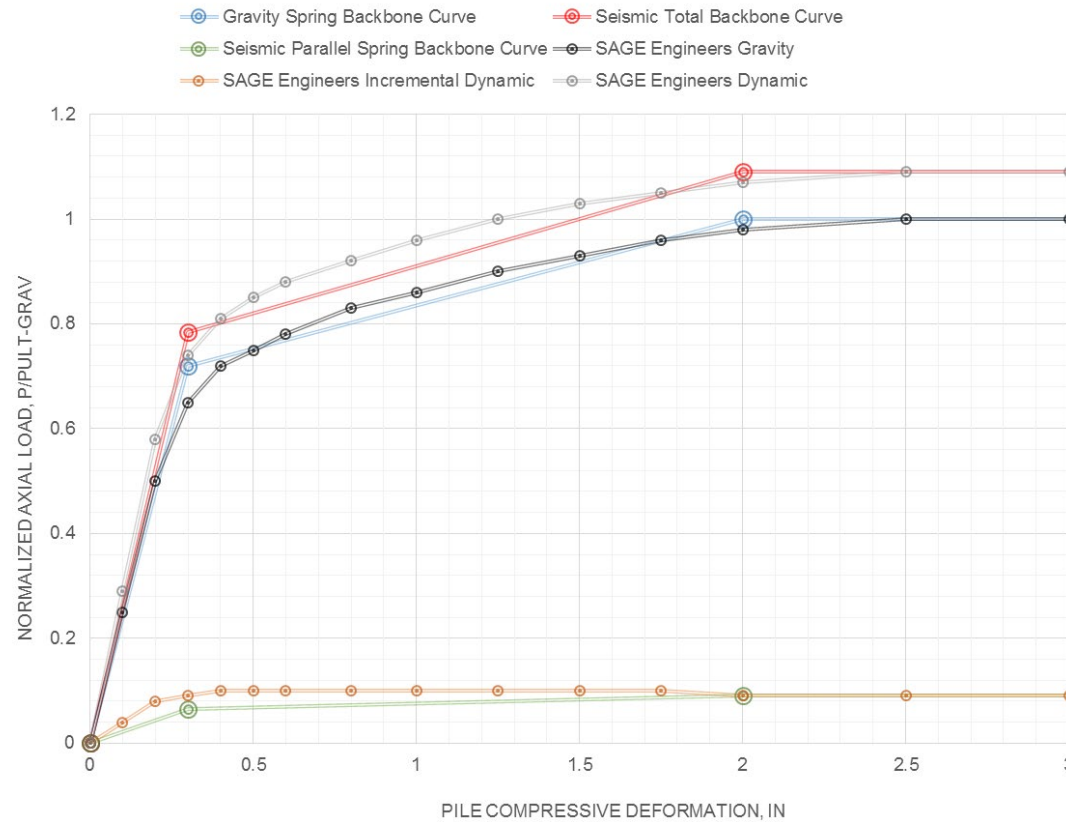
Gravity

- DCR > 0
- DCR > 0.25
- DCR > 0.50



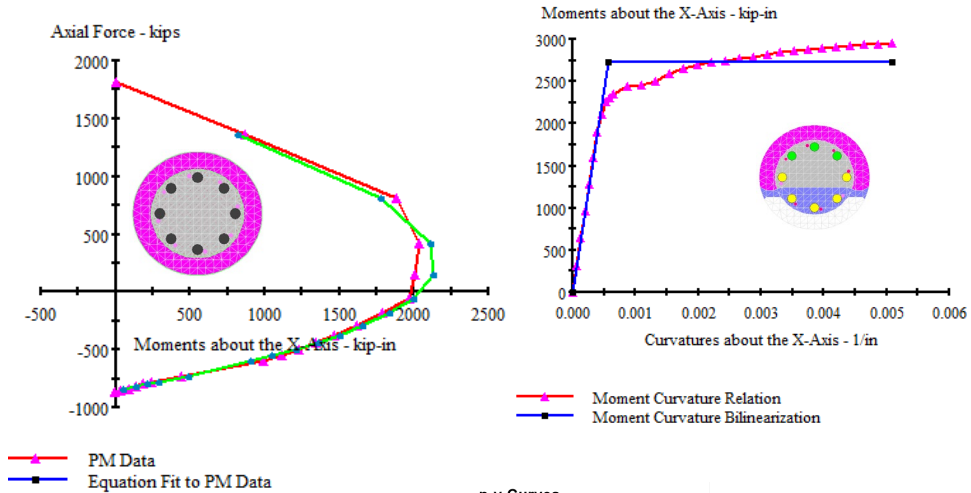
Max = 0.4%

Pile Dynamic Compressive Capacity

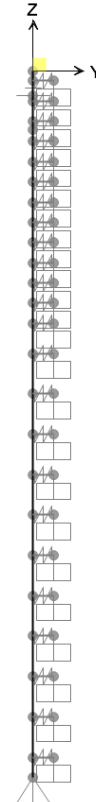
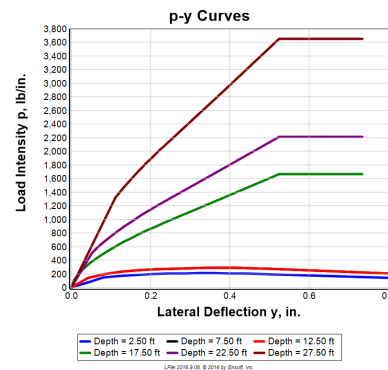


Pile Lateral Response

XTRA
CT

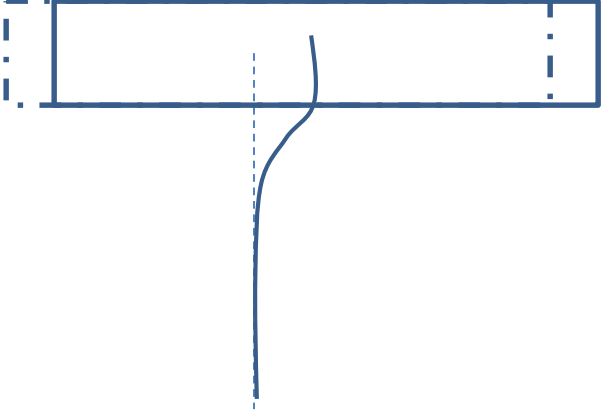
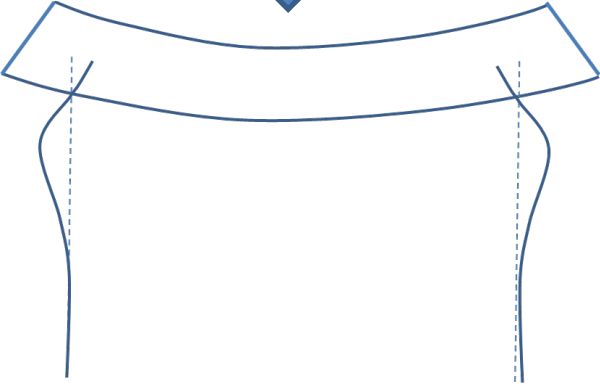


