

# Foundation Performance of Millennium Tower in San Francisco, CA

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*UCLA Samueli Engineering*

# Acknowledgements

- Support from Mission Street Development during legal proceedings;  
*my engagement ended in early 2020*
- Slate Team: Nathaniel Wagner, Debra Murphy, many others
- Shannon & Wilson Team: Jeremy Butkovich, Hamid Nouri, others
- Ron Hamburger, SGH

# Outline

- Millennium Tower: why it matters
- Site conditions
- MT structure and construction timelines
- Foundation movement mechanisms
- Foundation performance
- Simulations
- Status
- Lessons learned







Constructed 2005-2009

*Courtesy: RO Hamburger*

58 stories, 197 m (645 ft) 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 M

Construction Cost - \$600 M Cumulative Sales - \$750 M

# *What happened?*

## 2005: Groundbreaking

- Predicted settlement 10-15 cm

## 2009: Tower & Podium construction completed

- Predicted settlement was exceeded in March 2008
- Settlement reached ~18 cm by early 2009
- Settlement estimates updated as part of permitting process

## 2010: Construction begins adjacent to Millennium Tower

## 2013: Last unit sold

- Settlement 28 cm

## 2016: Legal proceedings initiated

- Settlement 35 cm

## 2018: Adjacent construction ends

- Settlement 40 cm

*Rendering courtesy: RO Hamburger*

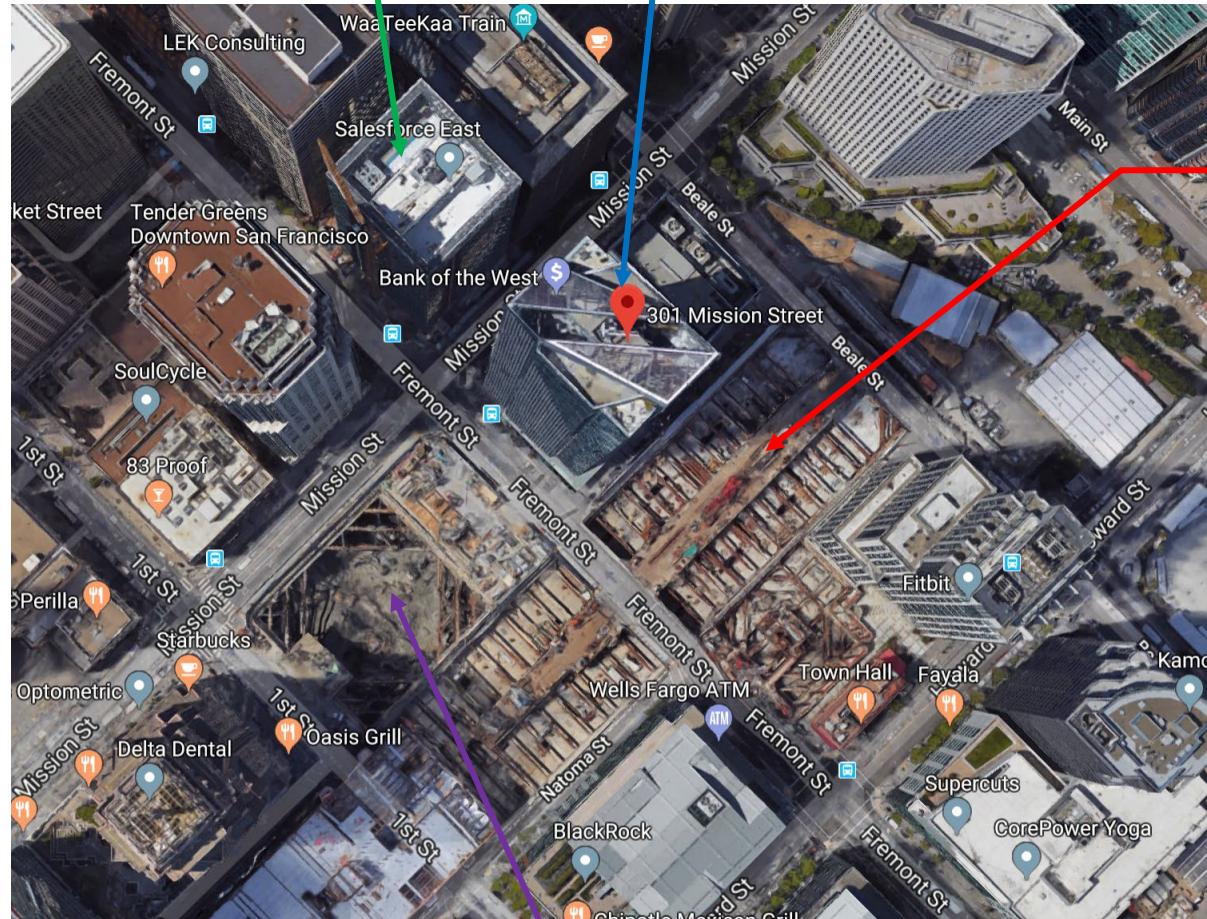




**Sales Force East 2013-2015**

**Millennium Tower 2005-2009**

**Transbay transit terminal 2010-2018**



**Salesforce Tower 2015-18**

*Courtesy: RO Hamburger*

# *Why is this case history important?*



## Foundation design practice changed

- New high rises on San Francisco “infirm soils” now use piles to rock
- City of San Francisco now requires geotechnical peer review for high rise buildings

## Learning opportunities

- What soil deformation mechanisms produced the movements?
- Could the movements have reasonably been anticipated?
- Secondary compression prediction and settlement mitigation

Are the recent changes in practice appropriate?



*Rendering courtesy: RO Hamburger*



# Outline

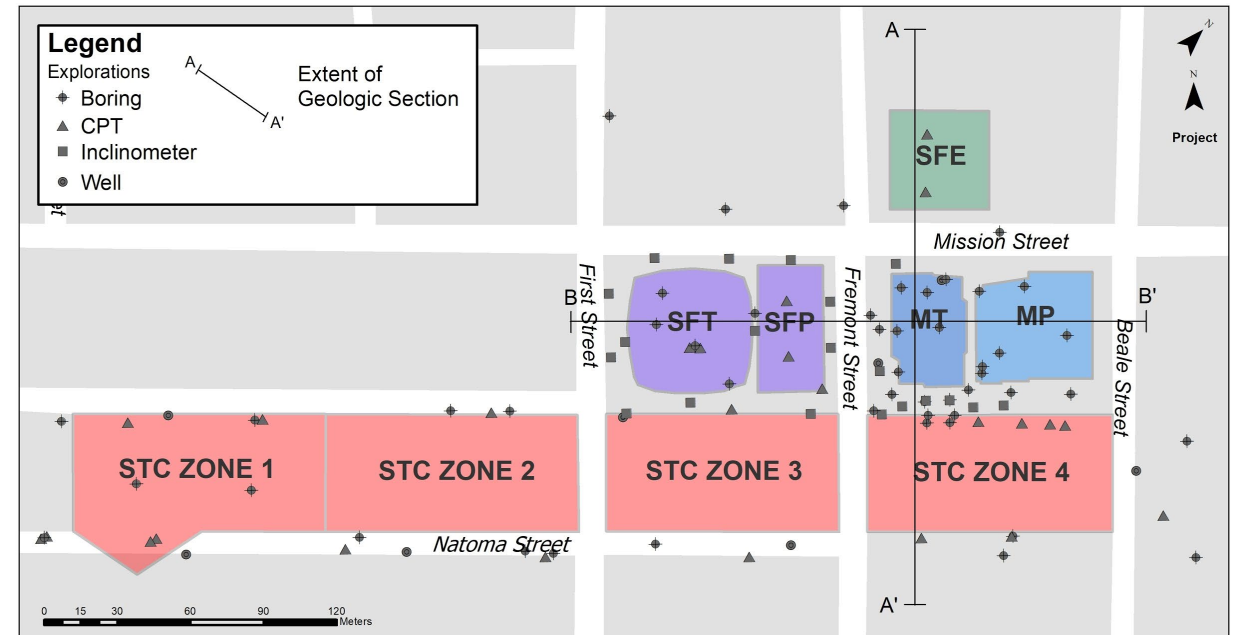
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# Site Conditions

10 geotechnical investigations

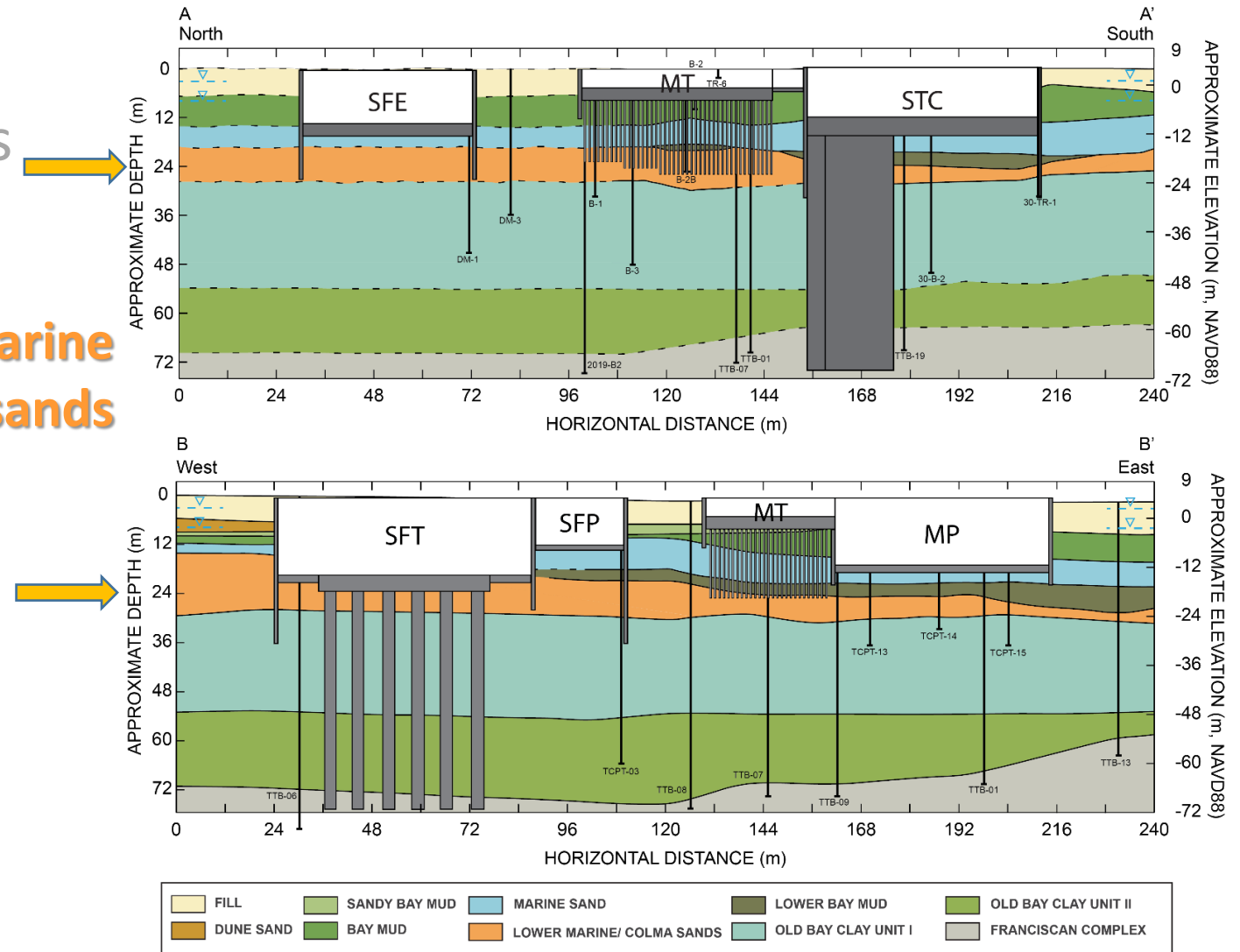


# Site Conditions

10 geotechnical investigations

Stratigraphy

Lower marine  
(Colma) sands



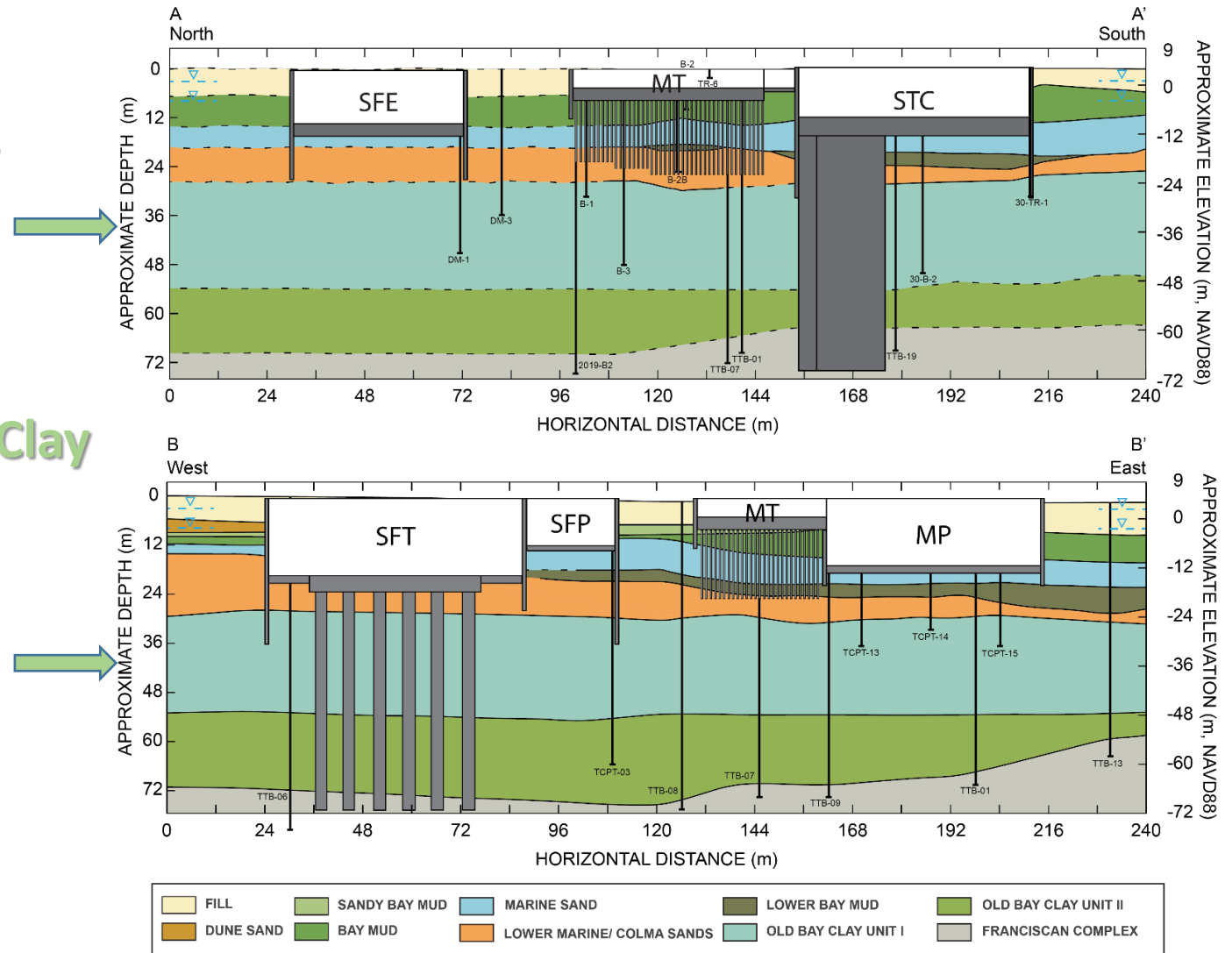


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Old Bay Clay

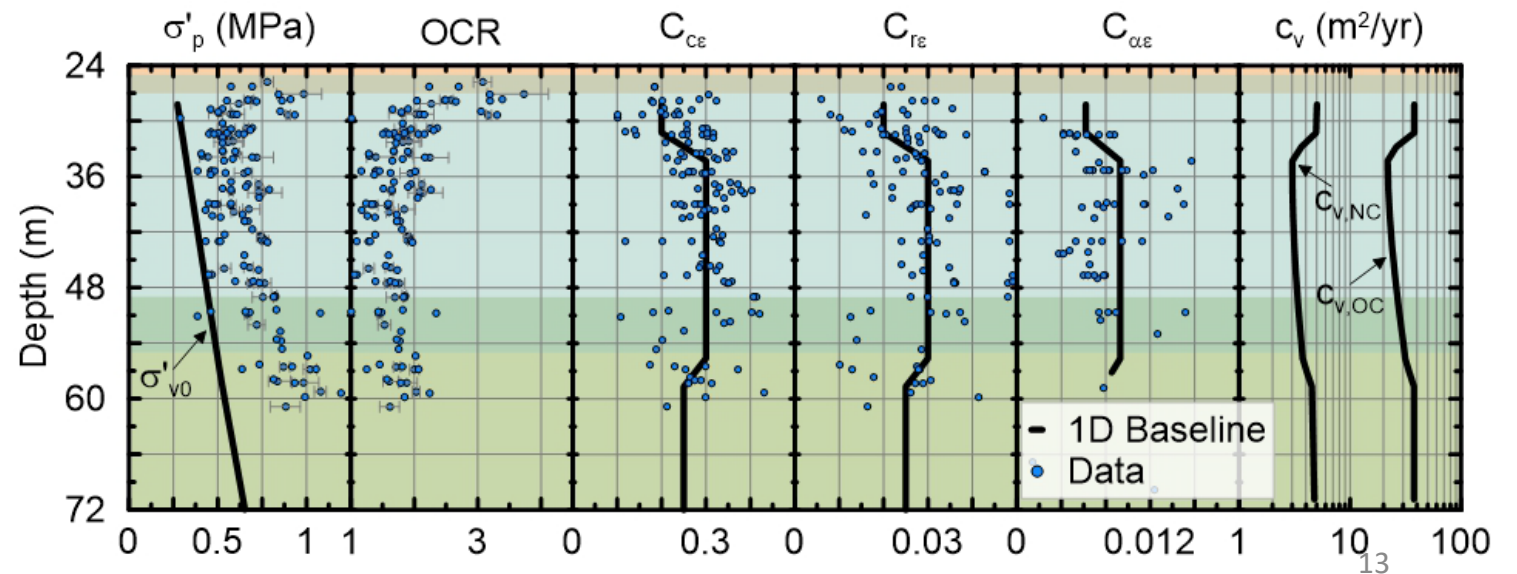
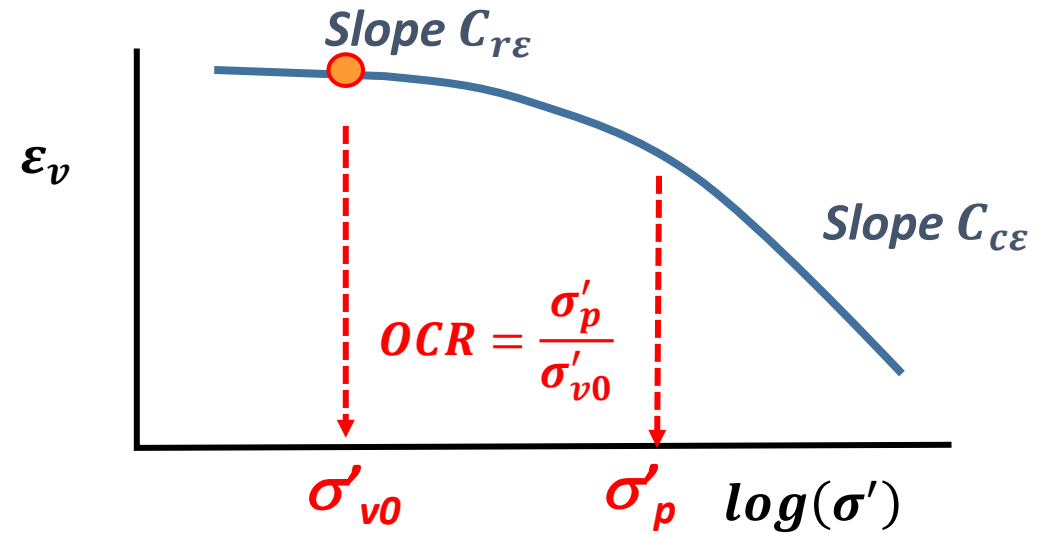