LPile



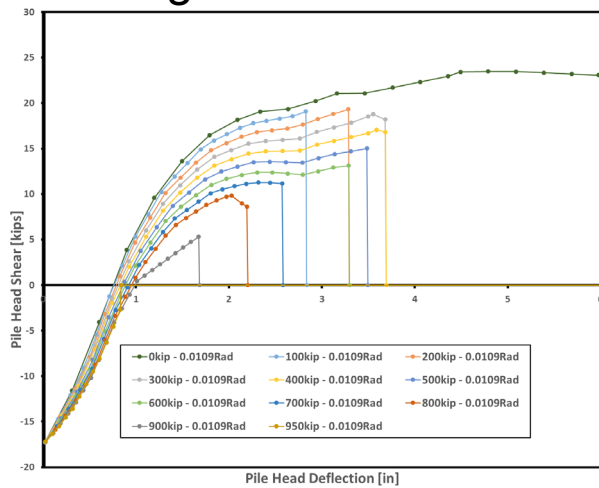
SAP20
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Pushover Conditions

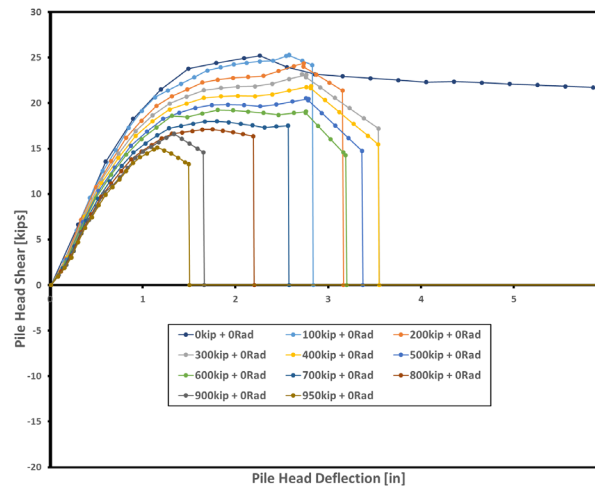


Pushover Analyses

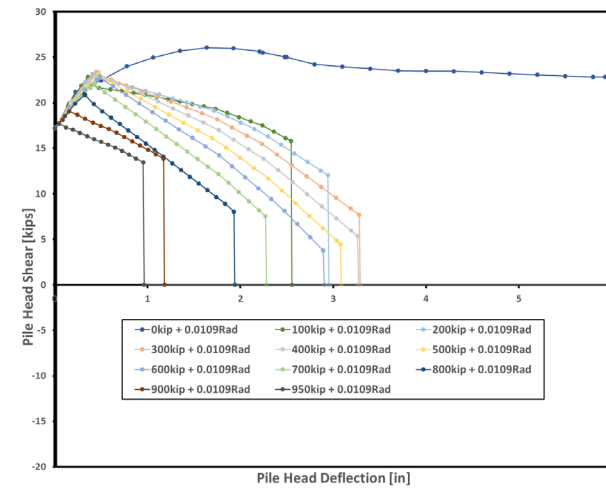
Negative 1% rotation



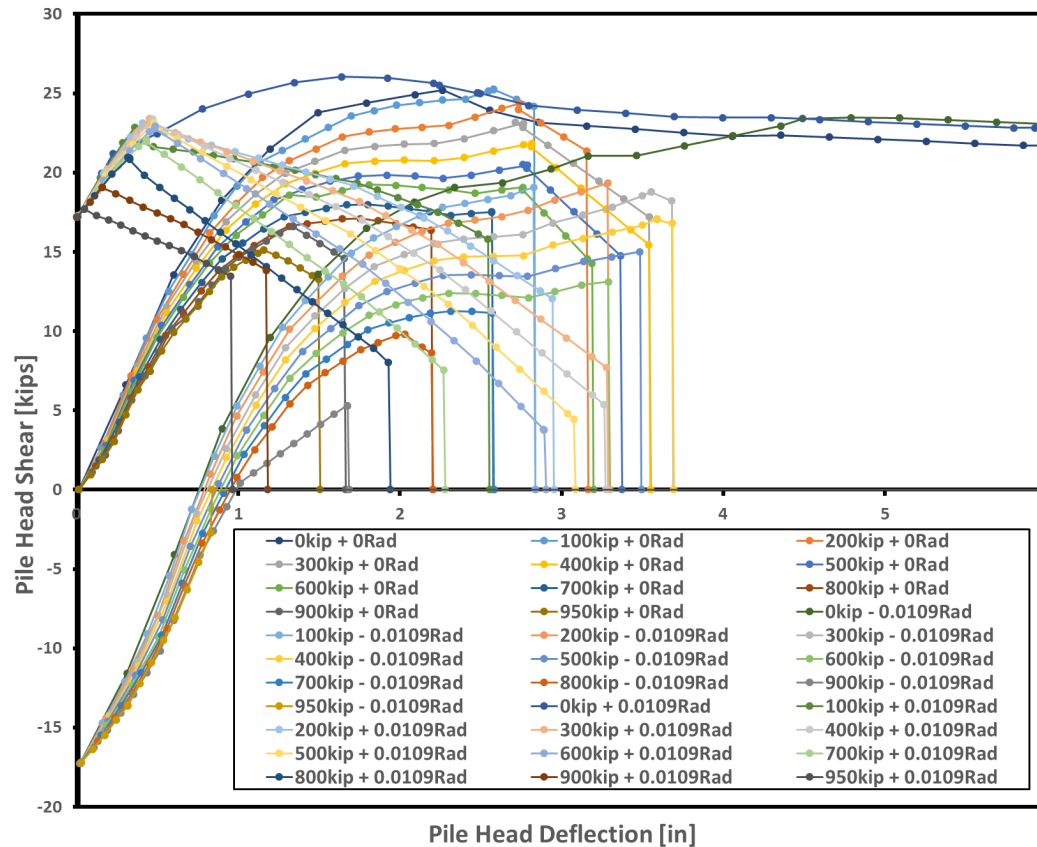
Nil rotation



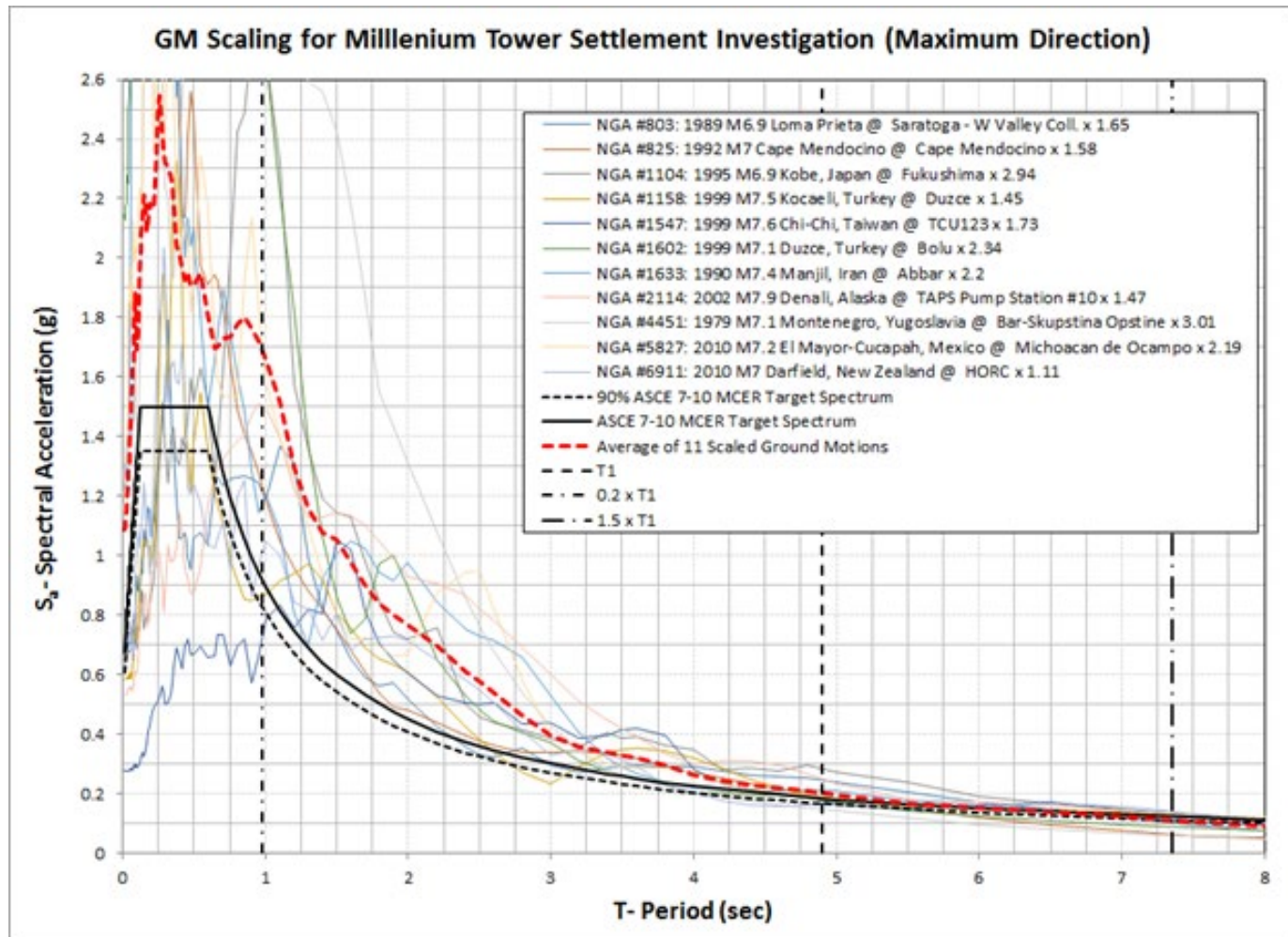
Positive 1% rotation