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Stratigraphy

Properties of Old Bay Clay





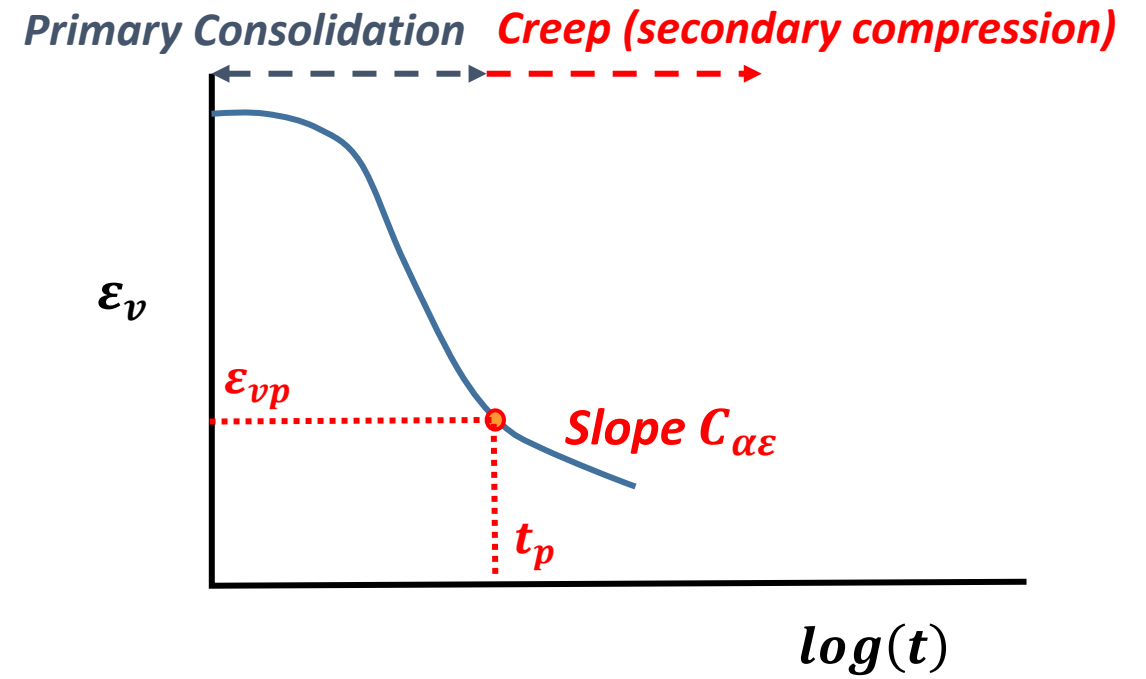
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Properties of Old Bay Clay

Secondary compression  
properties



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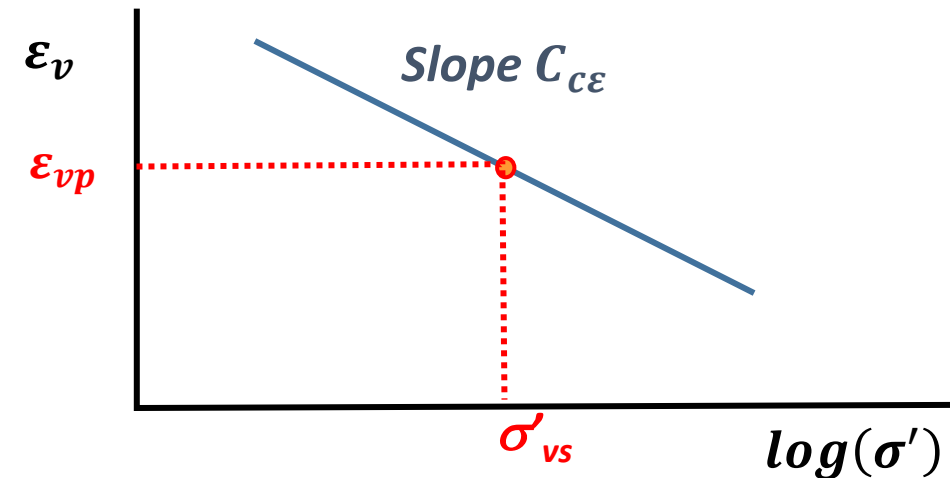
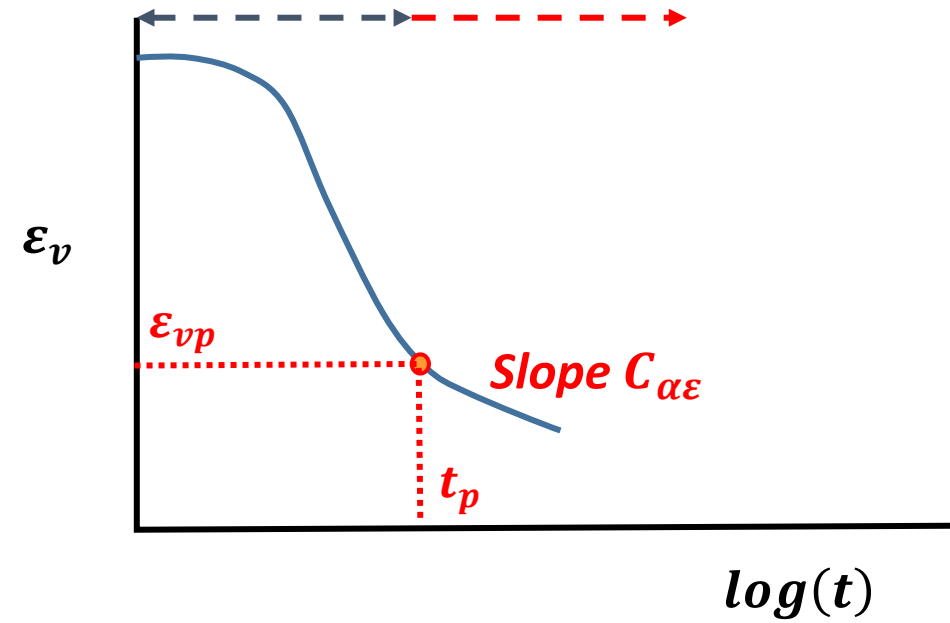
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Secondary compression  
properties

Primary Consolidation    *Creep (secondary compression)*





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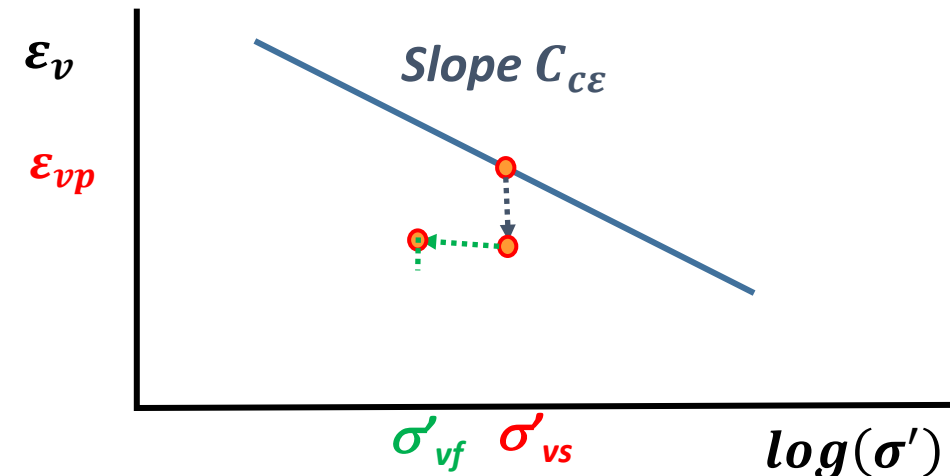
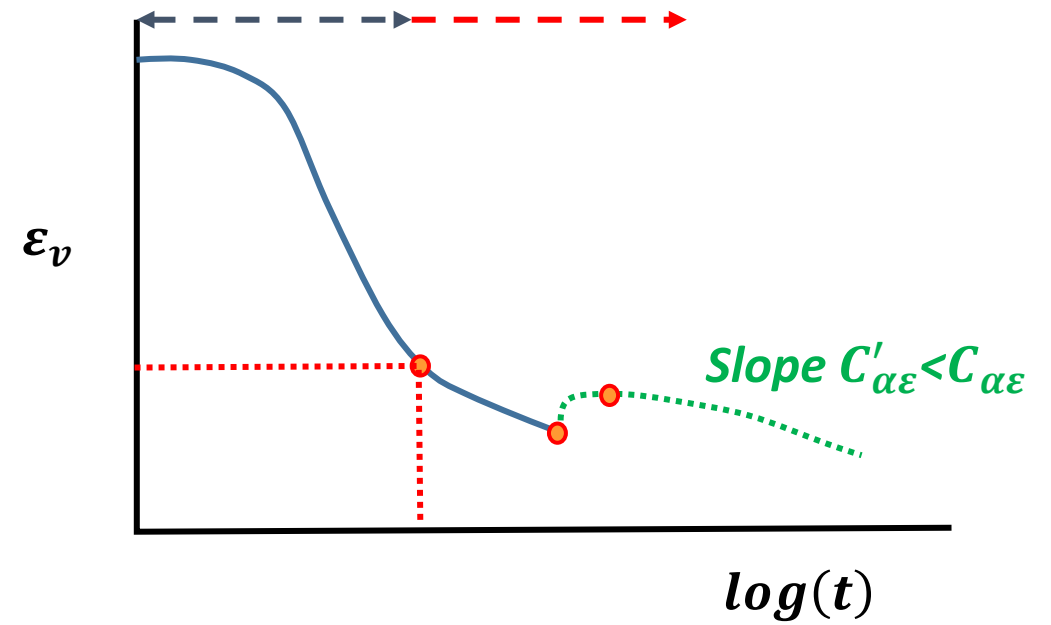
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Secondary compression  
properties (Wagner et al. 2021)

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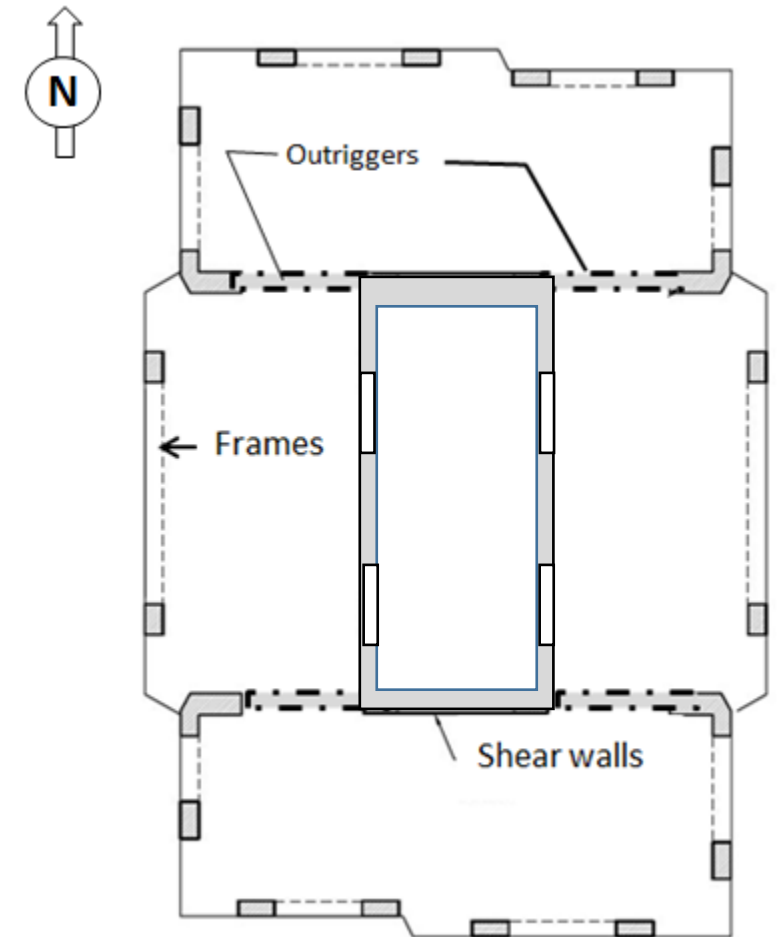
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# Structure and Timelines

MT structural system

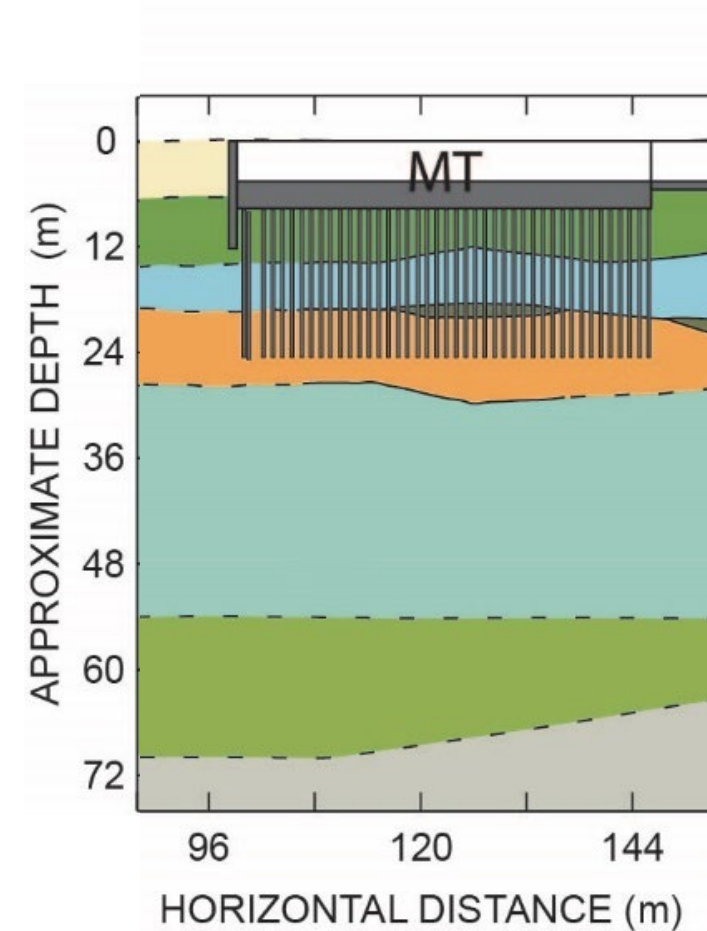


*Courtesy: RO Hamburger*

# Structure and Timelines

MT structural system

Sub-structure: one level  
basement, 4.6 m, 3 m pile  
supported mat

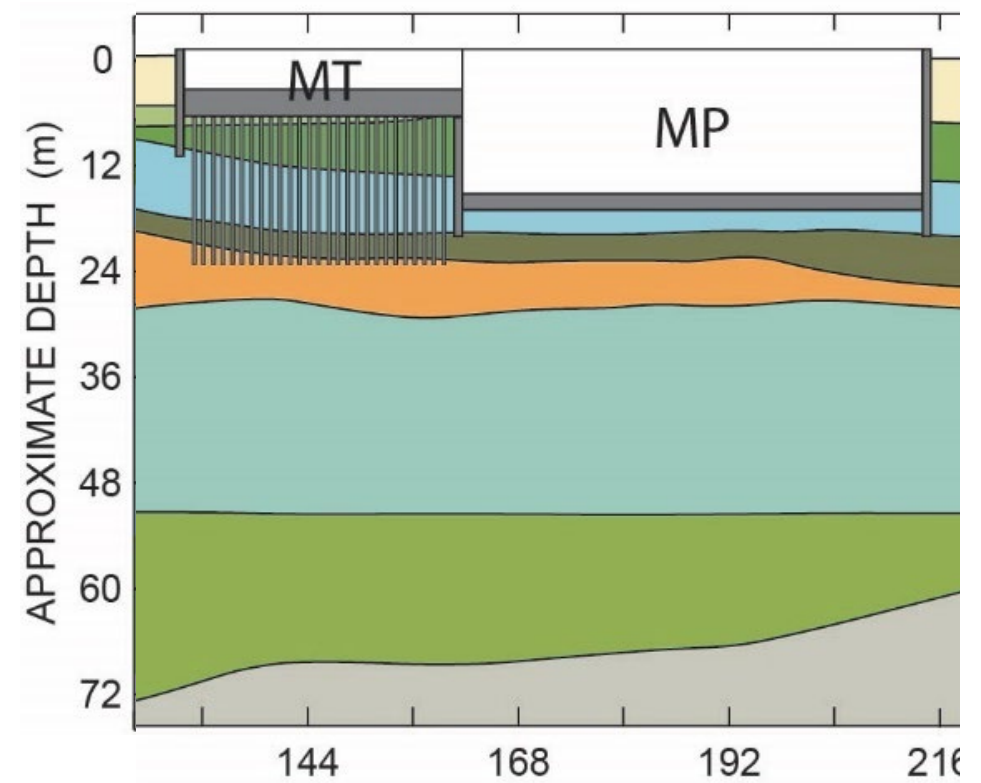


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Podium east of MT





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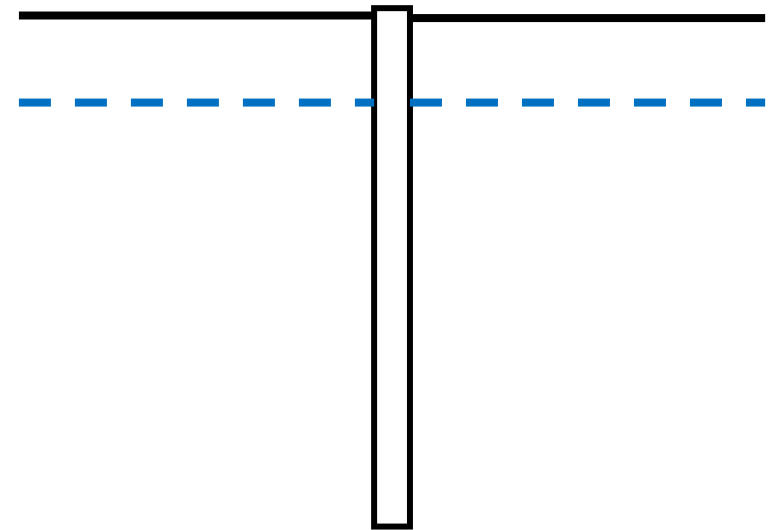
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Construction timelines

Cutoff walls



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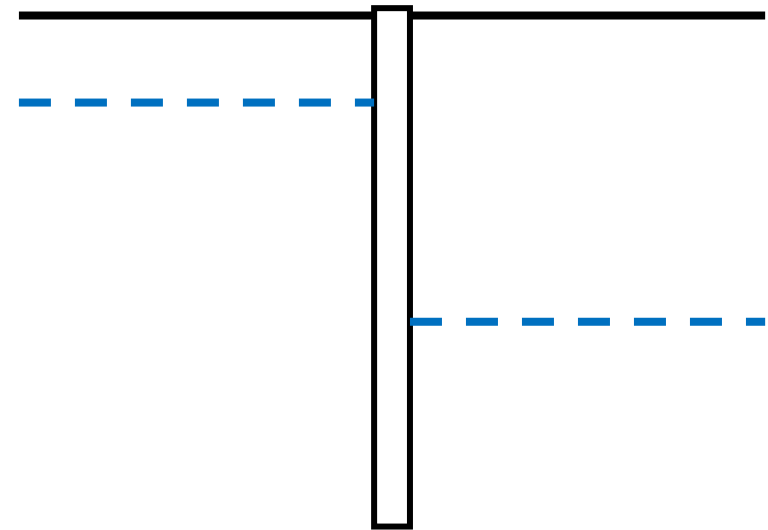
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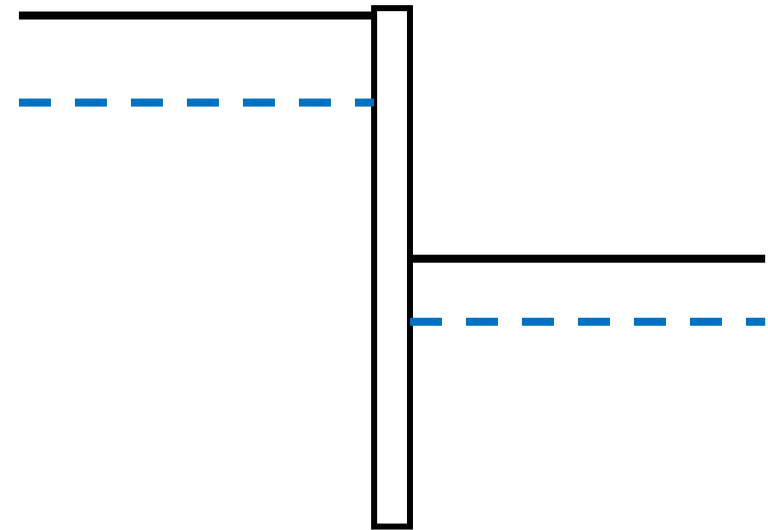
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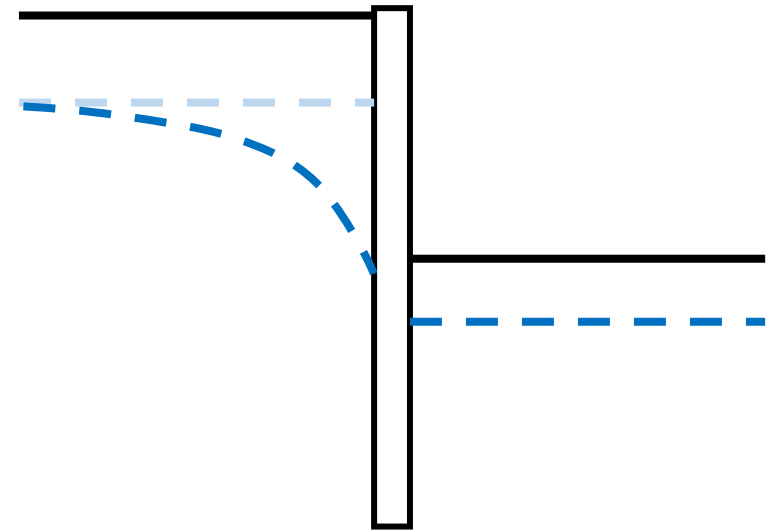
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Podium east of MT