Pile Pushover Analyses



Ground Motions





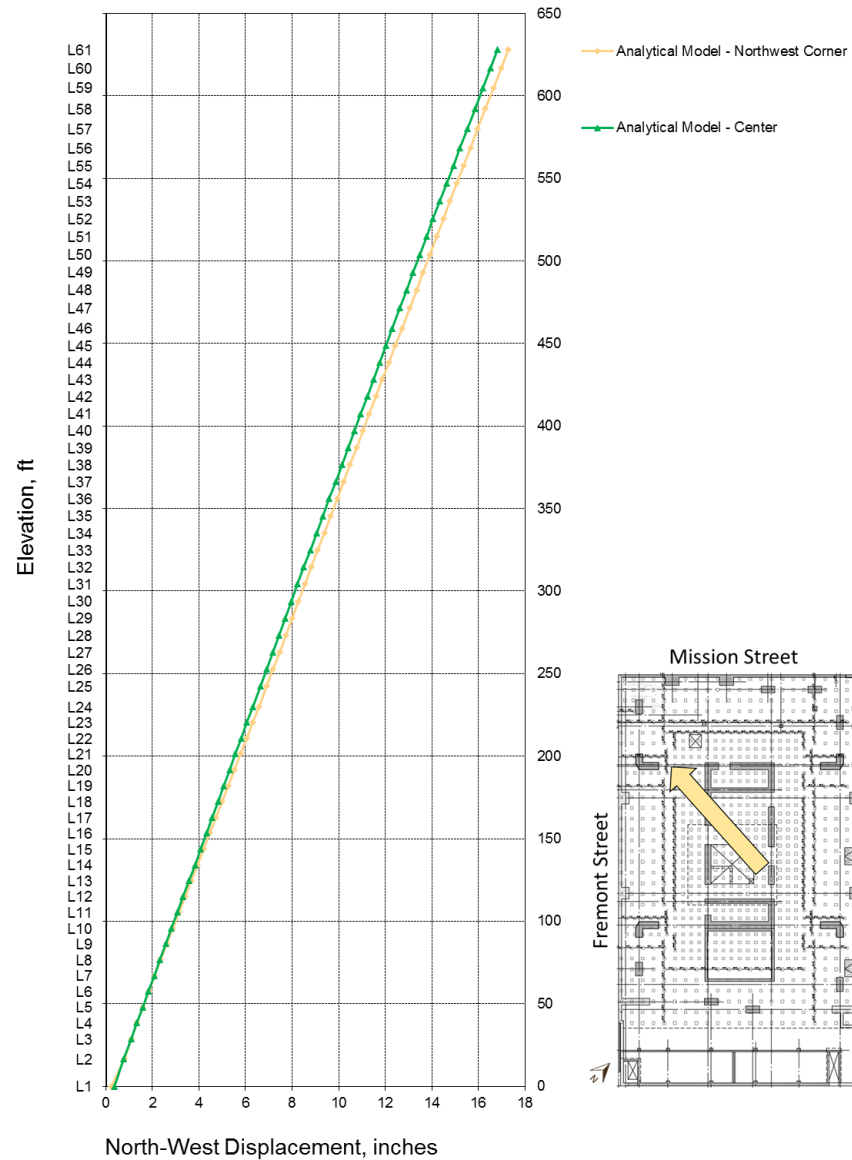
Results

Acceptance Evaluation



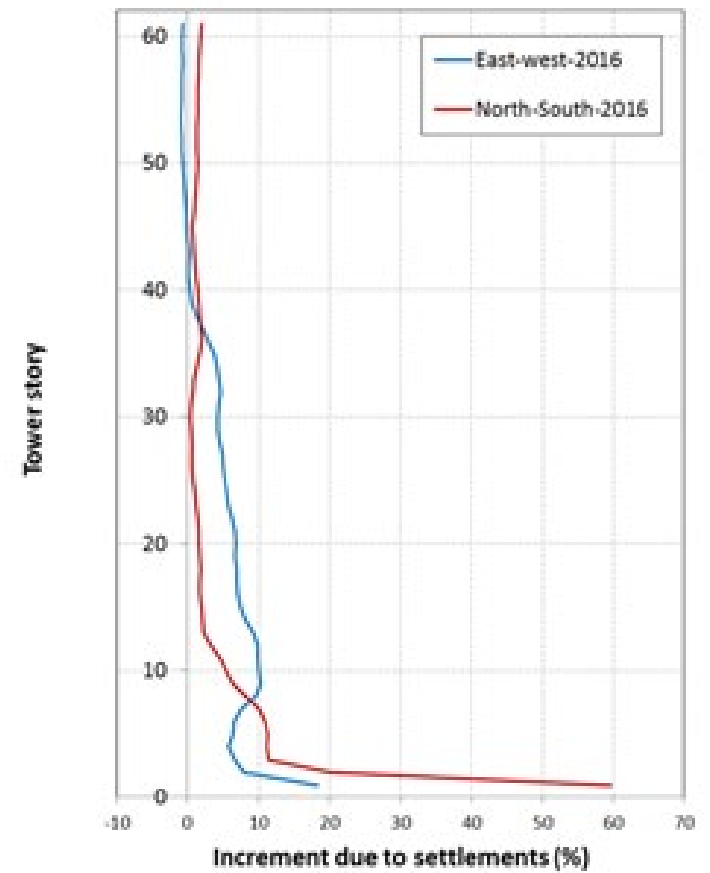
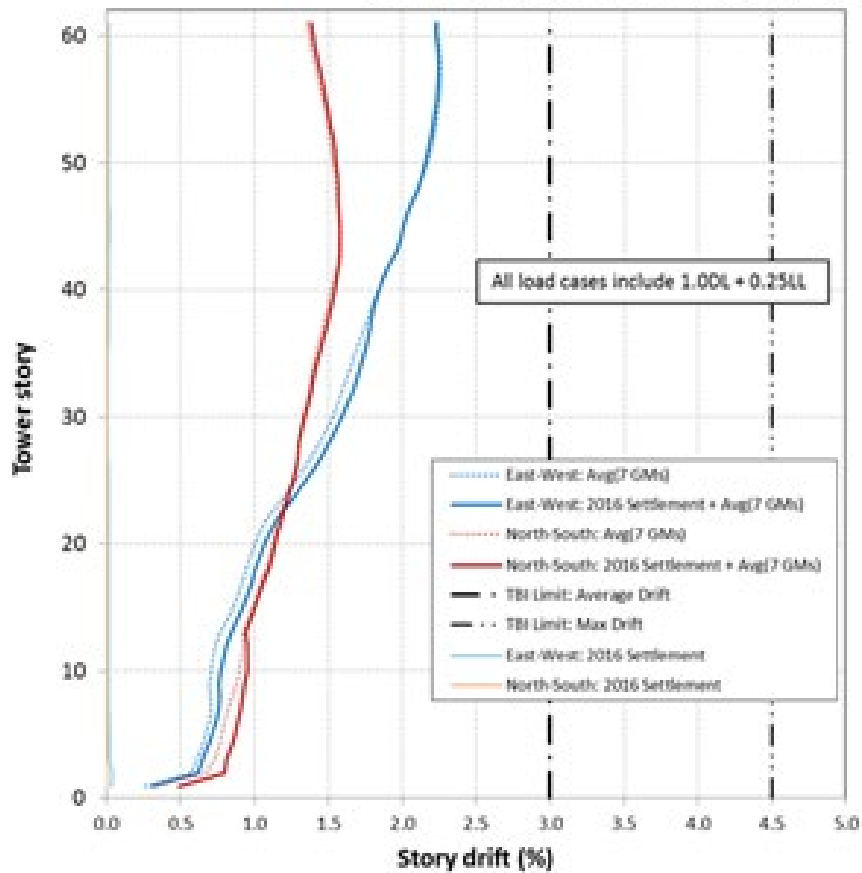
- **Acceptance evaluation used PEER TBI - Tall Building Guidelines**
 - Performance-based design procedure
 - Global performance
 - Residual and permanent drift
 - Unacceptable response limited
 - Element Performance
 - Response does not exceed valid range of modeling
 - Force-controlled elements provide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

Building Tilt - Gravity + Settlement



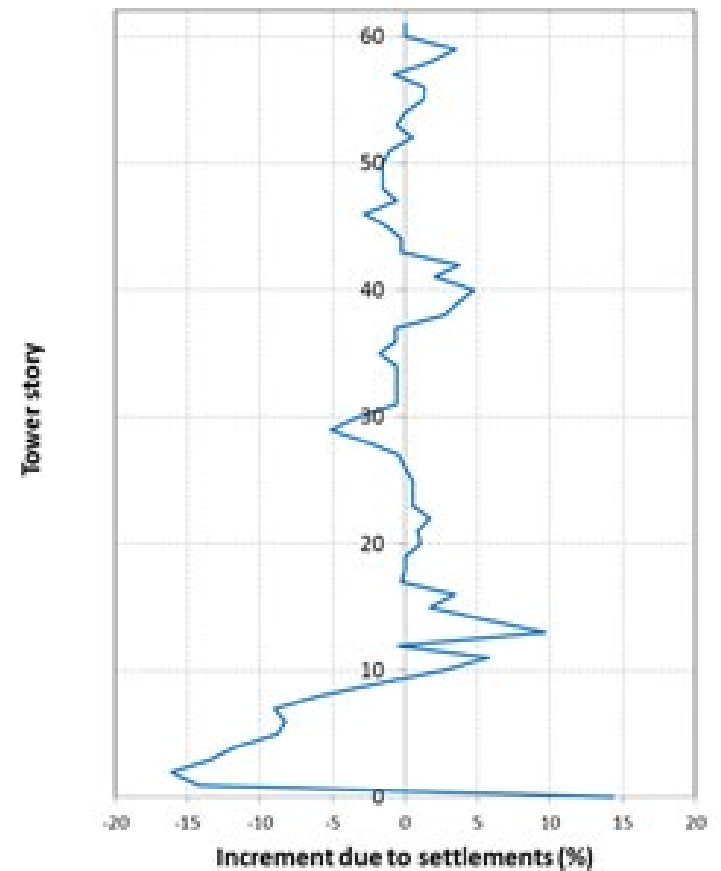
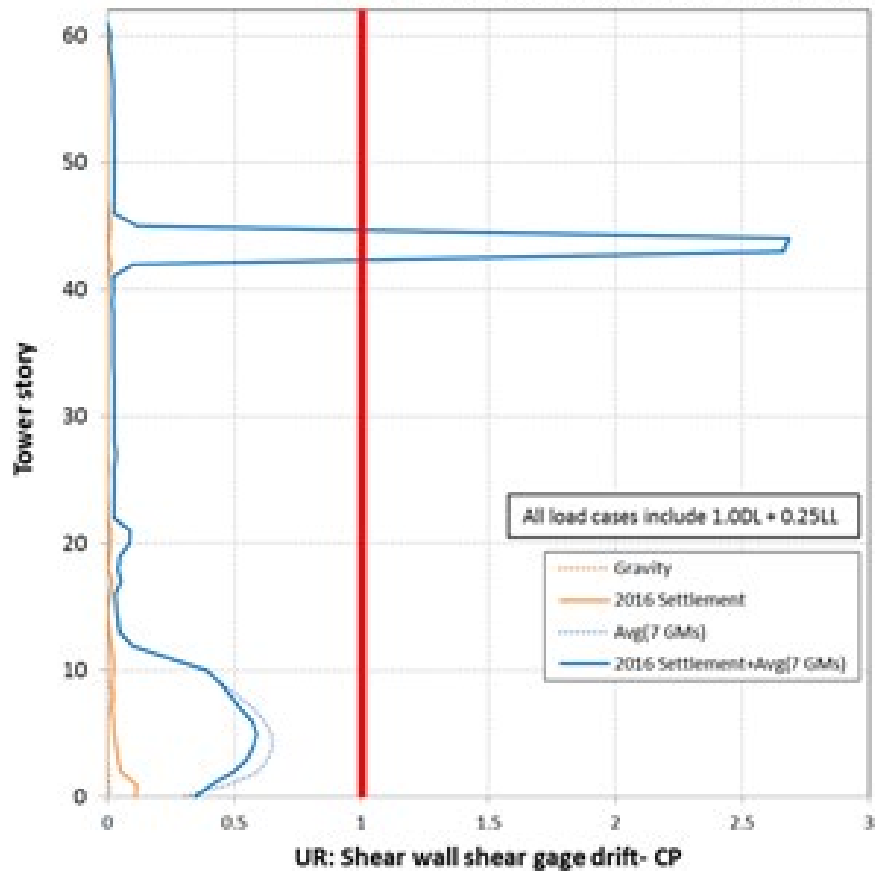
Story Drift – Gravity + Settlement + Seismic