Construction timelines

Cutoff walls; gw lowering possible if:

- Leaks through walls
- Gaps in walls
- Underseepage



# Structure and Timelines

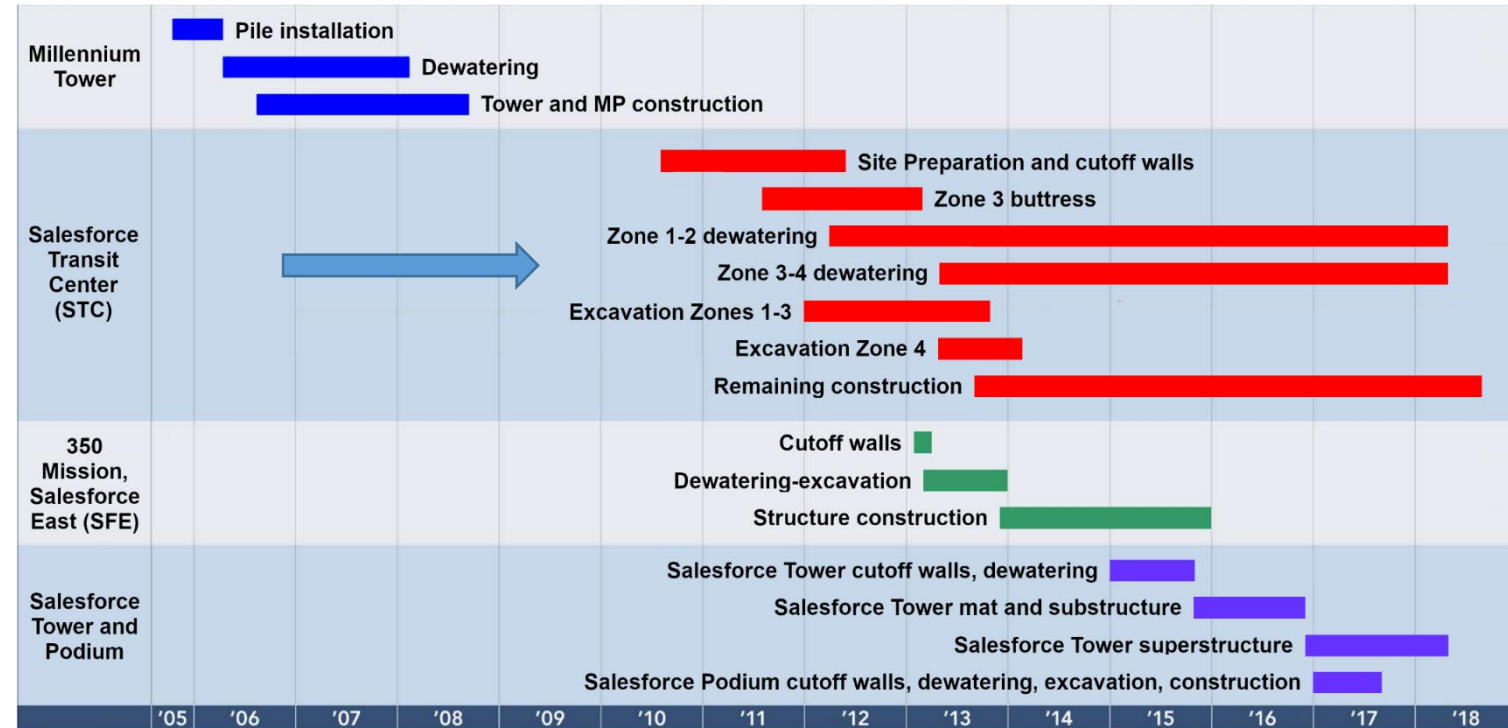
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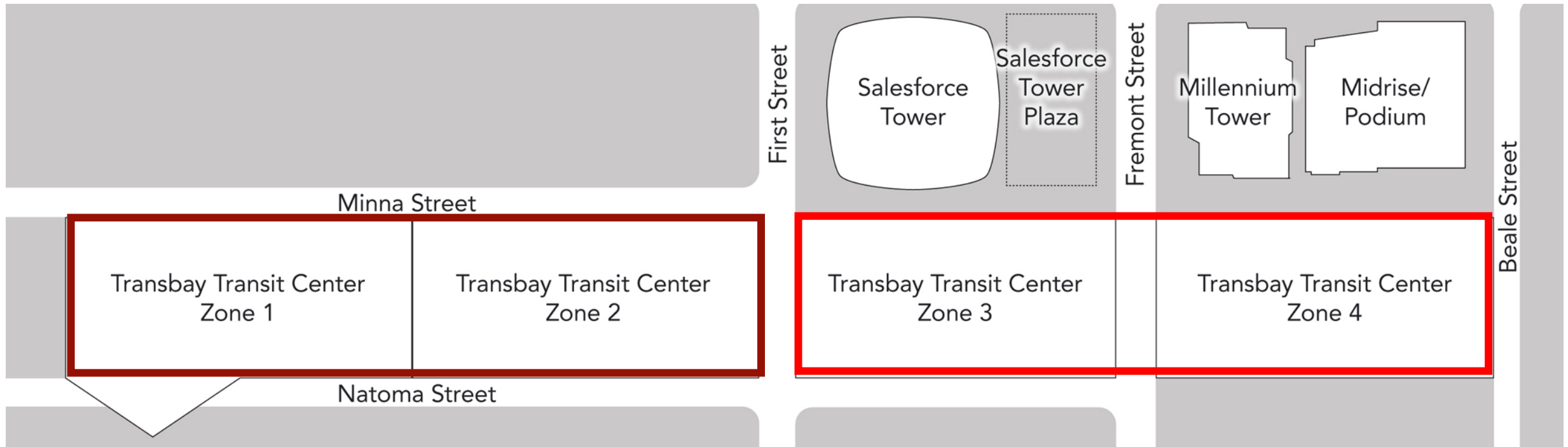
Cutoff walls



# Transit center constructed in four “zones”

Zones 1-2 dewatering began in 2012

Zones 3-4 dewatering began in 2013





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# Volume Change

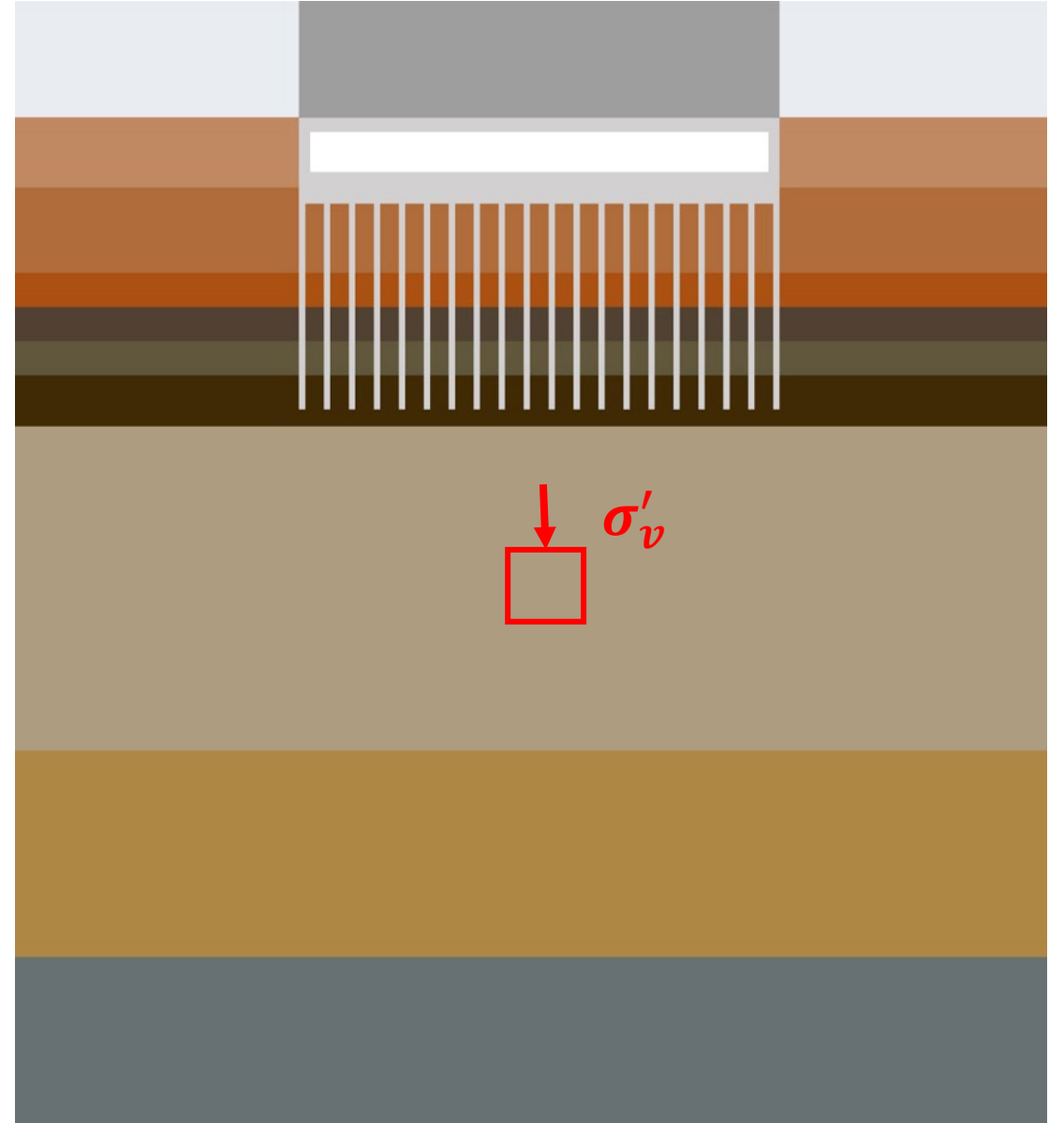
Effective stress on soil element:

$$\sigma'_v = \sigma_{v0} + \Delta\sigma - u$$

Tower construction causes  $\Delta\sigma$  increase

Lowering of groundwater decreases  $u$

Both increase  $\sigma'_v$ , inducing consolidation



# Volume Change

Effective stress on soil element:

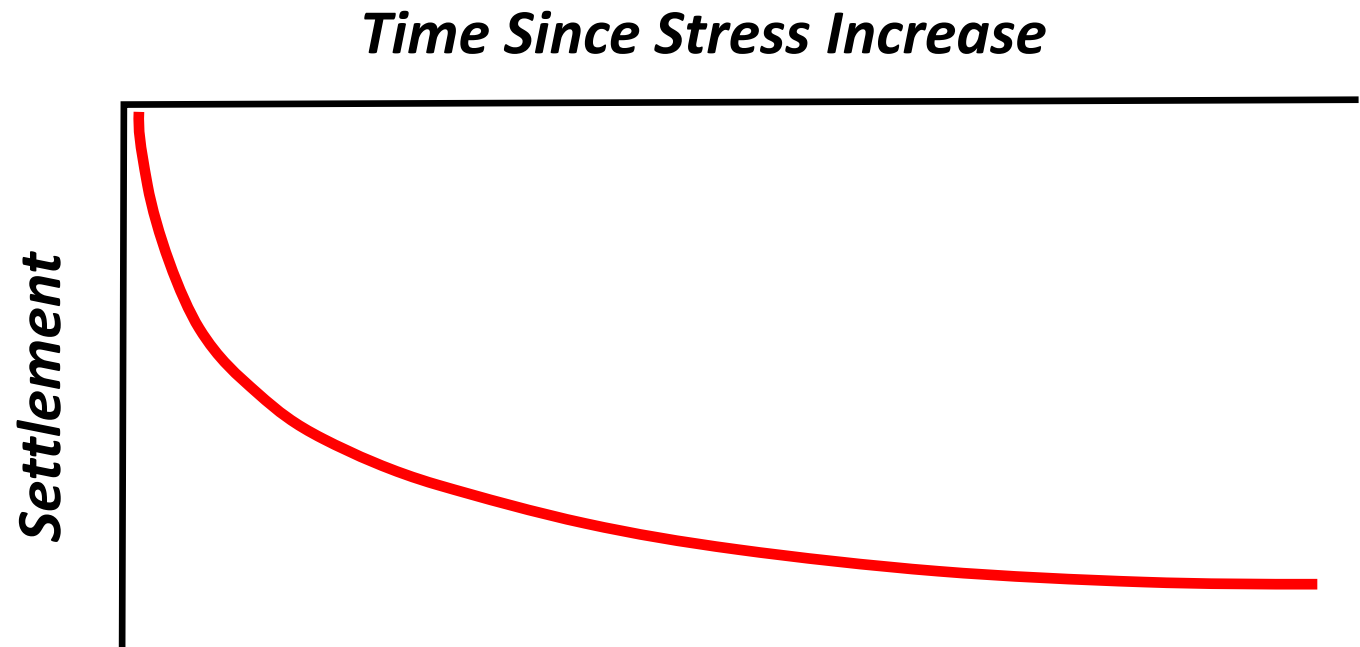
$$\sigma'_v = \sigma_{v0} + \Delta\sigma - u$$

Tower construction causes  $\Delta\sigma$

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Both increase  $\sigma'_v$ , inducing consolidation

Settlement rate fast initially, then slows with time



# Shear Deformation of Braced Excavations

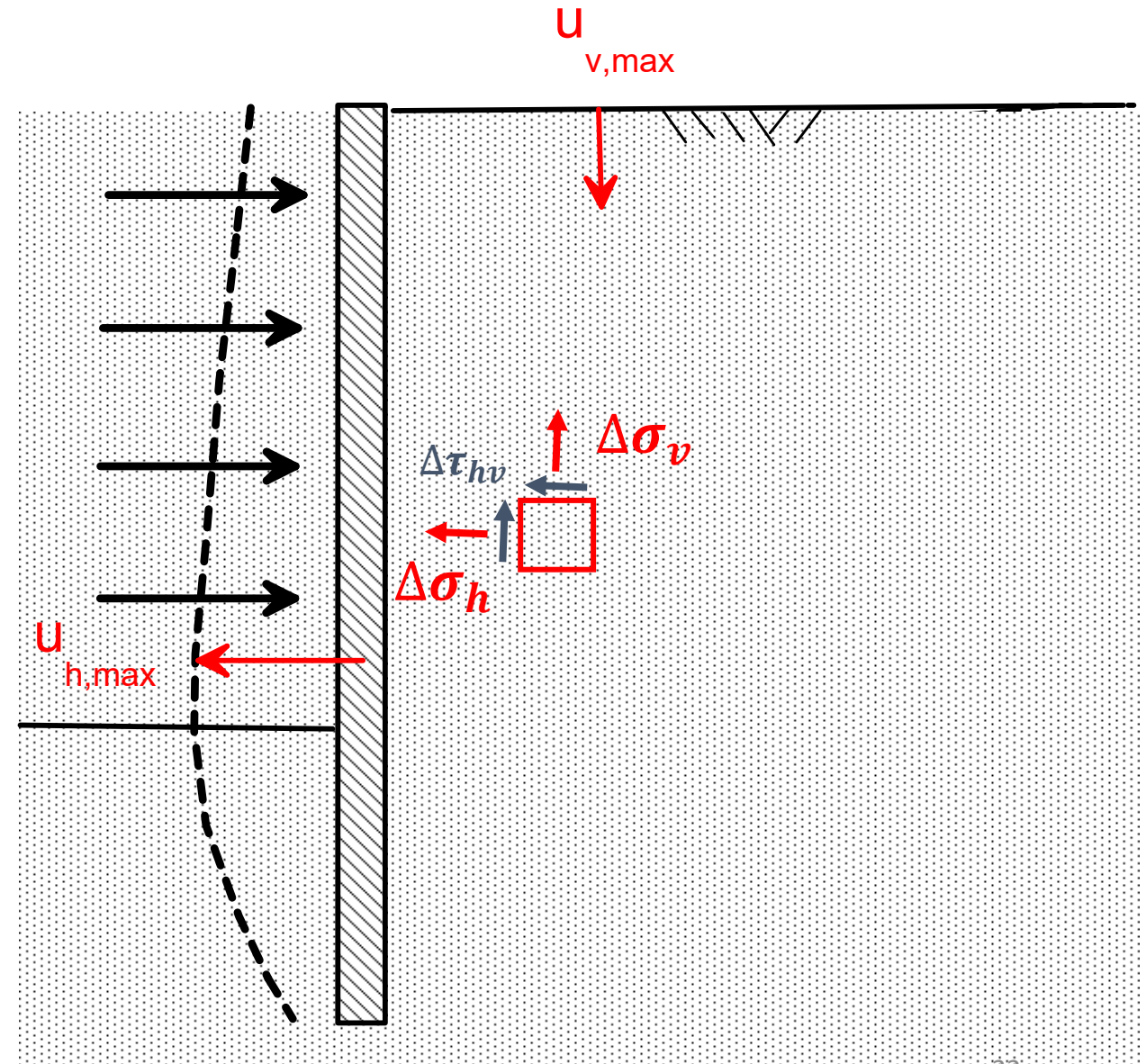
Supported excavations change stresses in retained soils

Wall movement inwards

Ground settlement behind wall

Produces tilt of structures towards excavation

e.g., Peck 1969; Clough et al. 1979; O'Rourke 1976, 1981; Hashash and Whittle 1996; Moorman 2004; Konda et al. 2010; Korff et al. 2016





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# Foundation Performance

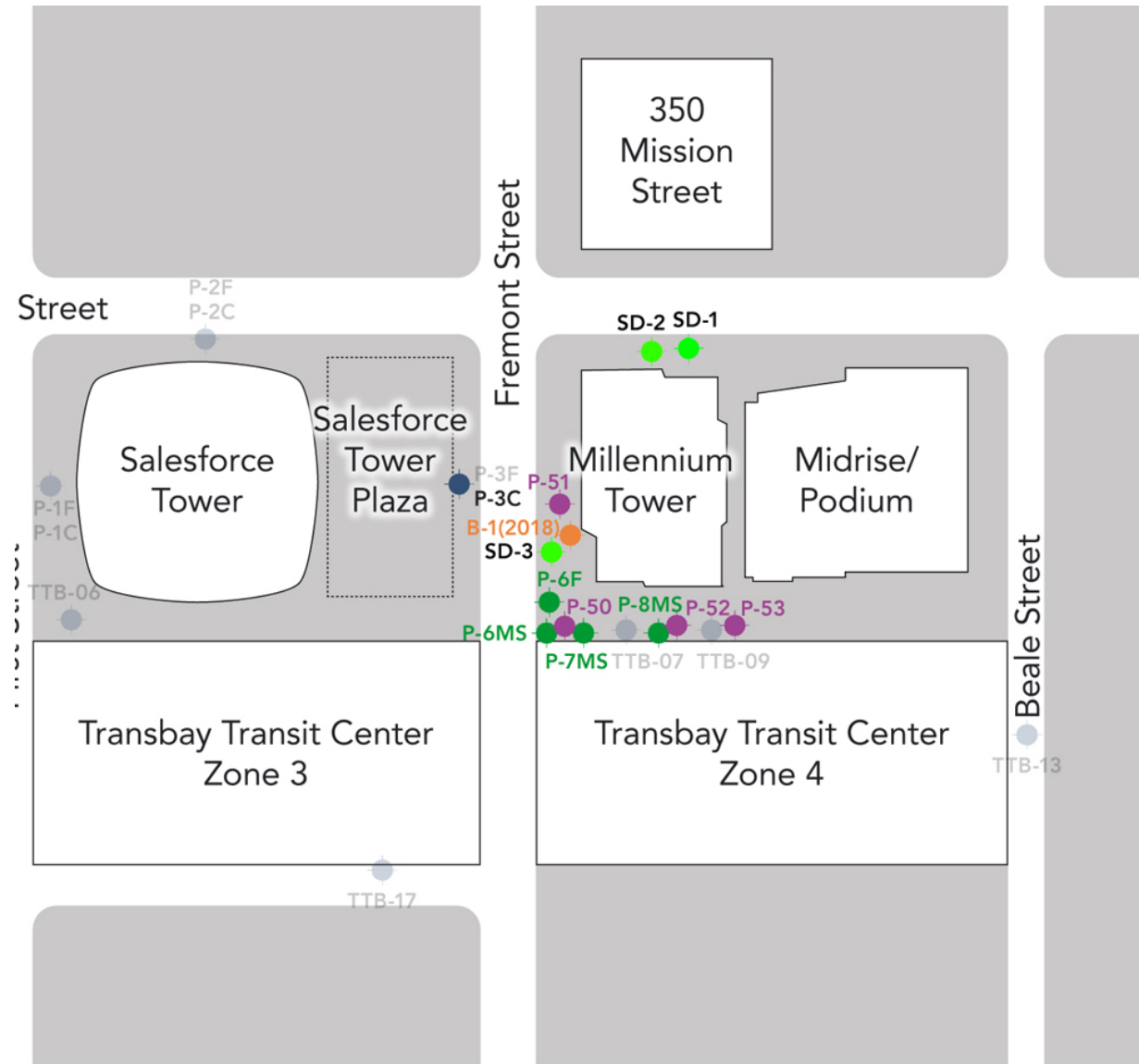
- Available instrumentation/data
- Interpretation