Interstory Drift Ratios- Average Results



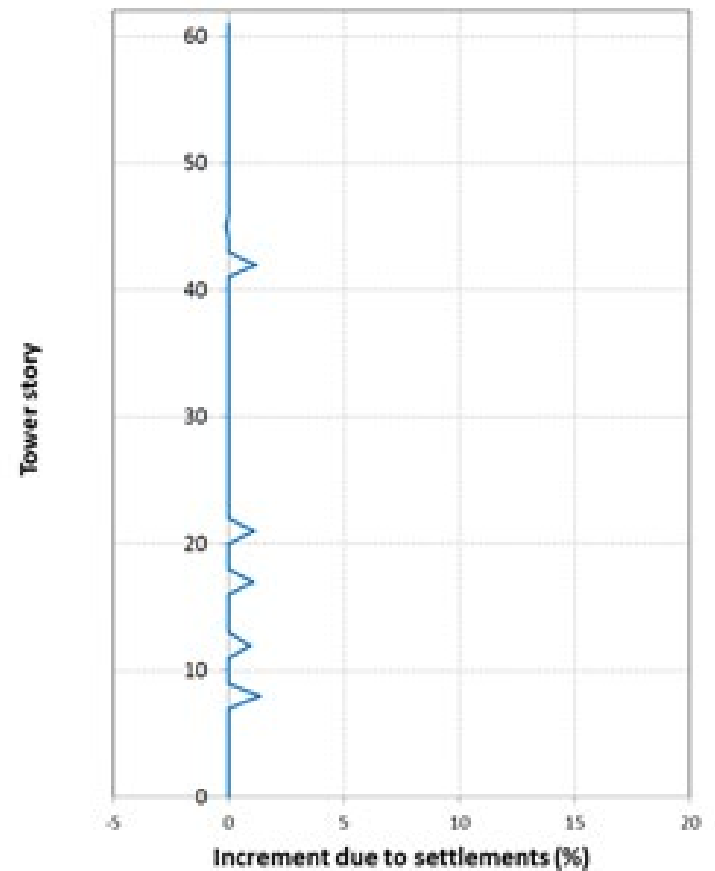
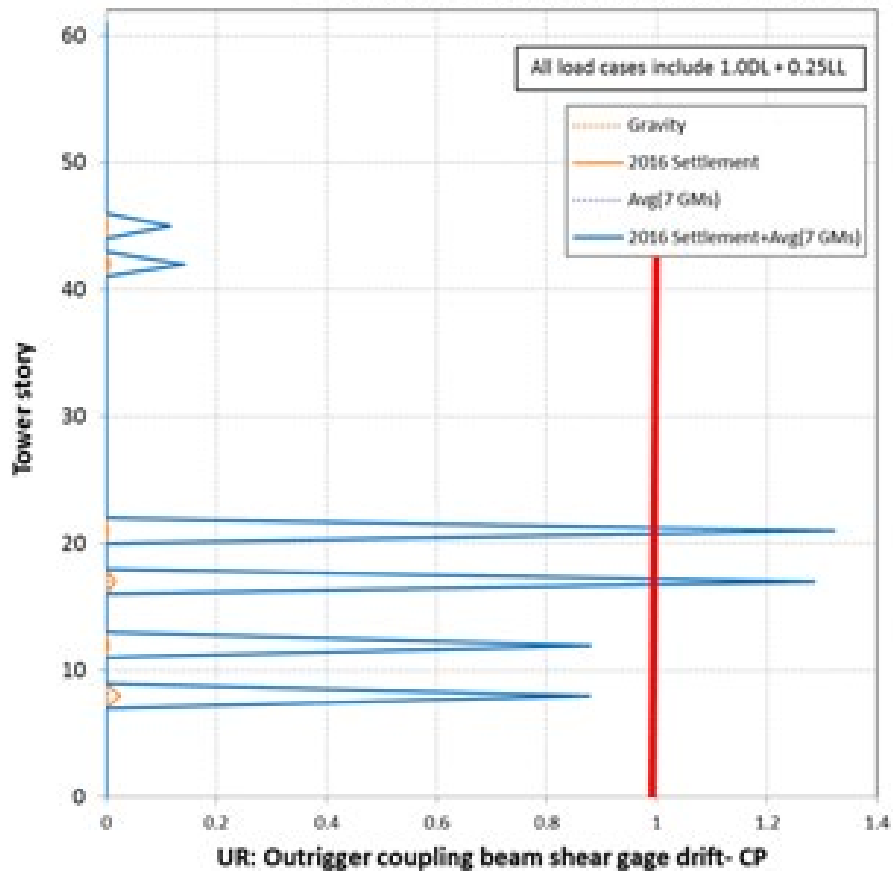
Shear Wall Shear Drift

Shear wall shear gage drift - Average Results



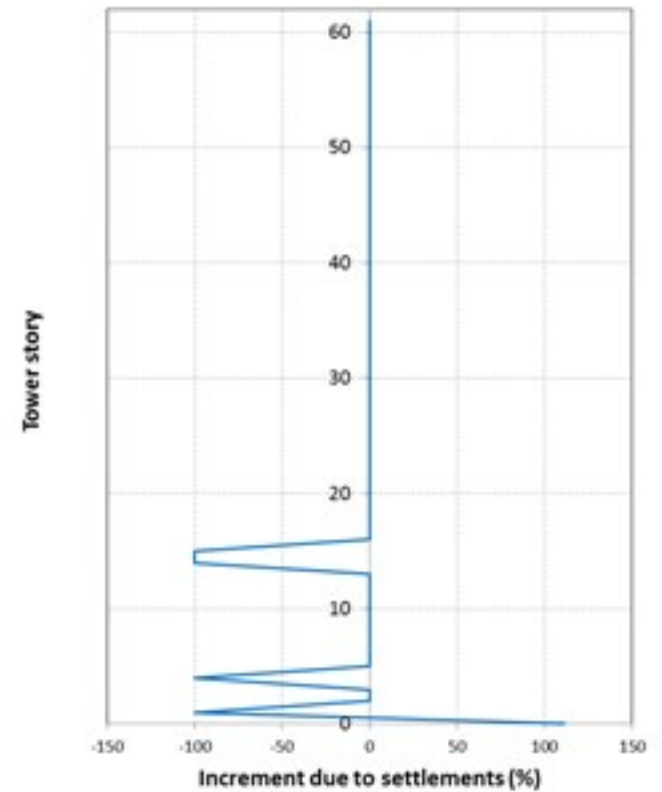
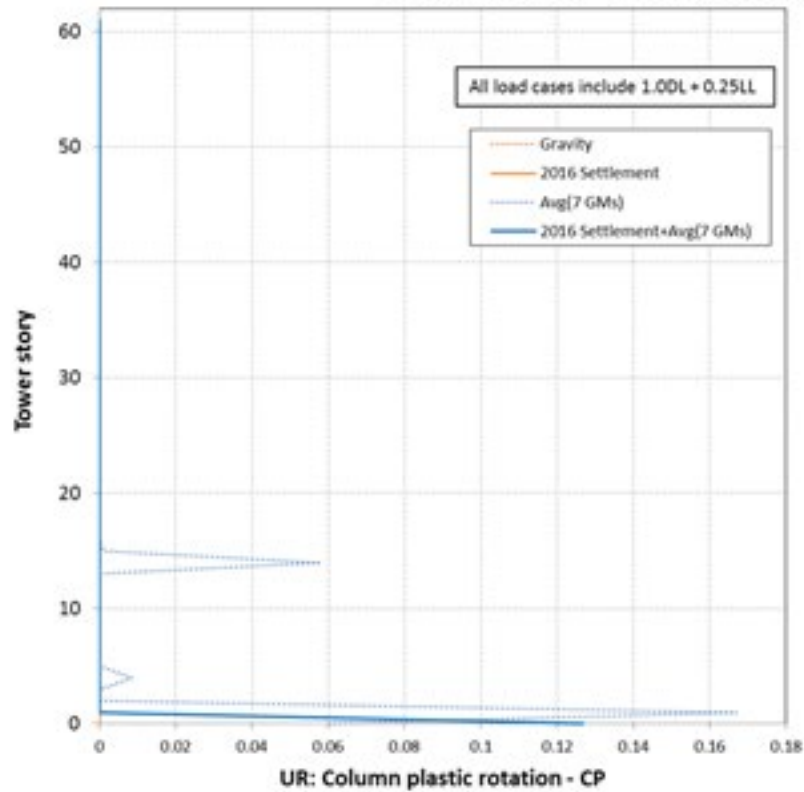
Outrigger Coupling Beams

Outrigger Coupling beam drift - Average Results

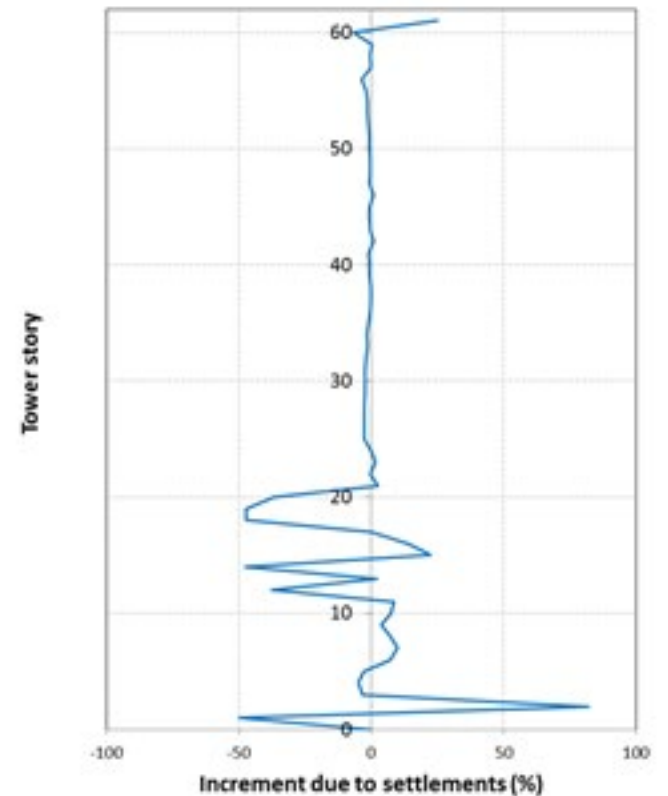
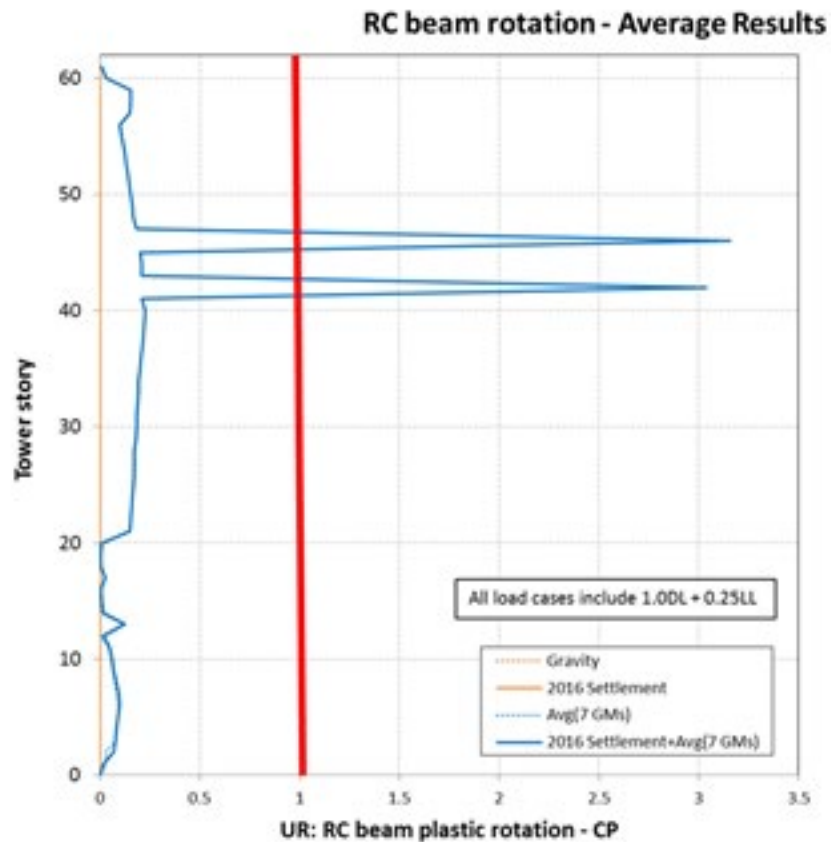