# Water Pressure

## Piezometers in Colma

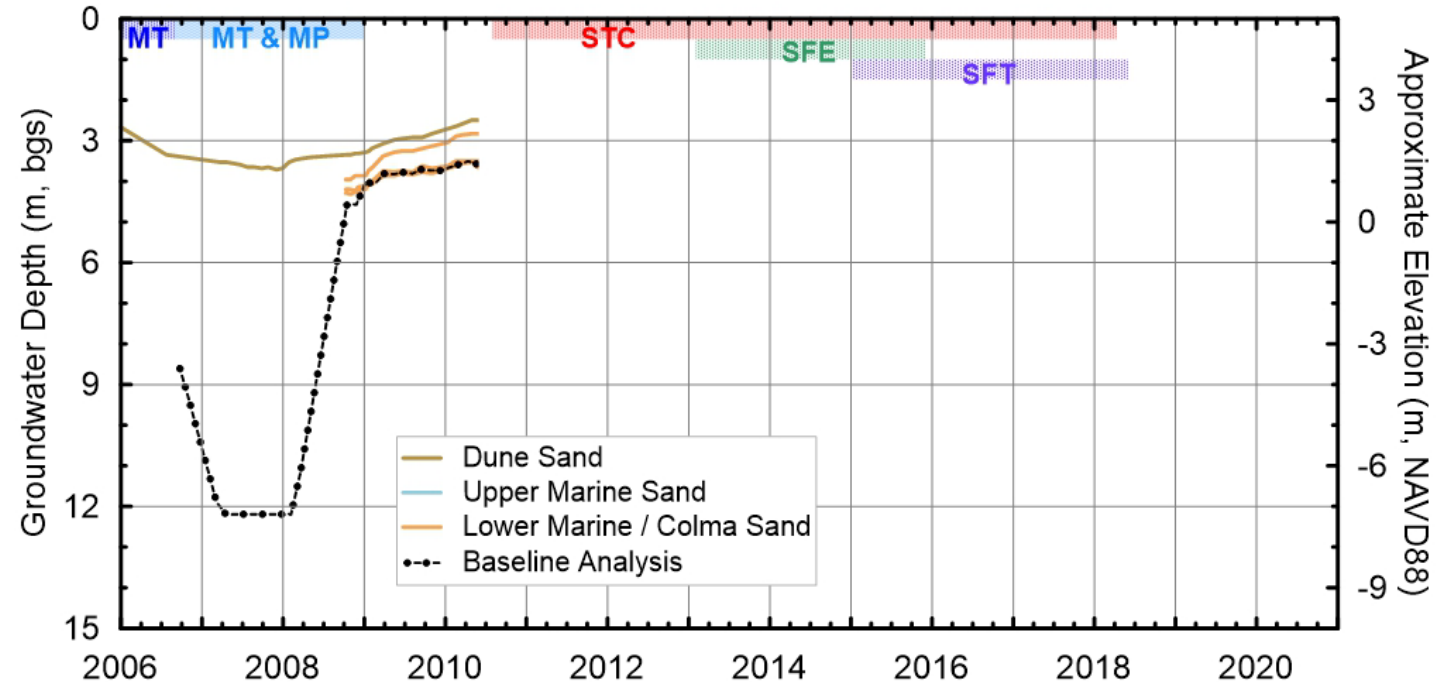
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# Water Pressure

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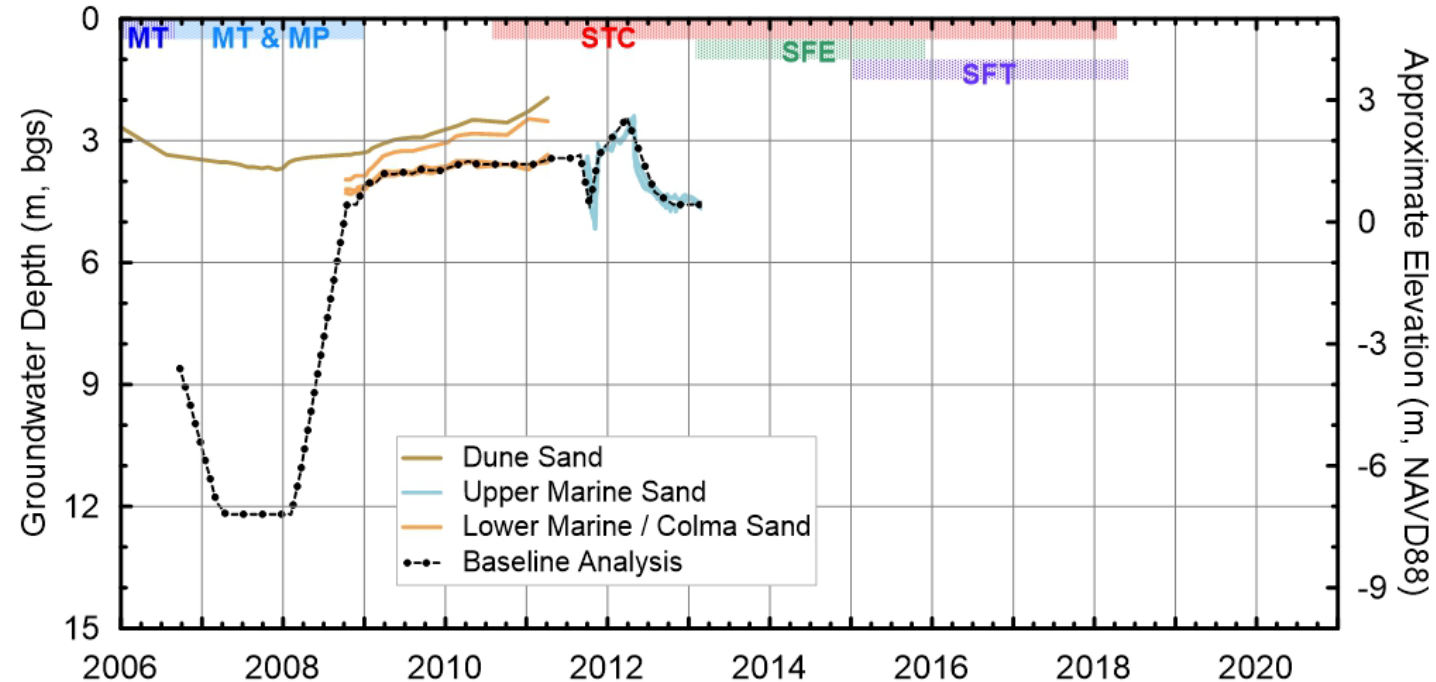
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- Pre-construction gwt at ~3 m
- 2007-08: podium construction; rapid recovery



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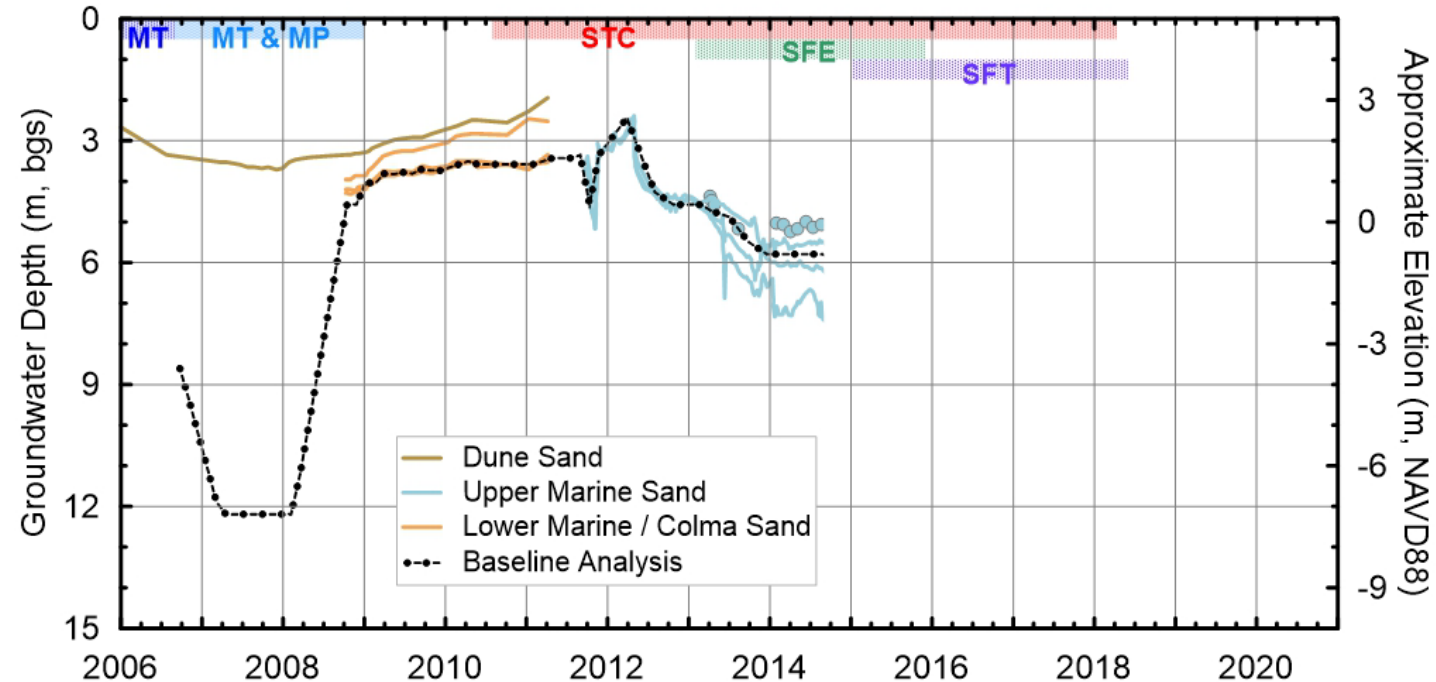
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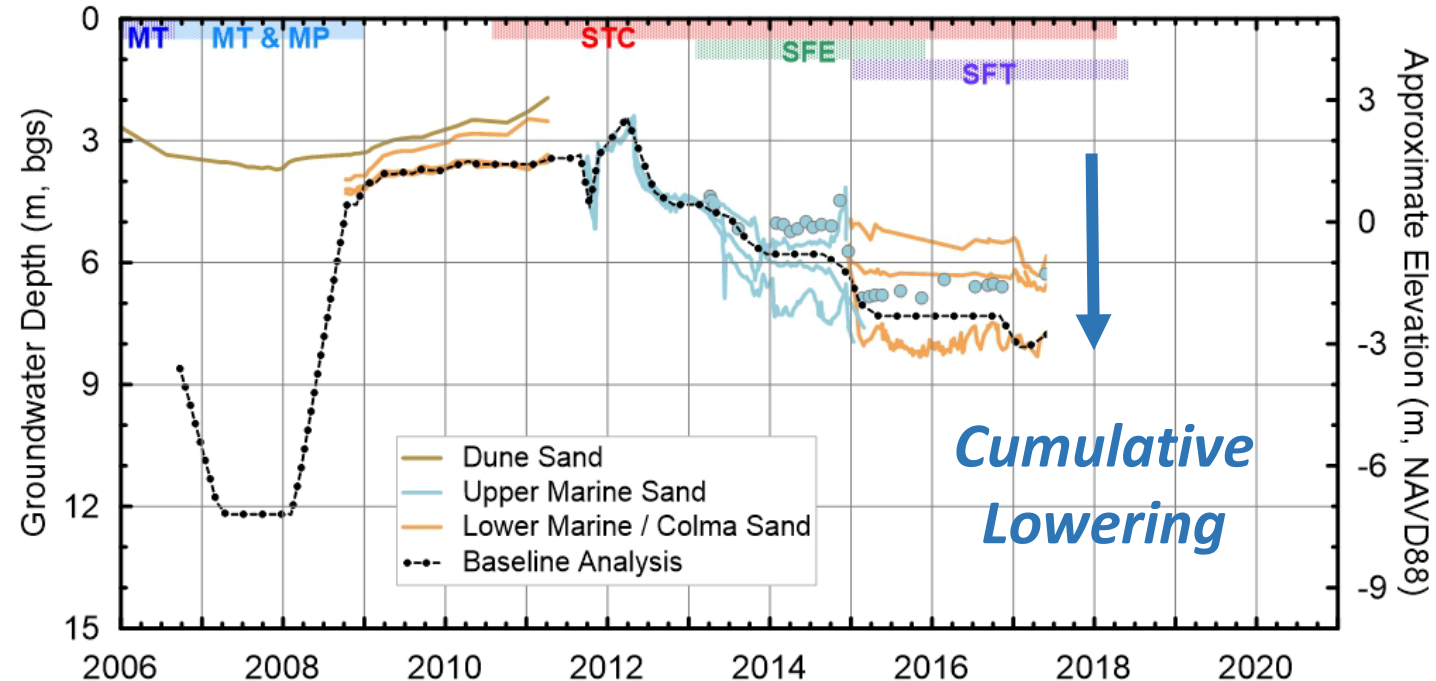




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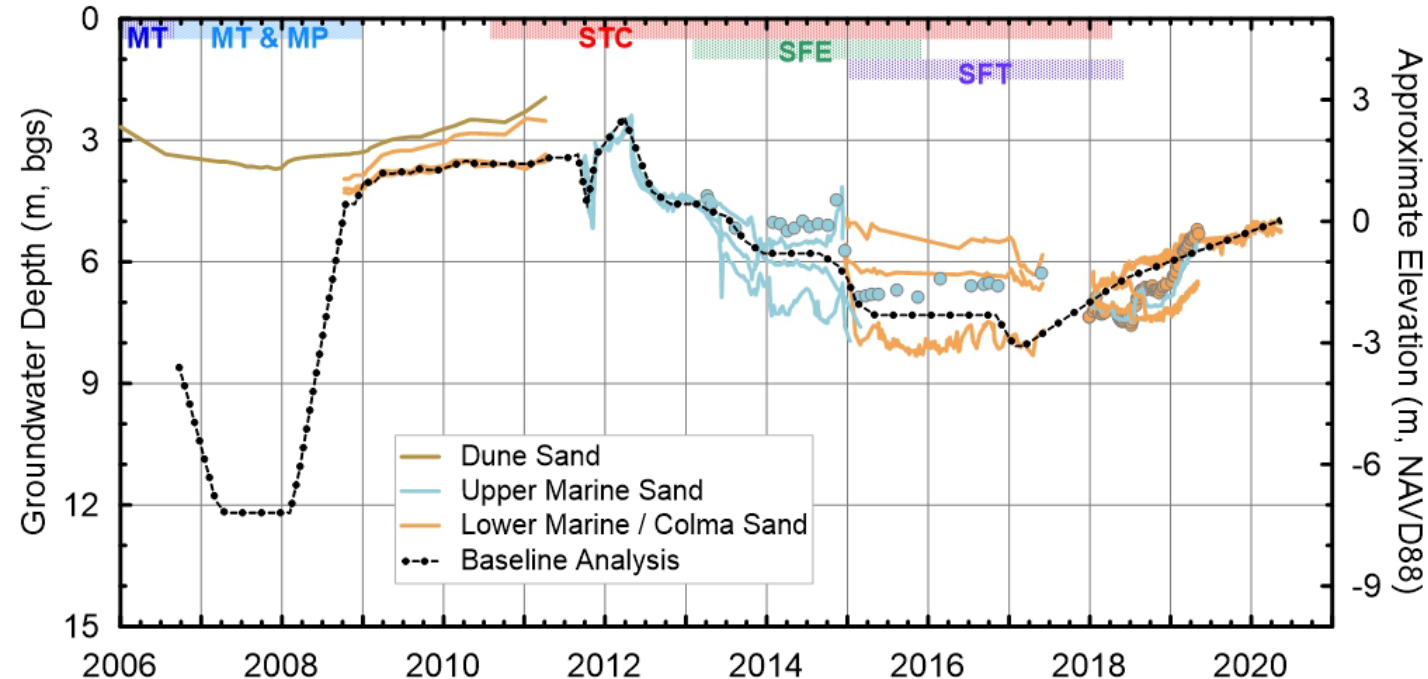
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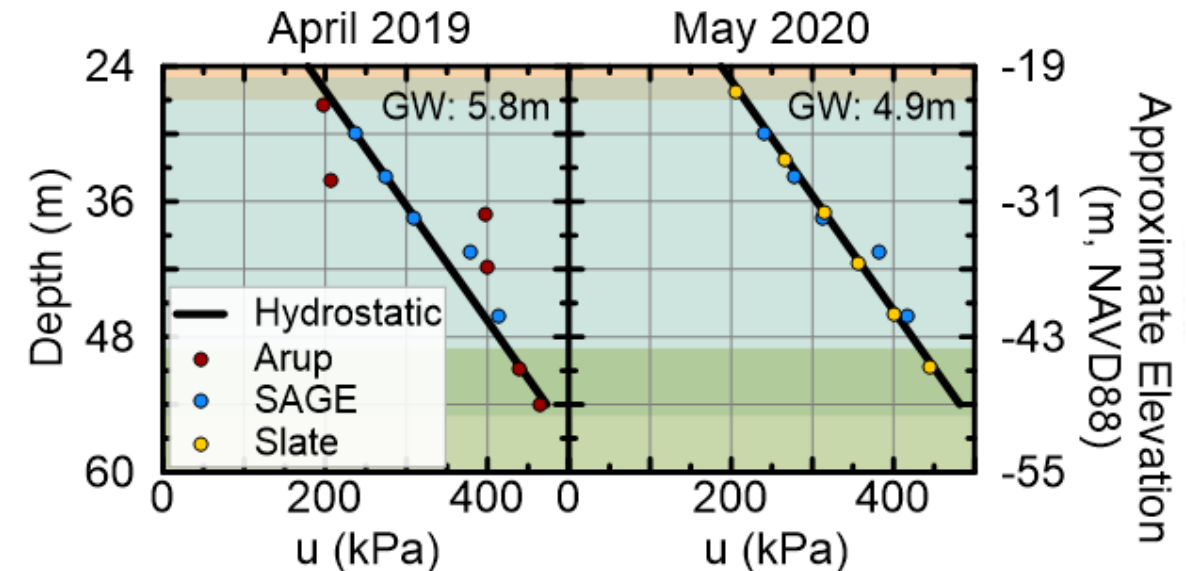
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- 2015-17: SFT dewatering
- > 2018: recovery



# Water Pressure

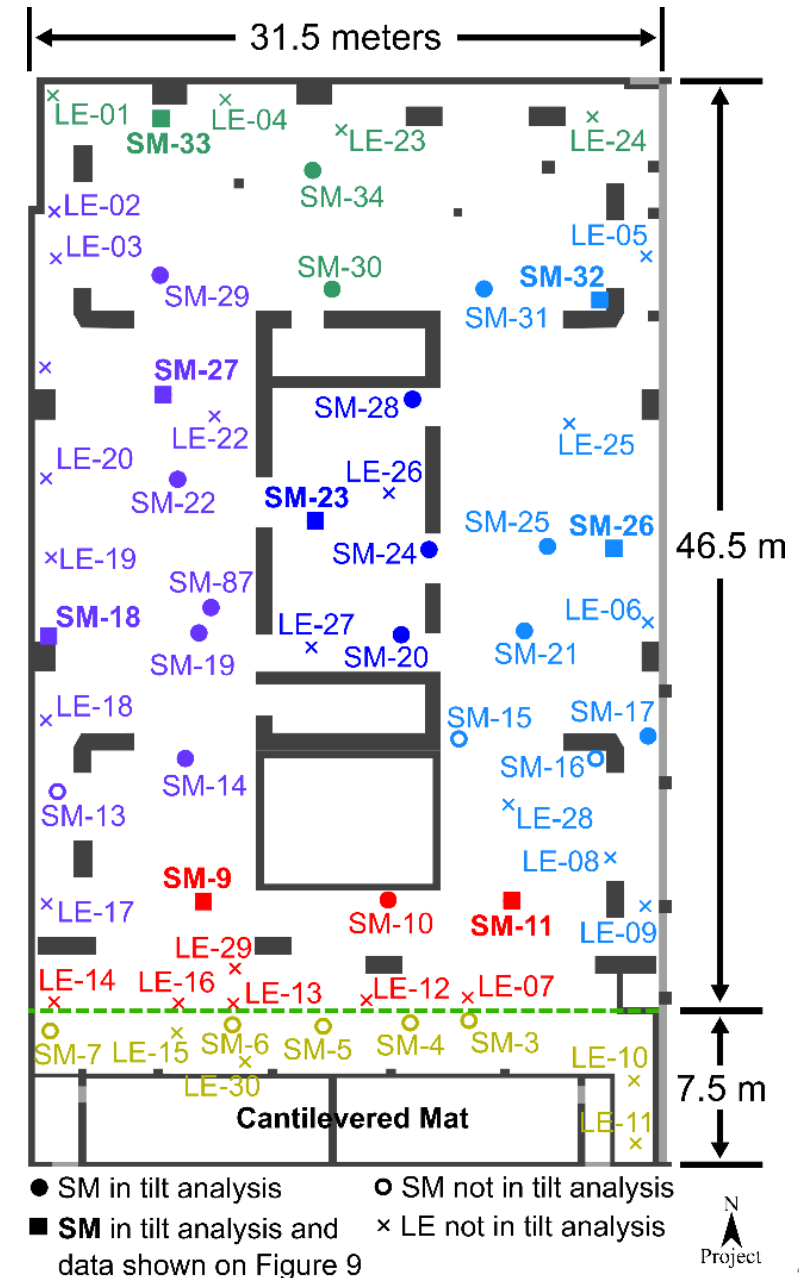
## Piezometers in OBC

- Used to evaluate potential under-consolidation
- Interpretation: Consolidation effectively complete in mid-2020 (maybe earlier)



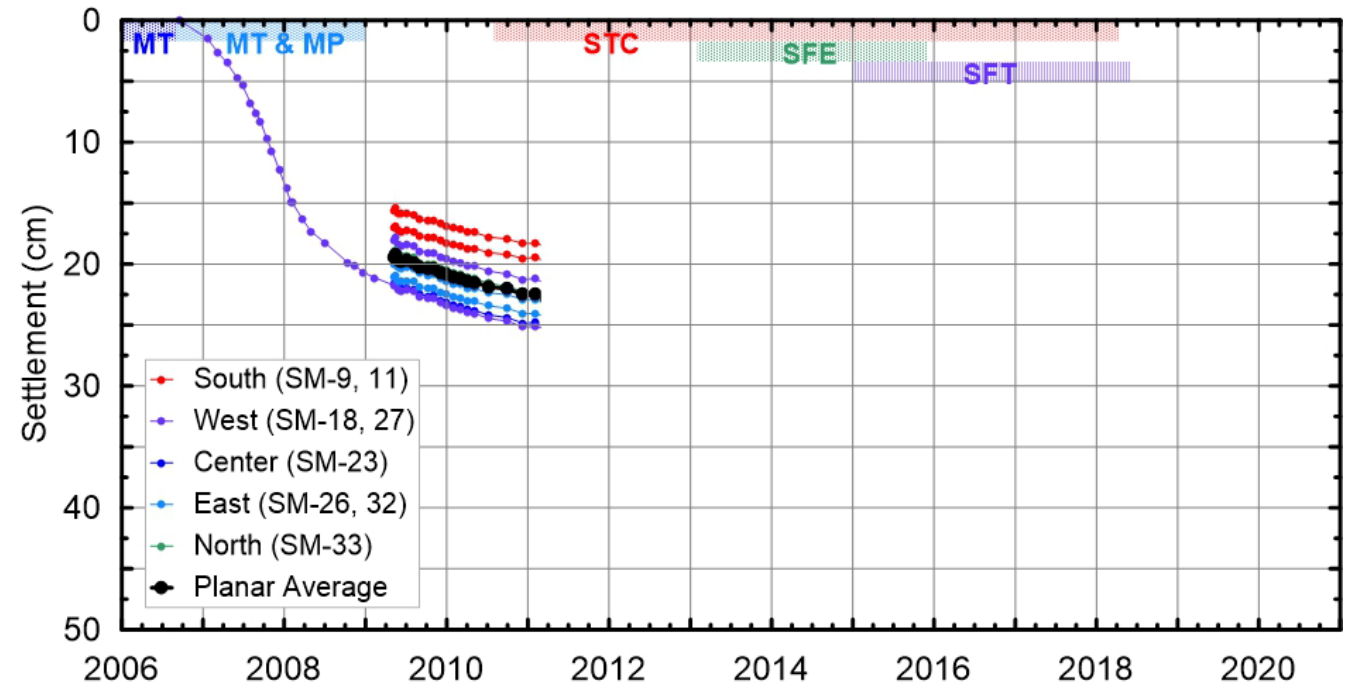
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- 2006-09: single monument on 1<sup>st</sup> floor
- May '09 – present: 31 markers



# Settlement Markers

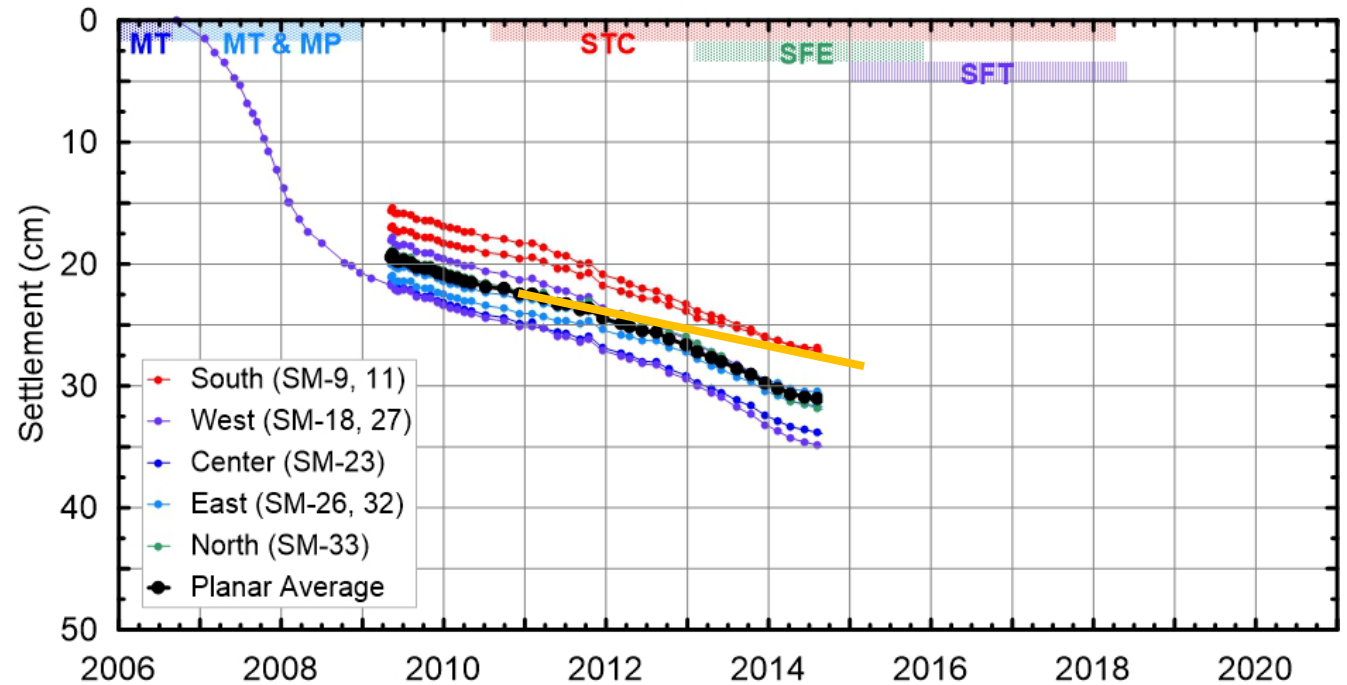
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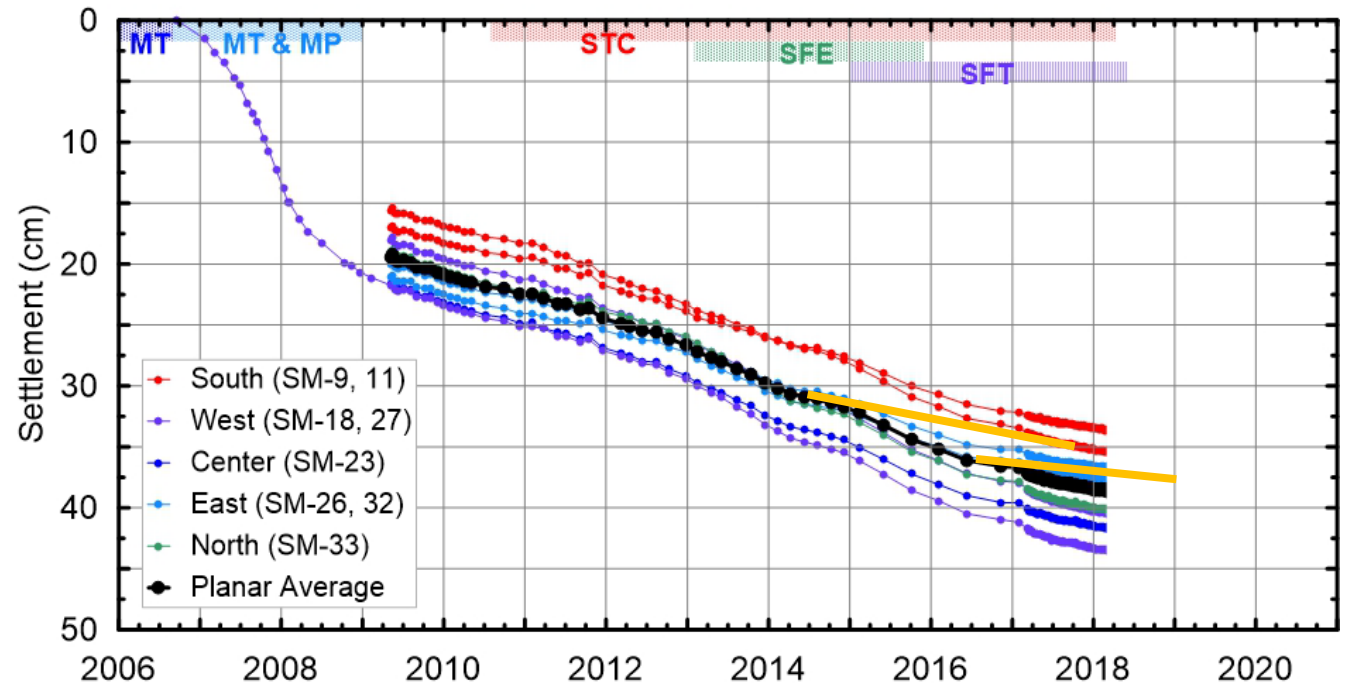
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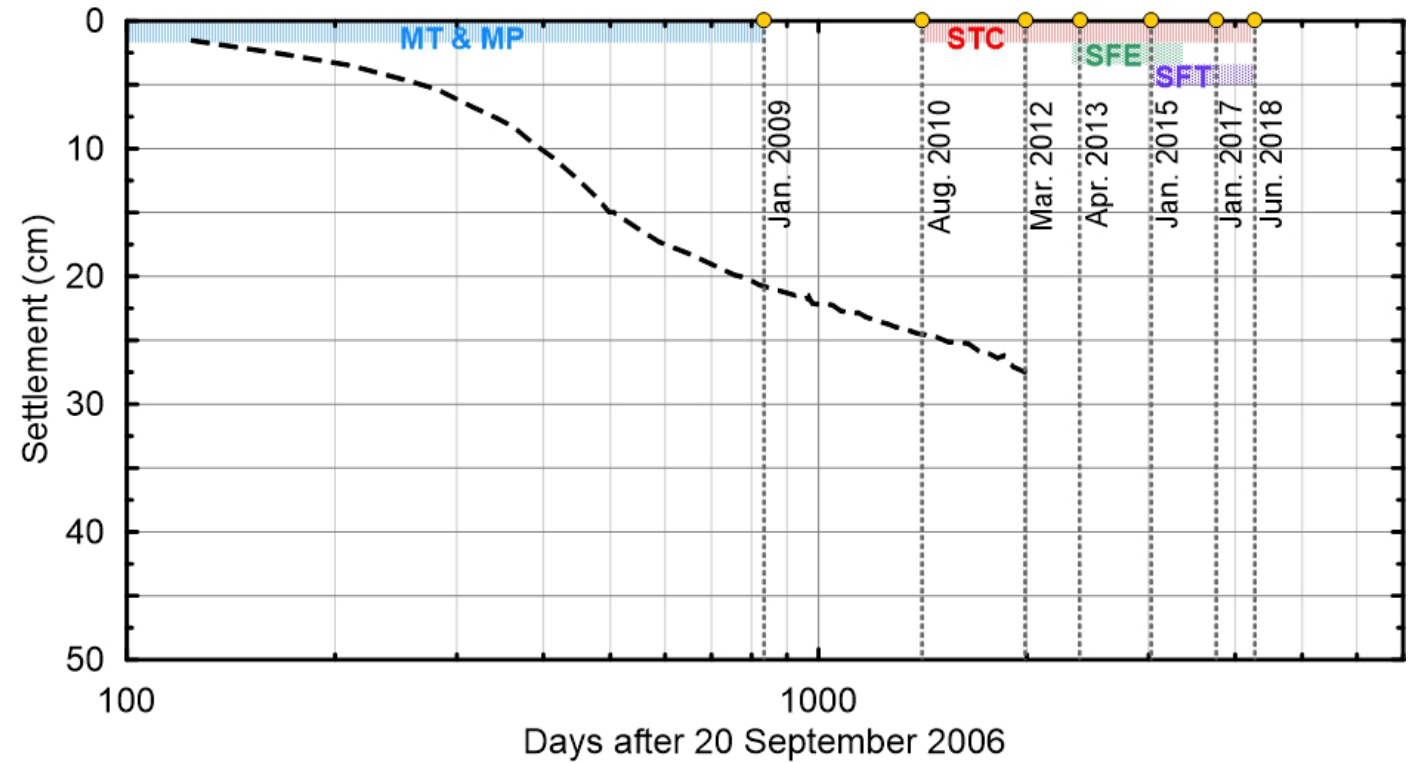
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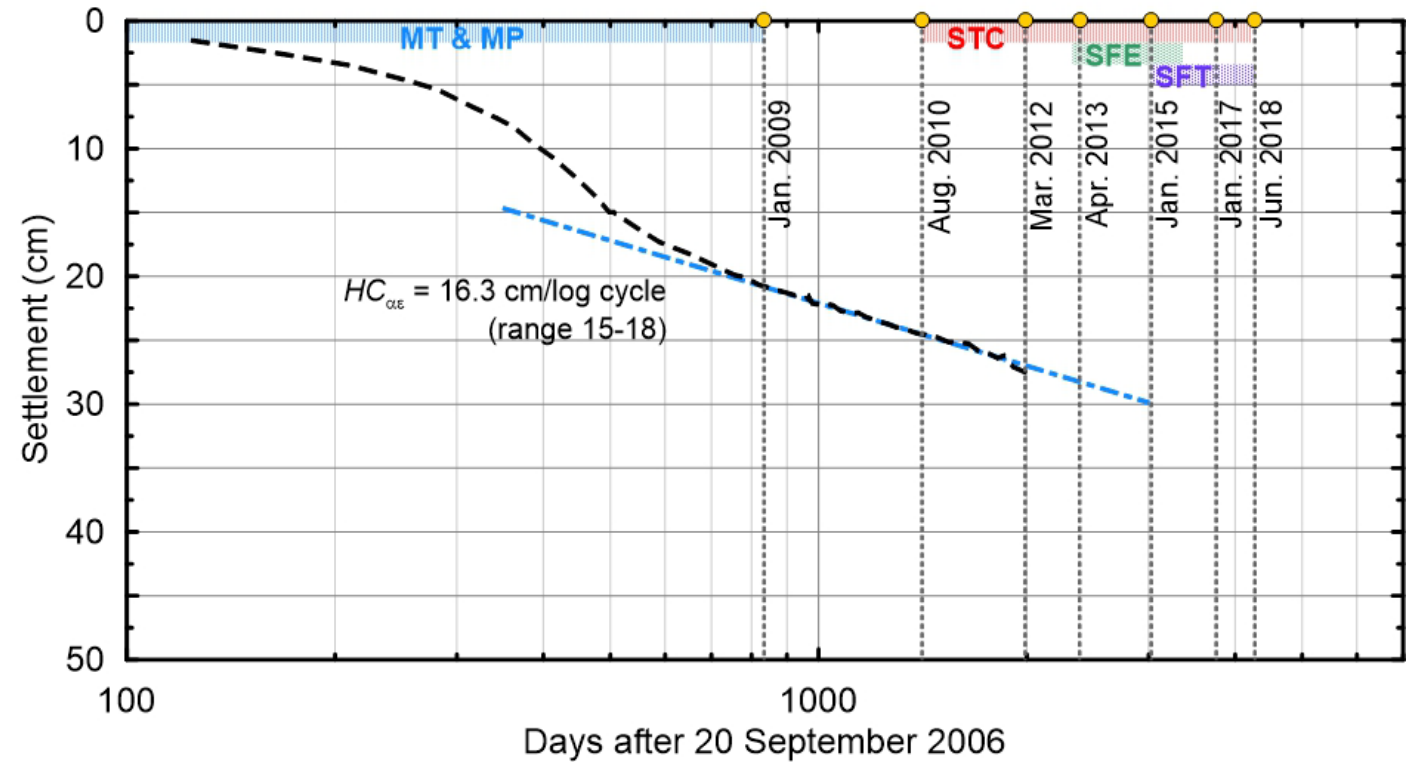
# Settlement Interpretation

Prior to adjacent construction



# Settlement Interpretation

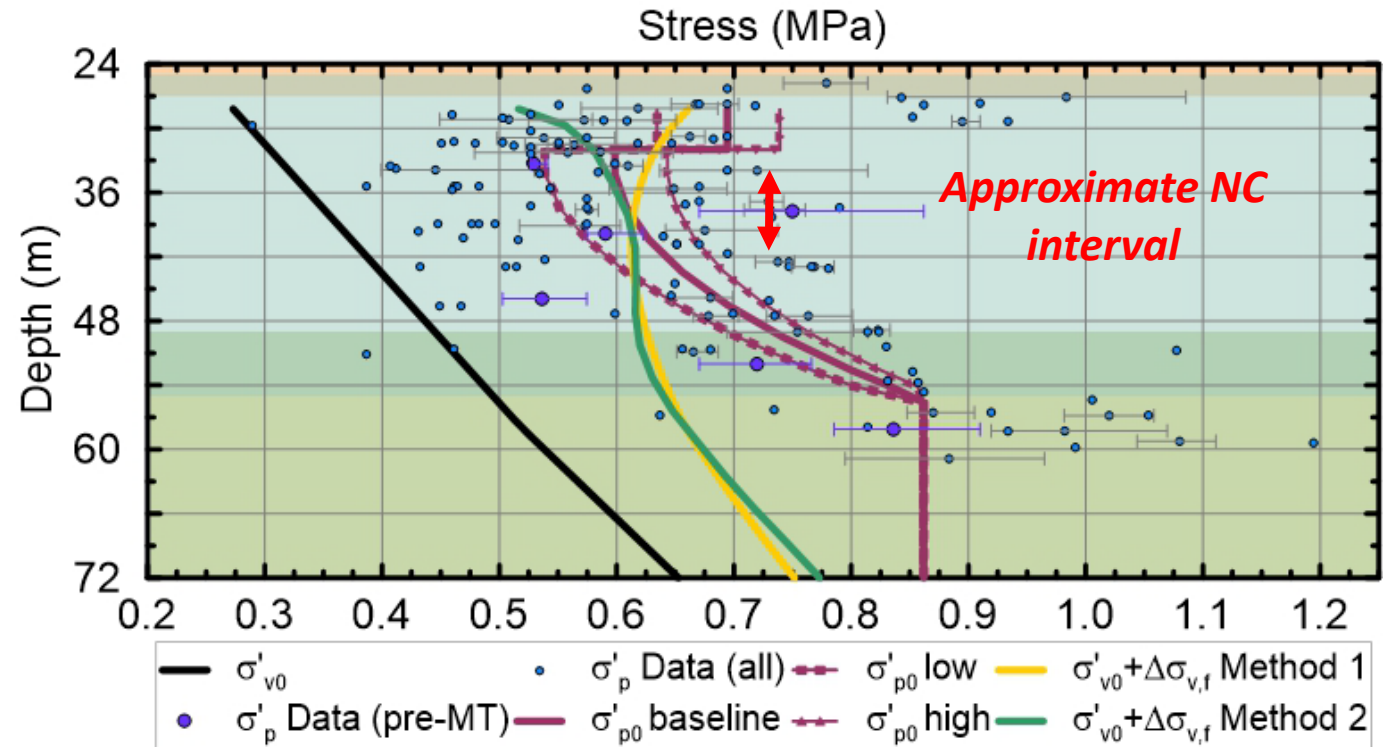
Prior to adjacent construction



# Settlement Interpretation

Prior to adjacent construction

- Stress comparison to  $\sigma'_p$

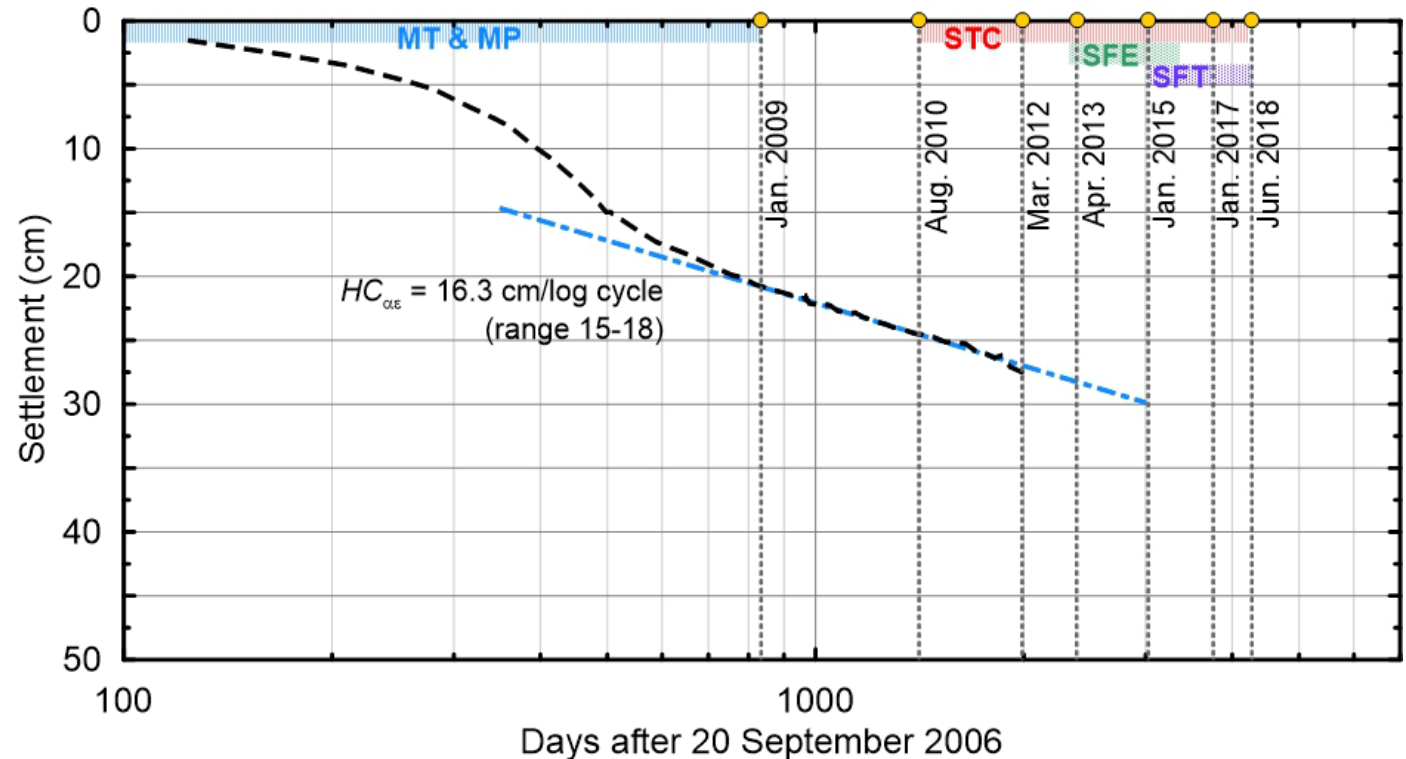




# Settlement Interpretation

## Prior to adjacent construction

- Stress comparison to  $\sigma'_p$
- Secondary compression was strong contributor
- Some consolidation may have still been occurring > 2009