Column Plastic Rotation

Column rotation - Average Results



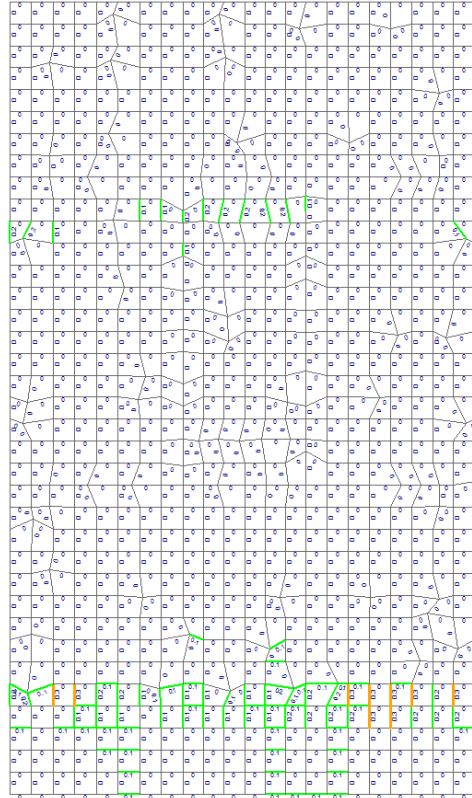
Frame Beam Plastic Rotation



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**

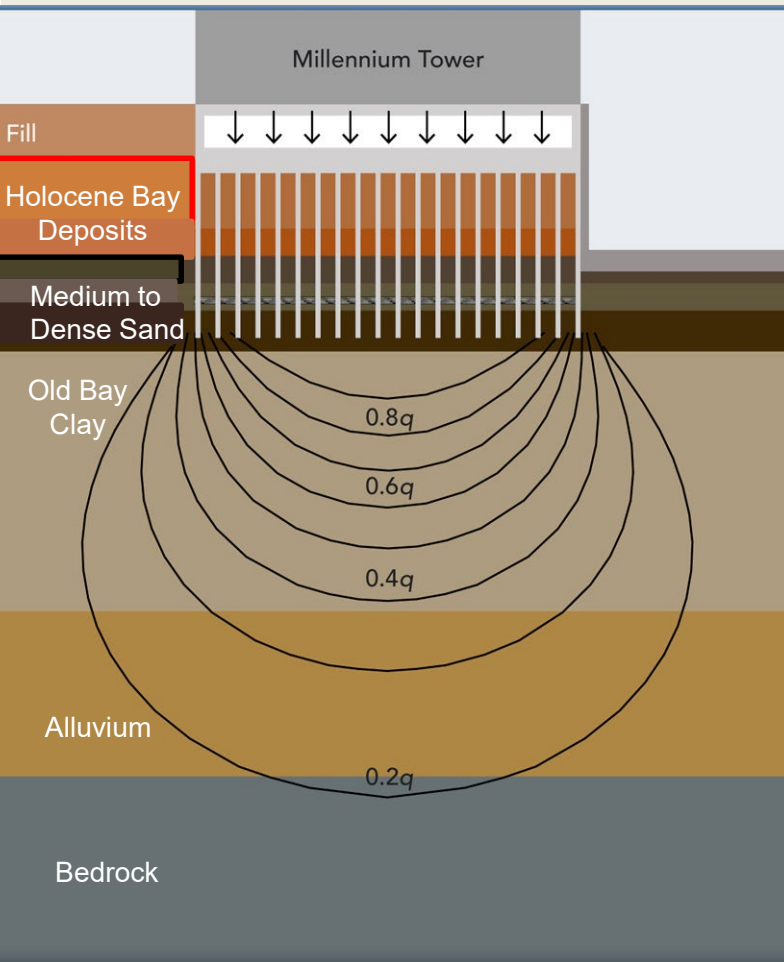


Perimeter Pile Upgrade

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

CITY AND COUNTY OF
SAN FRANCISCO

EXISTING BUILDING CODE
2016 Edition

[Includes legislation adopted by the Board of Supervisors
through December 31, 2016]



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DESIGN METHOD

Structural elements carrying lateral loads shall be designed in accordance with Section 1609 or 1613 of the Code, or where the alteration results in a frequency as defined in ASCE 7, or increases the capacity of any existing structural element, the structure or structure shall be shown to meet the provisions of Section 1609 or 1613 of the California Building Code.

Design Category E. Where the purpose of the alteration requires the alteration of the aggregate area of the building, the building shall be assigned to Seismic Design Category E. For purposes of earthquake design provisions Building Code, the purpose of earthquake loads need not be taken into account for those provided in Section 1609 of the California Building Code for new buildings, pre-emptive and location. New seismic connections required by this section shall comply with the provisions of this code for similar structure, purpose and

or unreinforced masonry parapets. The intended alteration requires a type of roof removal or replacement of the roof area of a building. Category D, E or F that has unreinforced masonry, the work shall be designed to resist out-of-plane seismic forces, unless an evaluation demonstrates compliance of such terms. For purposes of this section, design seismic forces need not be taken greater than 75 percent of those that would be required for the design of similar nonstructural components in new buildings of similar purpose and location.

[BS] 403.6 Wall anchorage for unreinforced masonry walls in major alterations. Where the purpose of the building undergoing the intended alteration exceeds 50 percent of the aggregate area of the building, the building is assigned to Seismic Design Category C, D, E or F, and the building's structural system includes unreinforced masonry walls, the

alteration work shall include installation of wall anchors at the roof line to resist seismic forces, unless an evaluation demonstrates compliance of existing wall anchorage. For purposes of this section, design seismic forces need not be taken greater than 75 percent of those that would be required for the design of new buildings of similar structure, purpose and location.

[BS] 403.7 Bracing for unreinforced masonry parapets in major alterations. Where the purpose of the building undergoing the intended alteration exceeds 50 percent of the aggregate area of the building, and where the building is assigned to Seismic Design Category C, D, E or F, parapets constructed of unreinforced masonry shall have bracing installed as needed to resist out-of-plane seismic forces, unless an evaluation demonstrates compliance of such terms. For purposes of this section, design seismic forces need not be taken greater than 75 percent of those that would be required for the design of similar nonstructural components in new buildings of similar purpose and location.