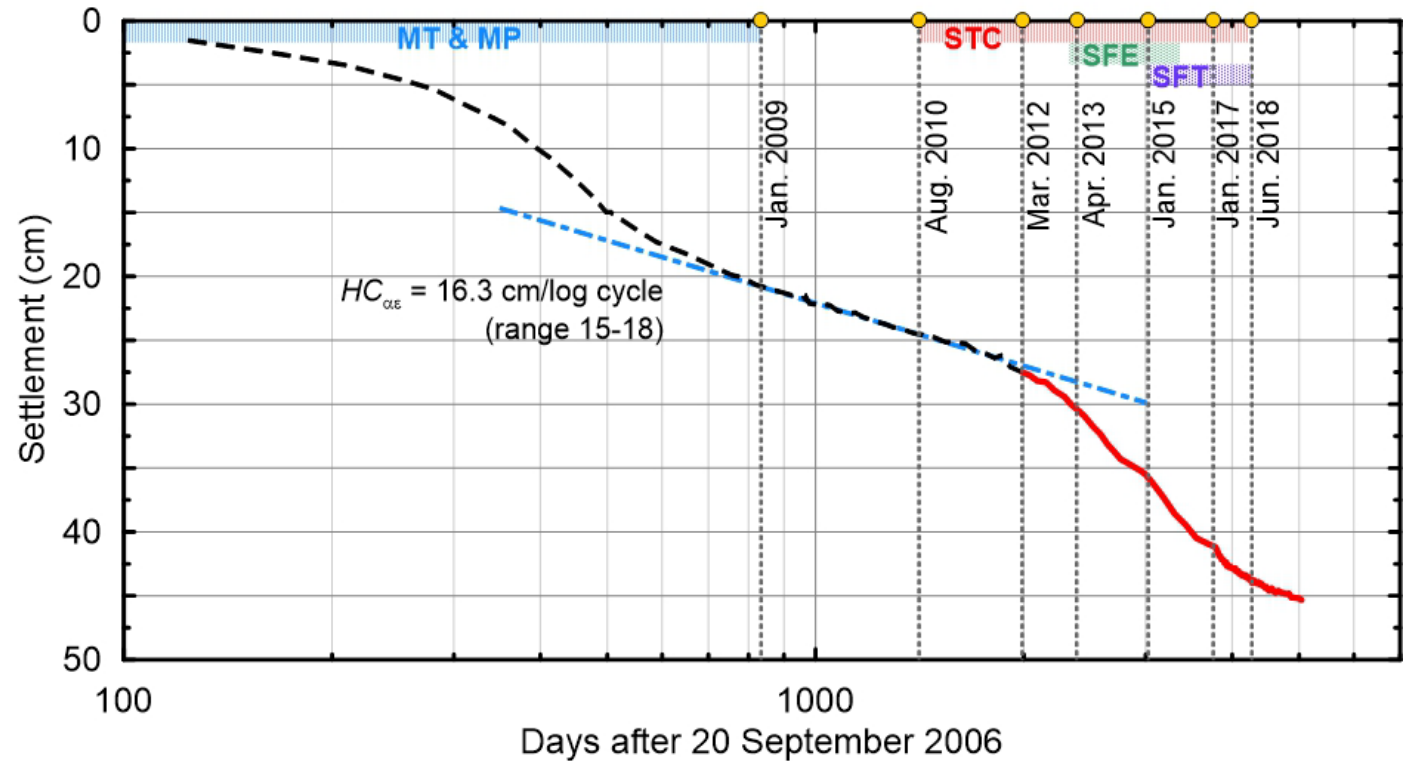
H=7-12 m  $\rightarrow$  implied  $C_{\alpha\epsilon} = 0.013 - 0.022$

Laboratory data: 0.006-0.016 (avg 0.01)

# Settlement Interpretation

## Prior to adjacent construction

- Stress comparison to  $\sigma'_p$
- Secondary compression was strong contributor
- Some consolidation may have still been occurring
- Acceleration following onset of adjacent construction

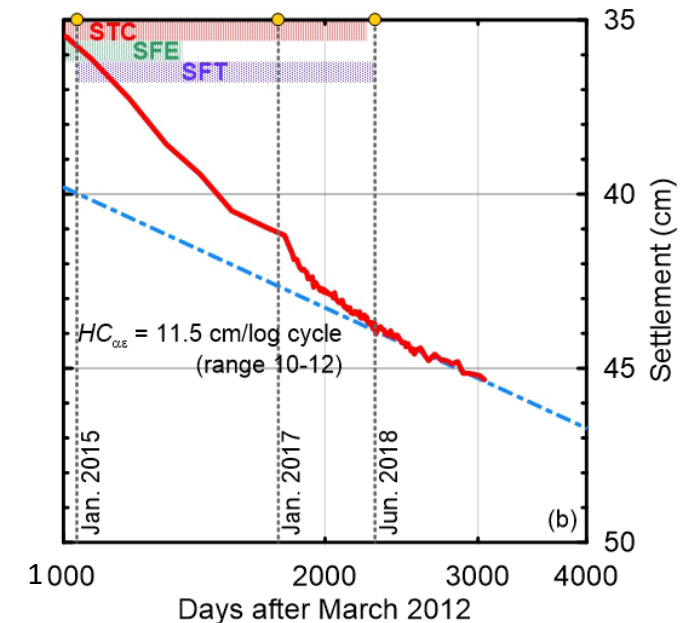
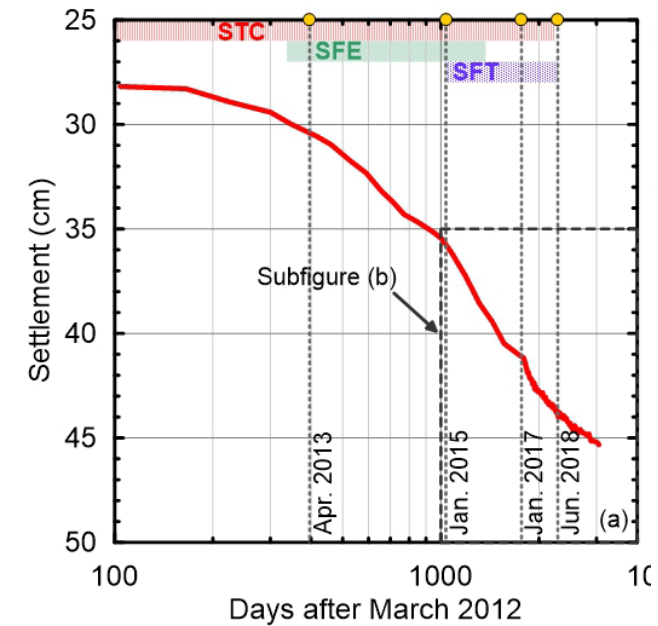


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Prior to adjacent construction

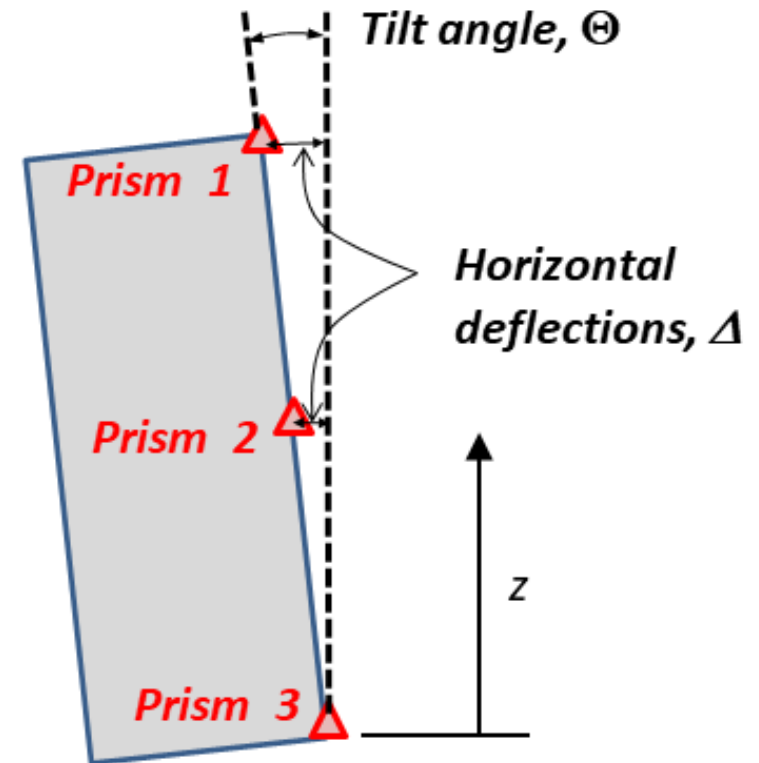
Since 2012

- Concept of time “reset”
- Reset in 2012
- Pattern complicated by multiple loading cycles
- Recent slope suggests consolidation is complete



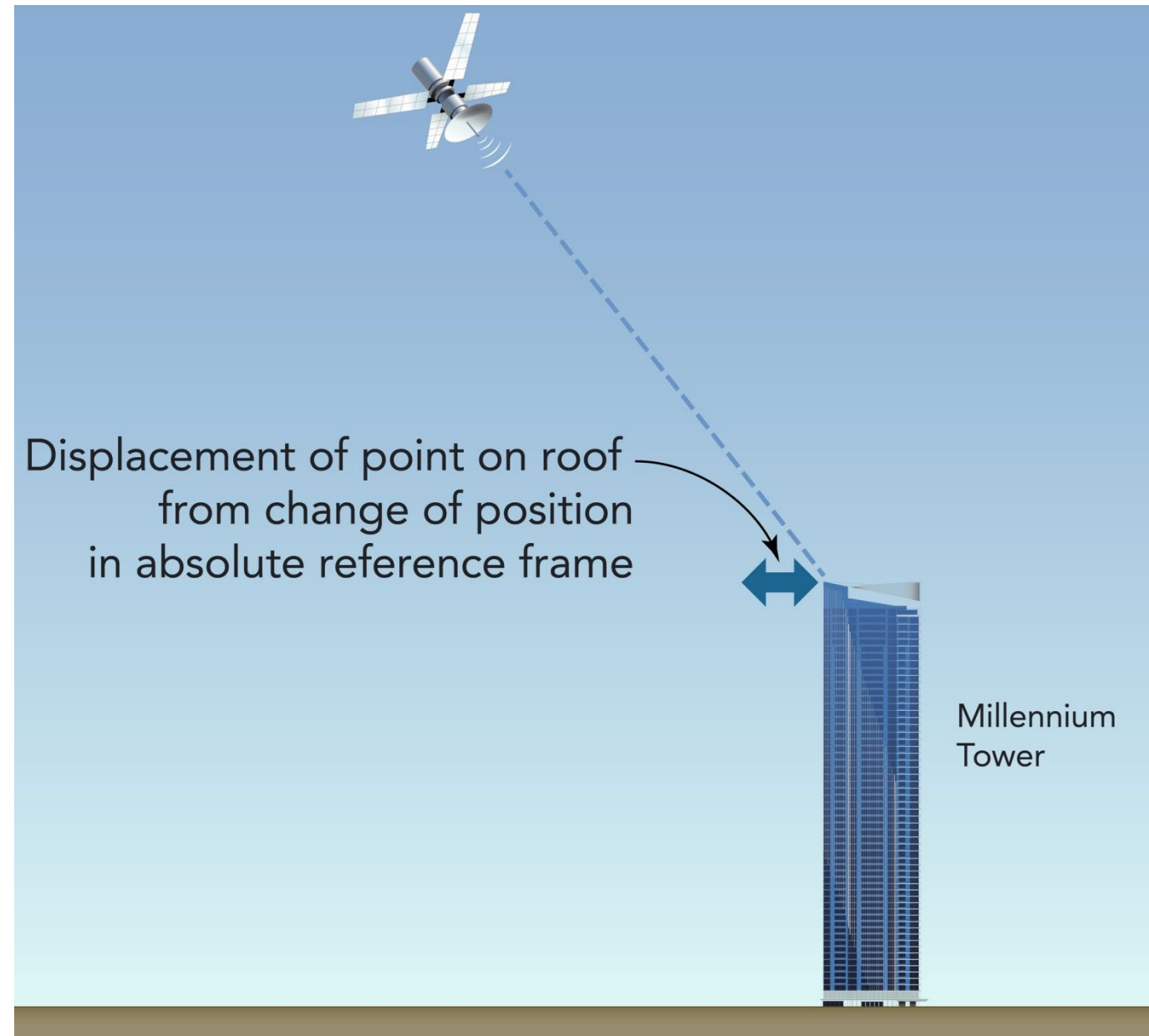
# Tower Tilt

- Prisms (Jan '17 – present)



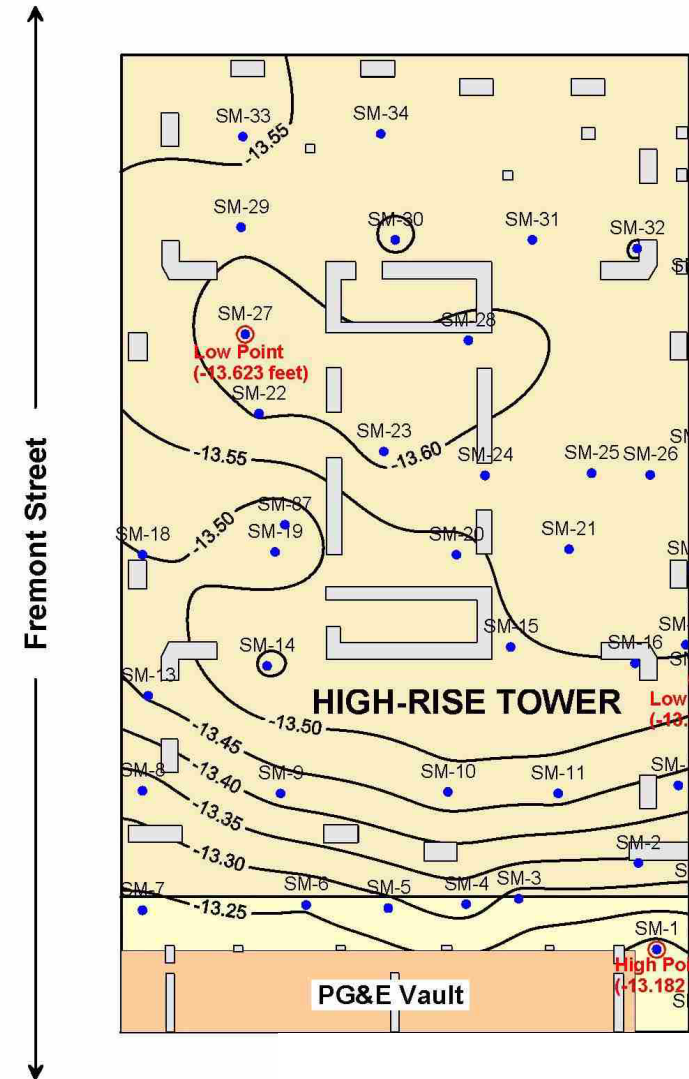
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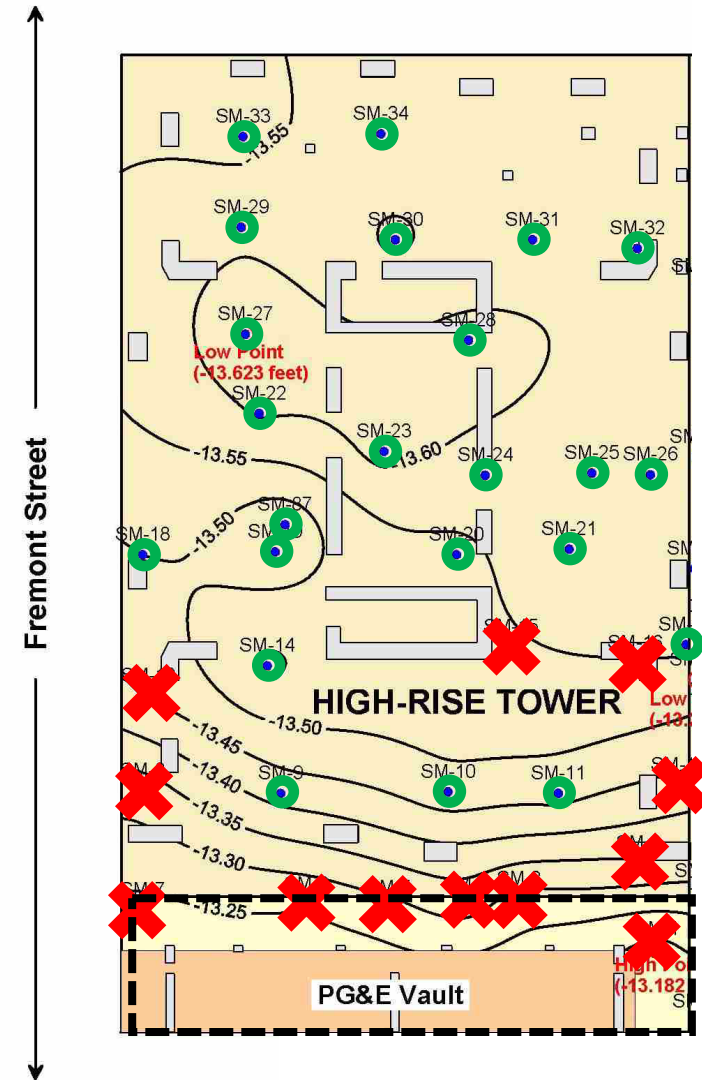
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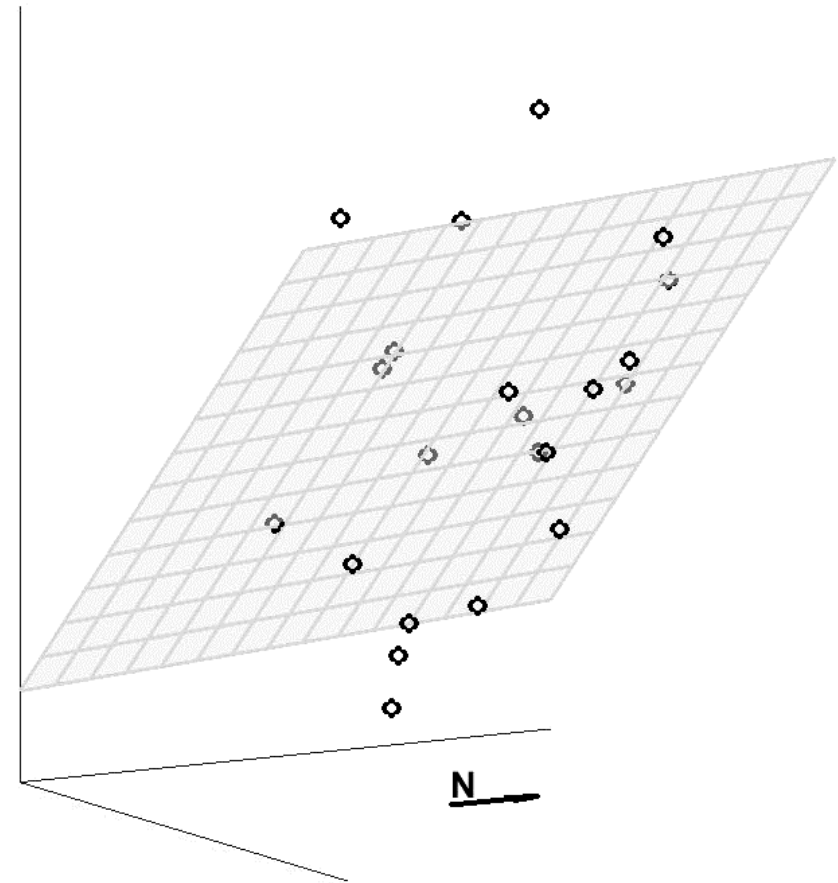
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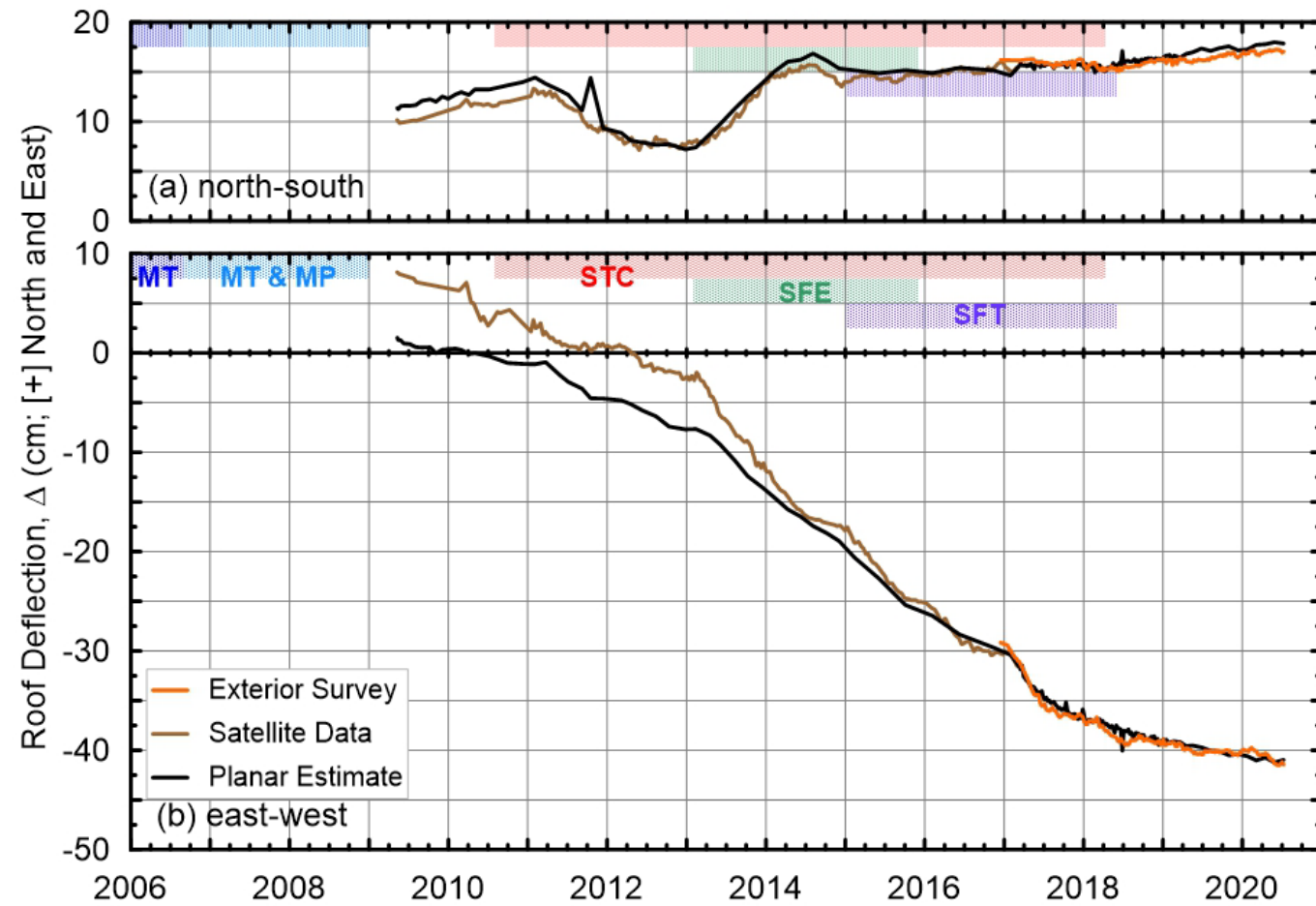
## Planar fit

Angles from horizontal:

$$\theta_{ew} \text{ \& } \theta_{ns}$$



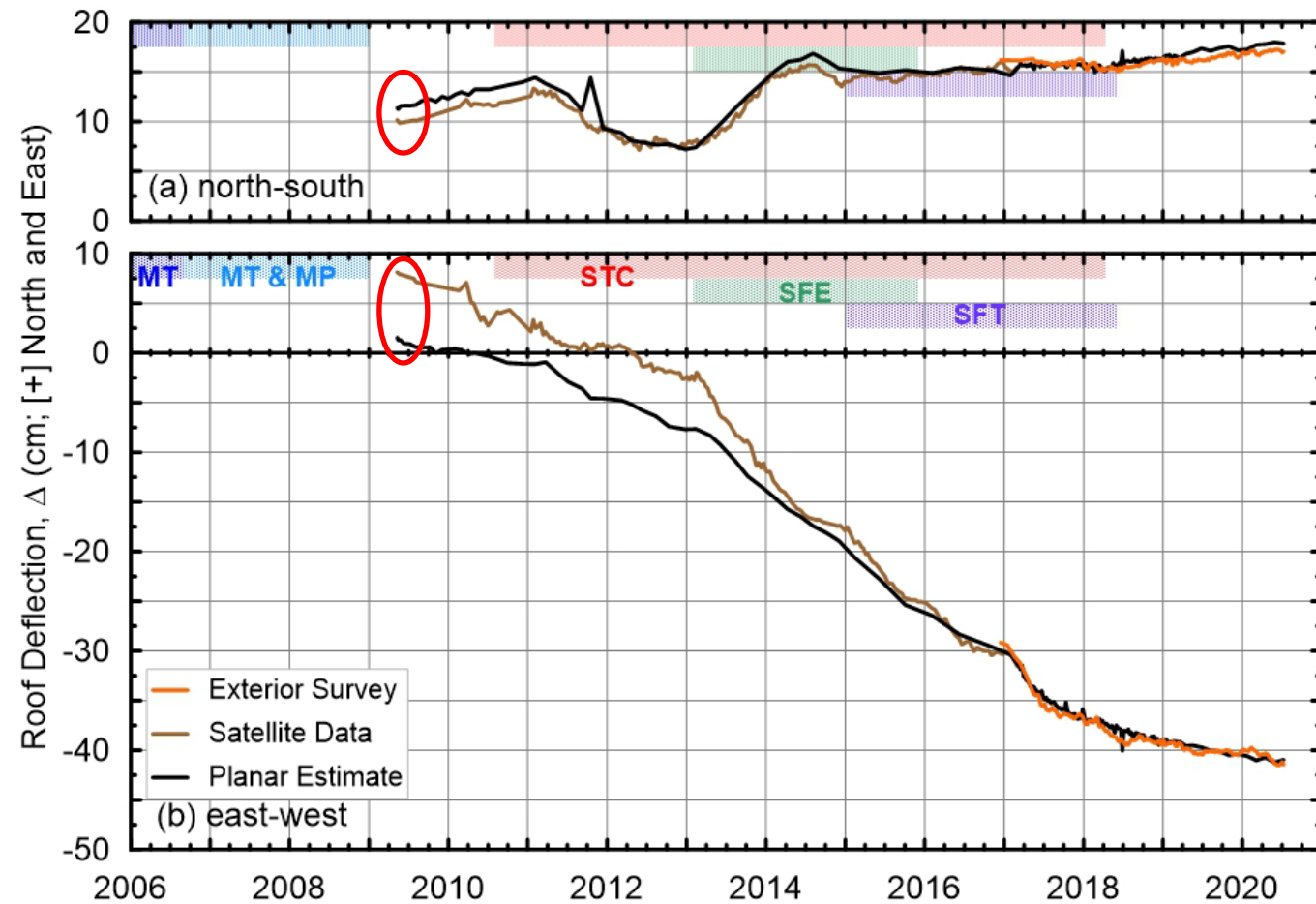
# Tower Tilt



# Tower Tilt

Initial (May '09) tilts estimated

- Why initial tilt to east?

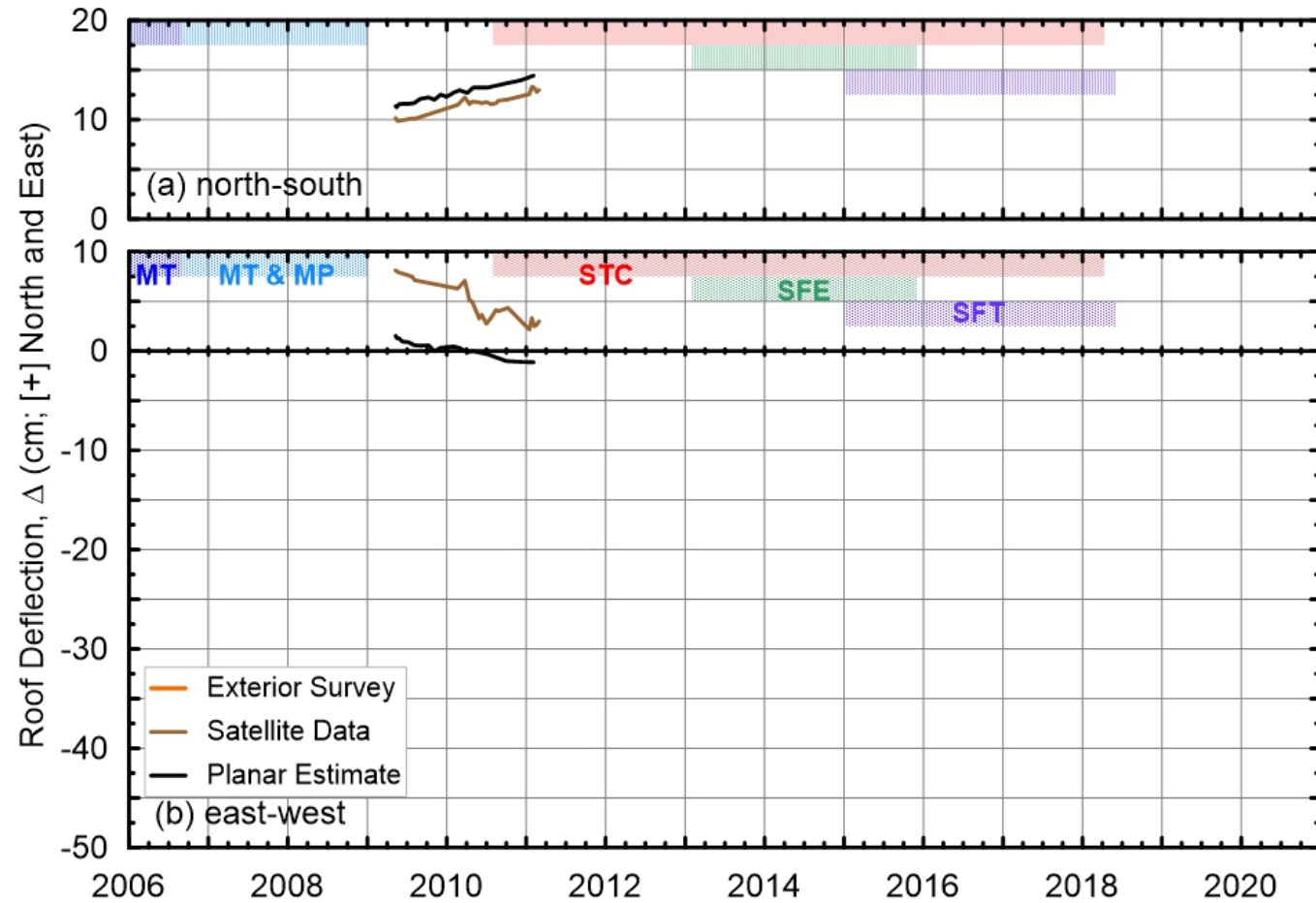
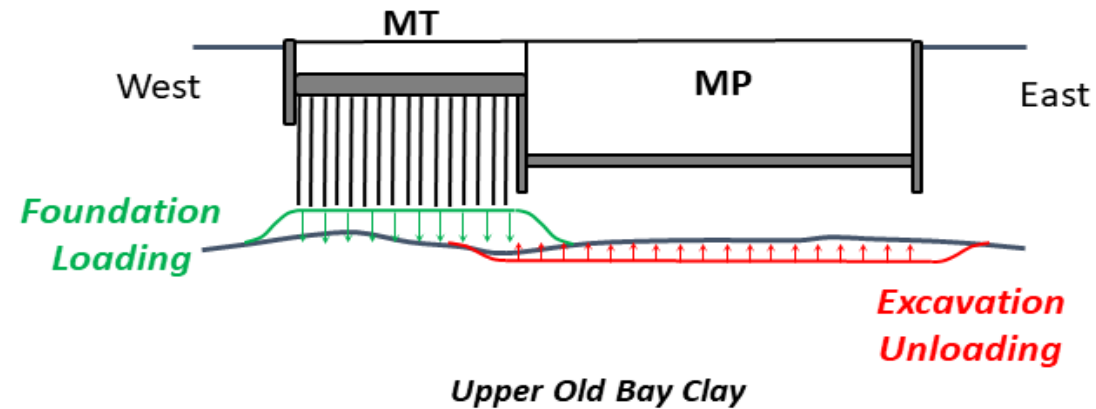


# Tower Tilt

Initial (May '09) tilts estimated

2009-11: movement to north and west

- Why the west trend in tilt?