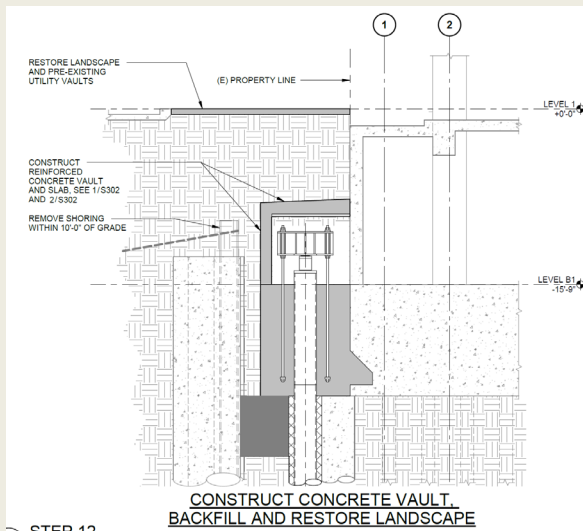
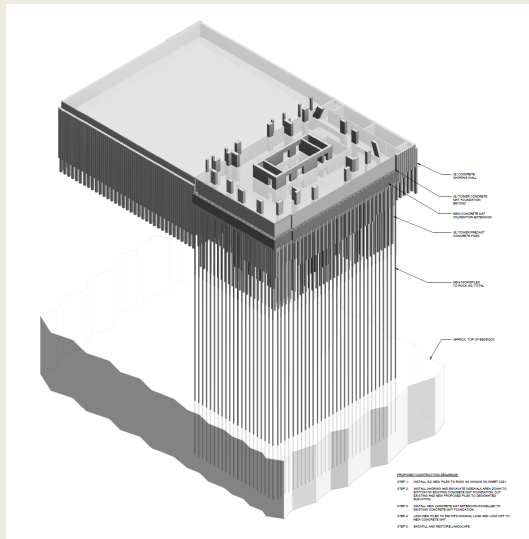
[BS] 403.8 Roof diaphragms retaining wind loads in high-rise regions. Where the intended alteration requires a permit for reroofing and involves removal of roofing materials from more than 50 percent of the roof diaphragm of a building or section of a building located where the ultimate design wind speed is greater than 115 mph (CS) in accordance with Figure 1609.3(1) of the California Building Code or in a special wind region as defined in Section 1609 of the California Building Code, roof diaphragms, connections of the roof diaphragms to roof framing members, and roof-to-wall connections shall be evaluated for the wind loads specified in Section 1609 of the California Building Code, including wind uplift. If the diaphragms and connections in their current condition are not capable of resisting at least 75 percent of those wind loads, they shall be replaced or strengthened in accordance with the provisions of Section 1609 of the California Building Code.

[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.

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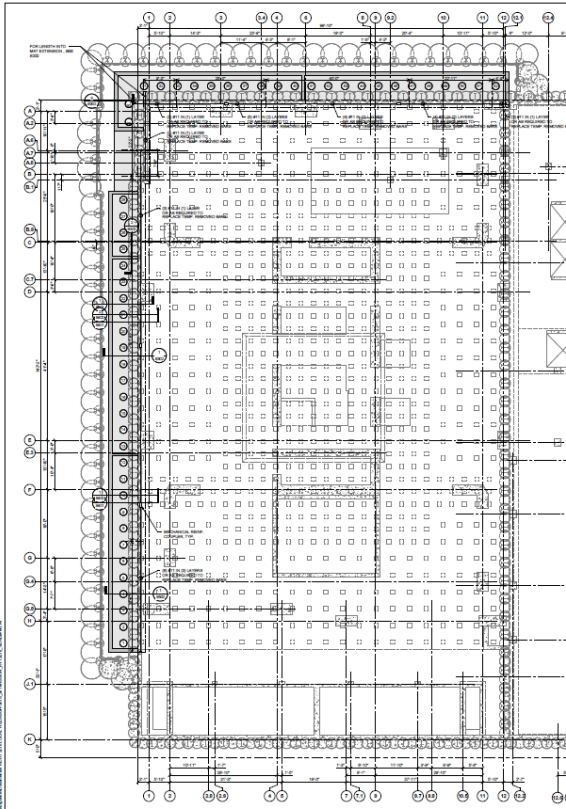
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2. New structural elements are detailed as required for new construction.
3. New or relocated nonstructural elements are detailed and connected to existing or new structural elements as required for new construction.
4. The alterations do not create 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

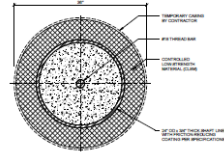
Retrofit Piles



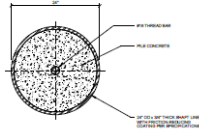
36 inch
through
Colma sands

24 inch to
Franciscan

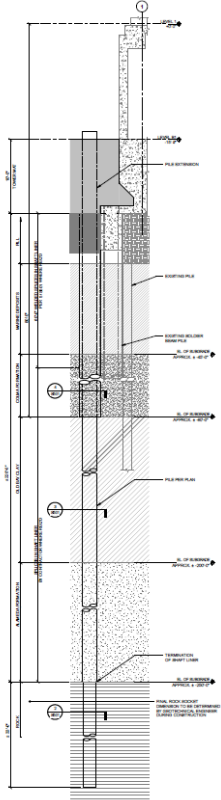
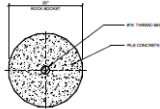
20 inch in
Franciscan



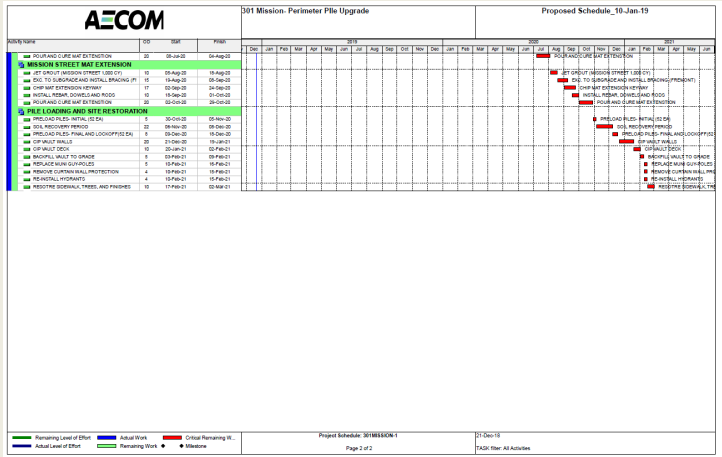
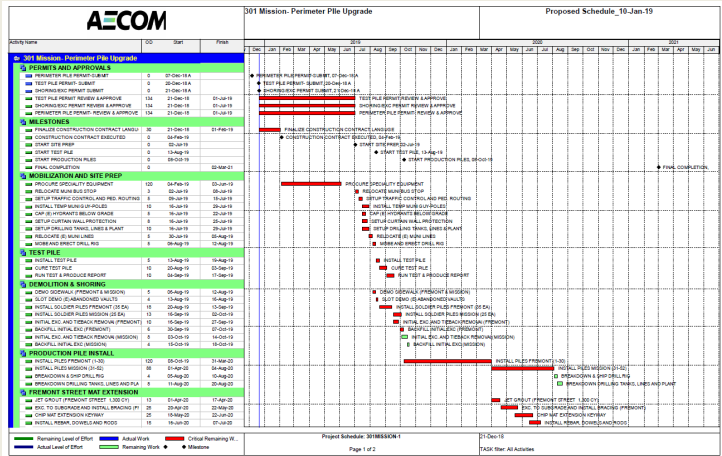
① PILE SECTION - AT TEMPORARY CLSM



② PILE SECTION - TYPICAL



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?