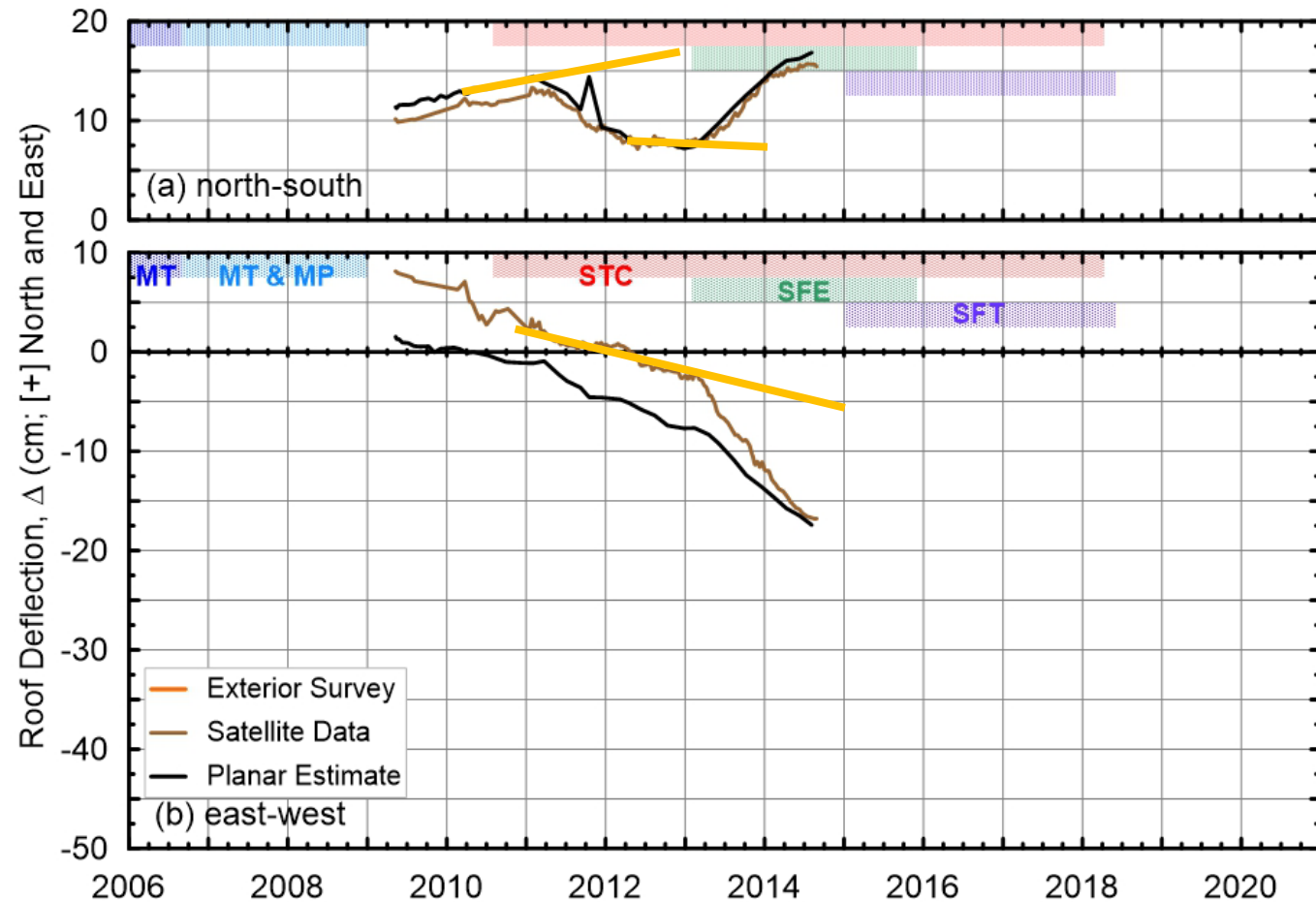


# Tower Tilt

Initial (May '09) tilts estimated

2009-11: movement to north  
and west

2012-13: STC dewatering &  
excavation. 2013 SFE





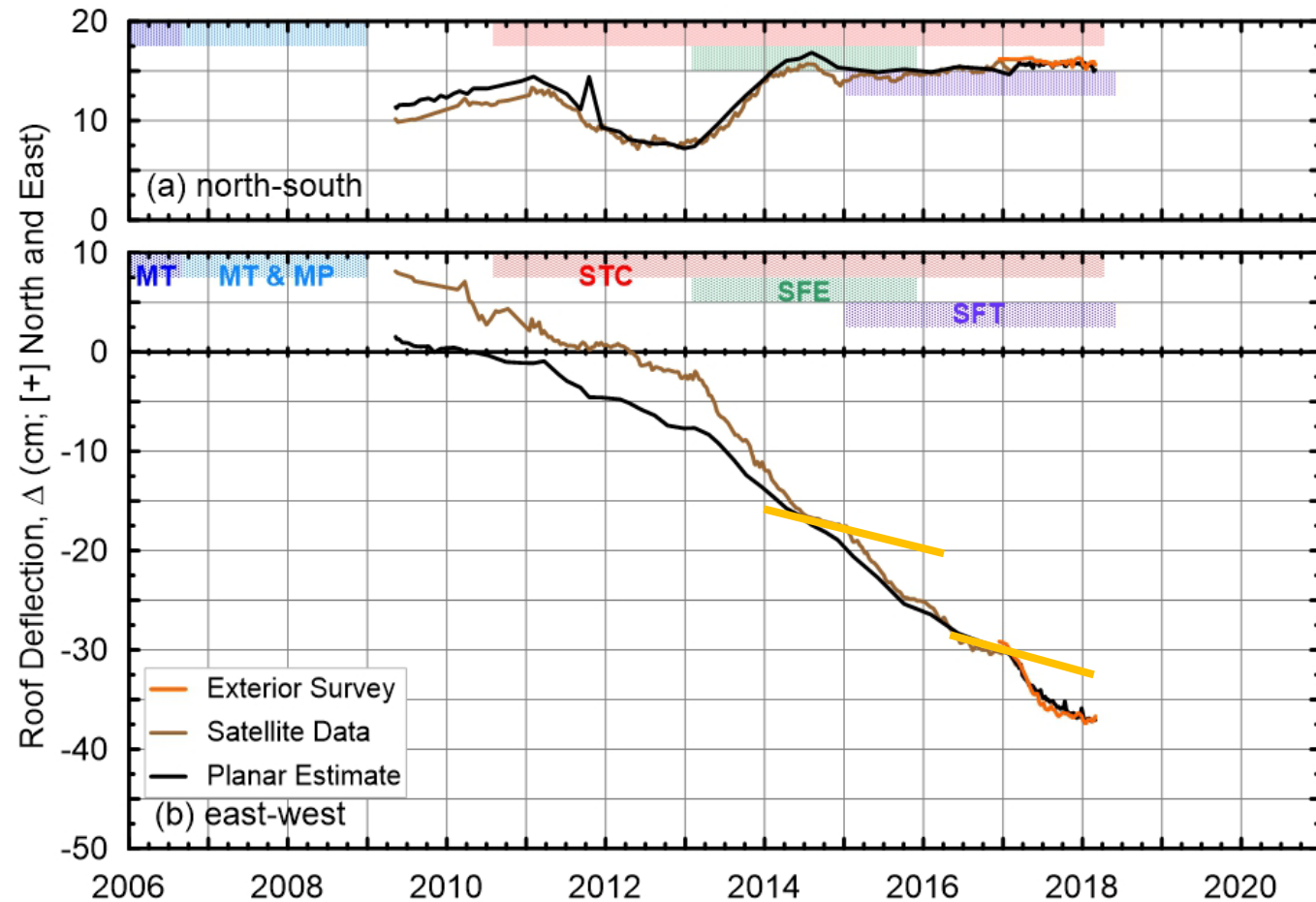
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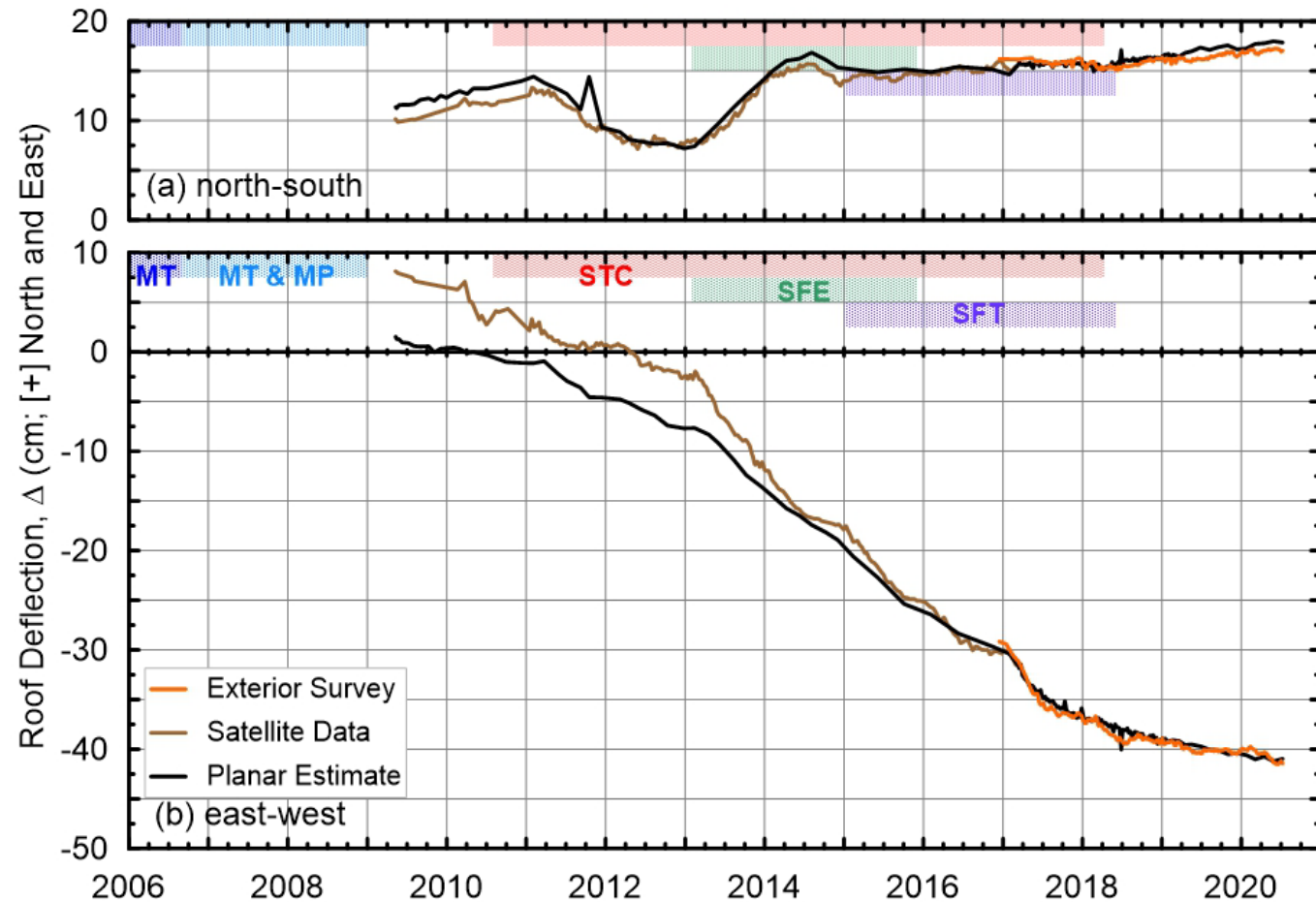
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2009-11: movement to north  
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2012-13: STC dewatering &  
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2015-18: SFT / plaza  
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After 2018: deceleration of W  
tilt



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# Simulations

- 1D & 3D
- Main objectives:
  - Are observed foundation movements predicable?
  - Relative significance of volume change and shear deformation on settlements

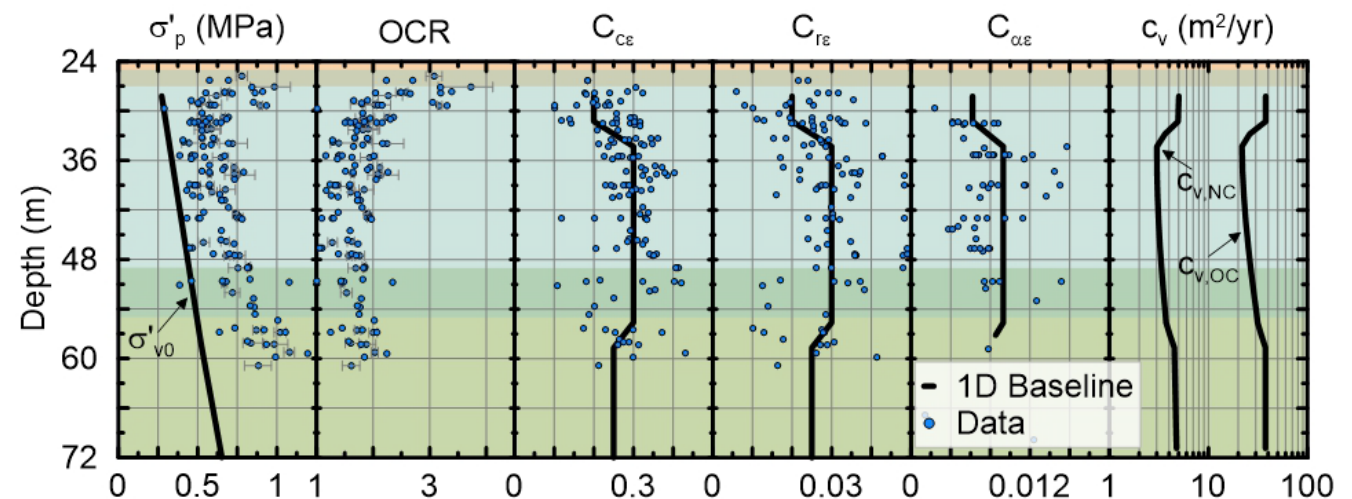


# 1D Settlement Predictions

Finite difference solution of Terzaghi (1925) diffusion PDE:

- Time-dependent: loading,  $u$ ,  $c_v$
- Creep considered during and after primary consolidation

Baseline soil properties and their variability



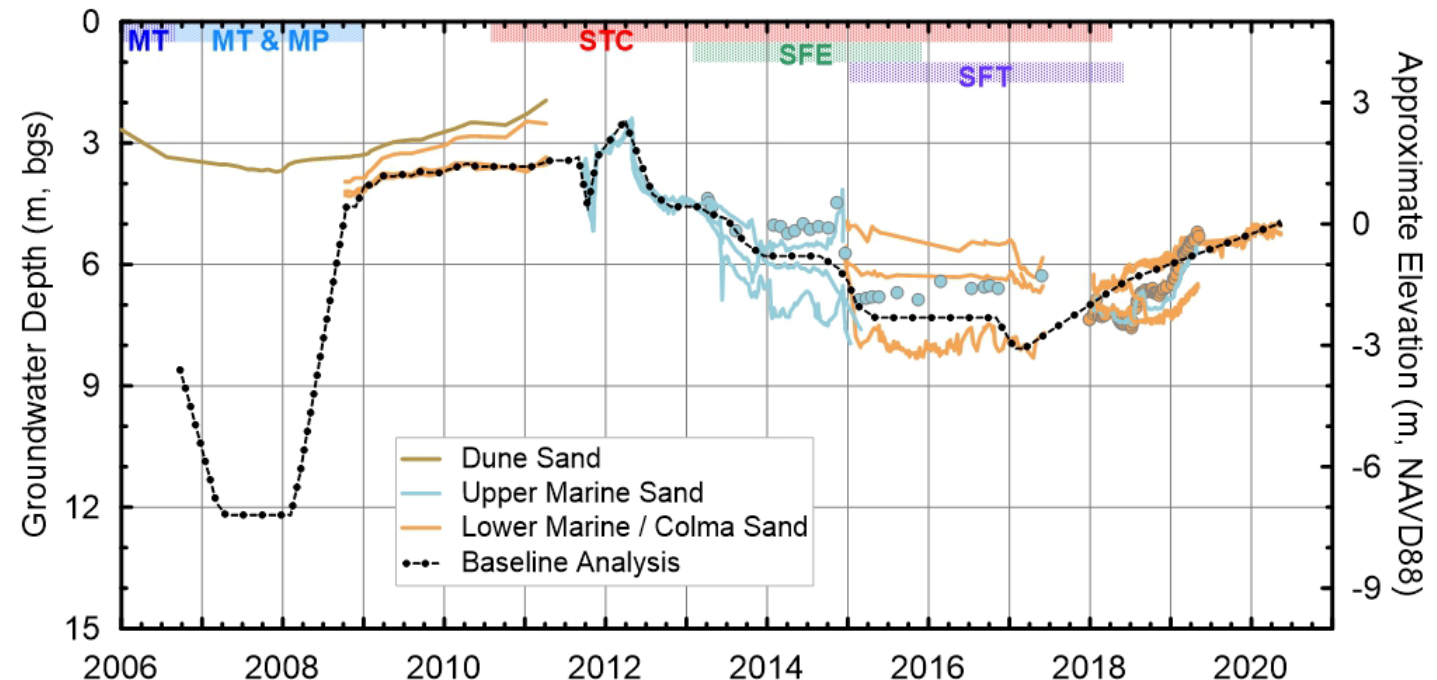
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Baseline soil properties and their variability

Adjacent construction considered through gw variations in time

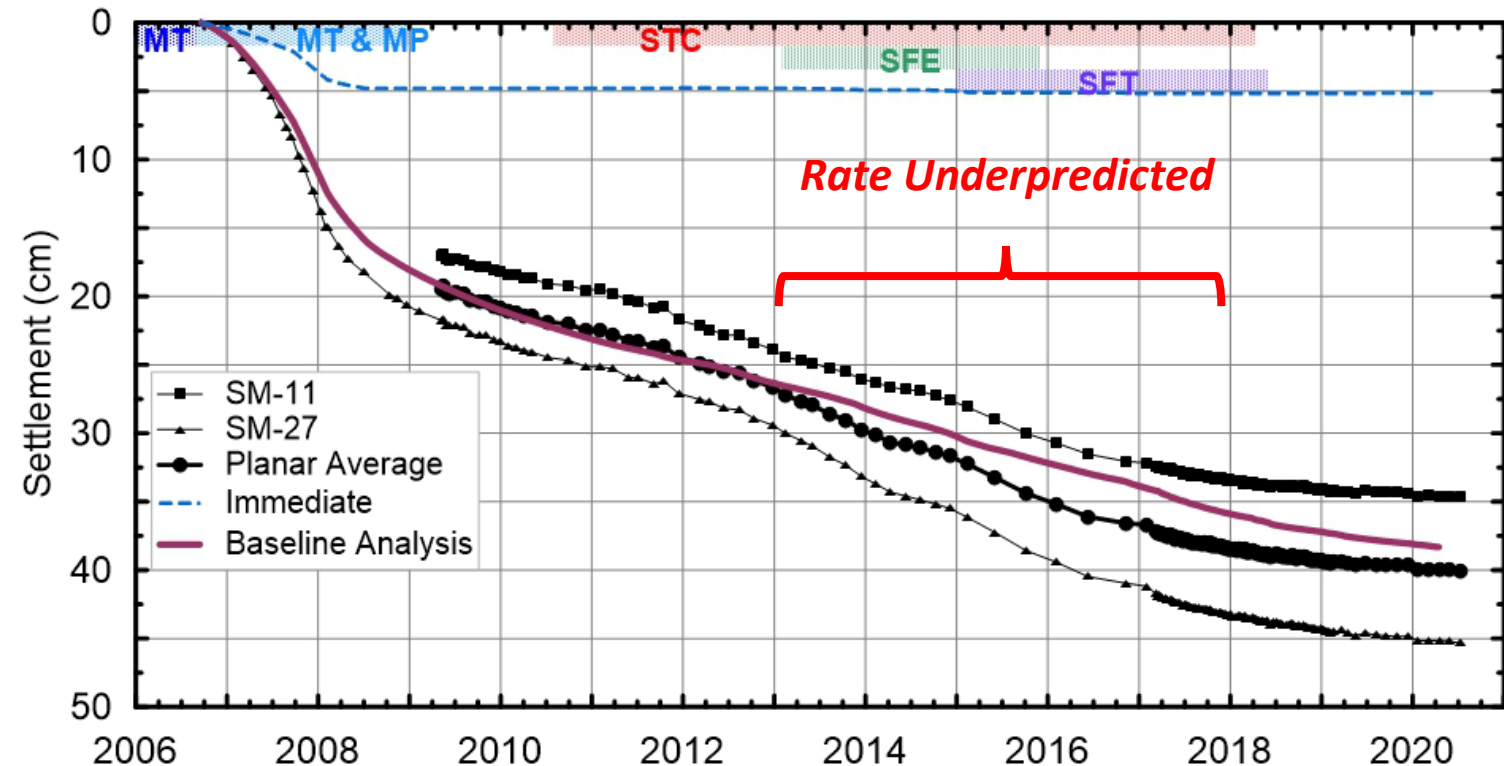




# 1D Settlement Results

## Baseline properties

- $U_{1D}$ =81% (late 2011)
- $U_{1D}$ =96% (late 4/2019)
- OCR = 1.02 in 5/2020 due to gw rebound (2.1 m)

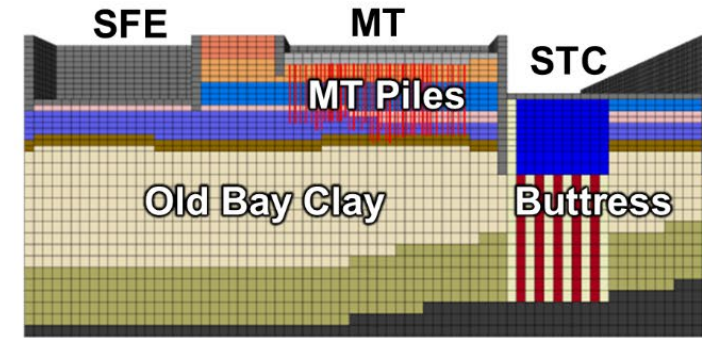
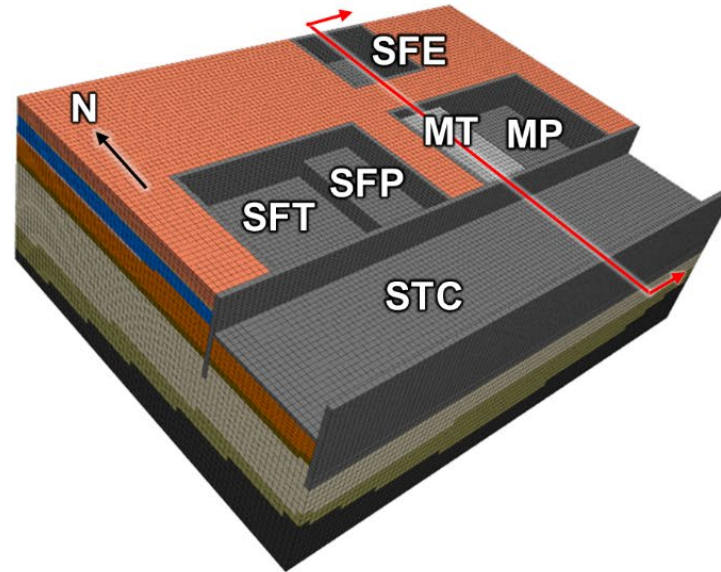


# 3D Settlement Predictions

FLAC3D Ver 7

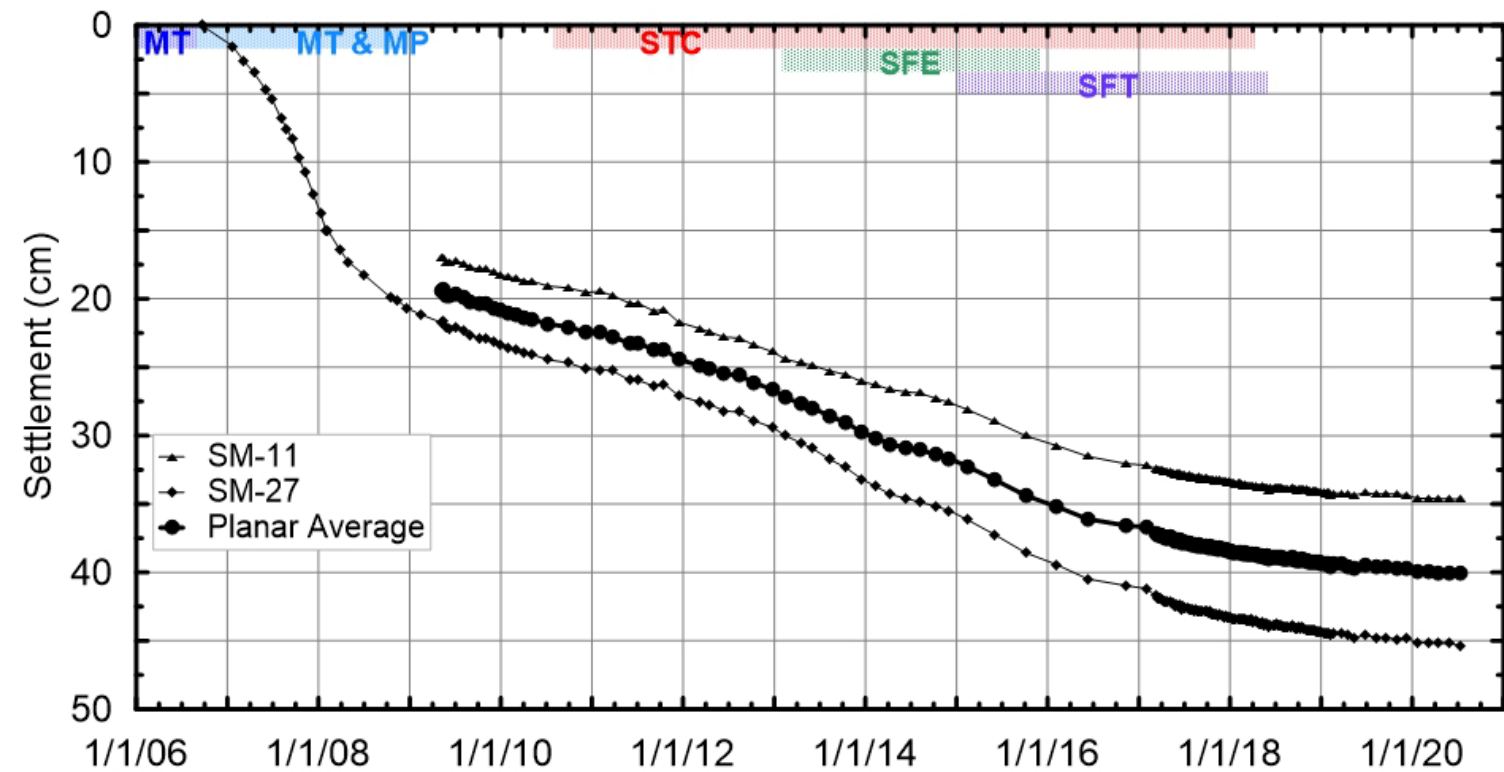
Same properties as 1D, but  
variable stratigraphy

Special calibration of soft  
soil creep model



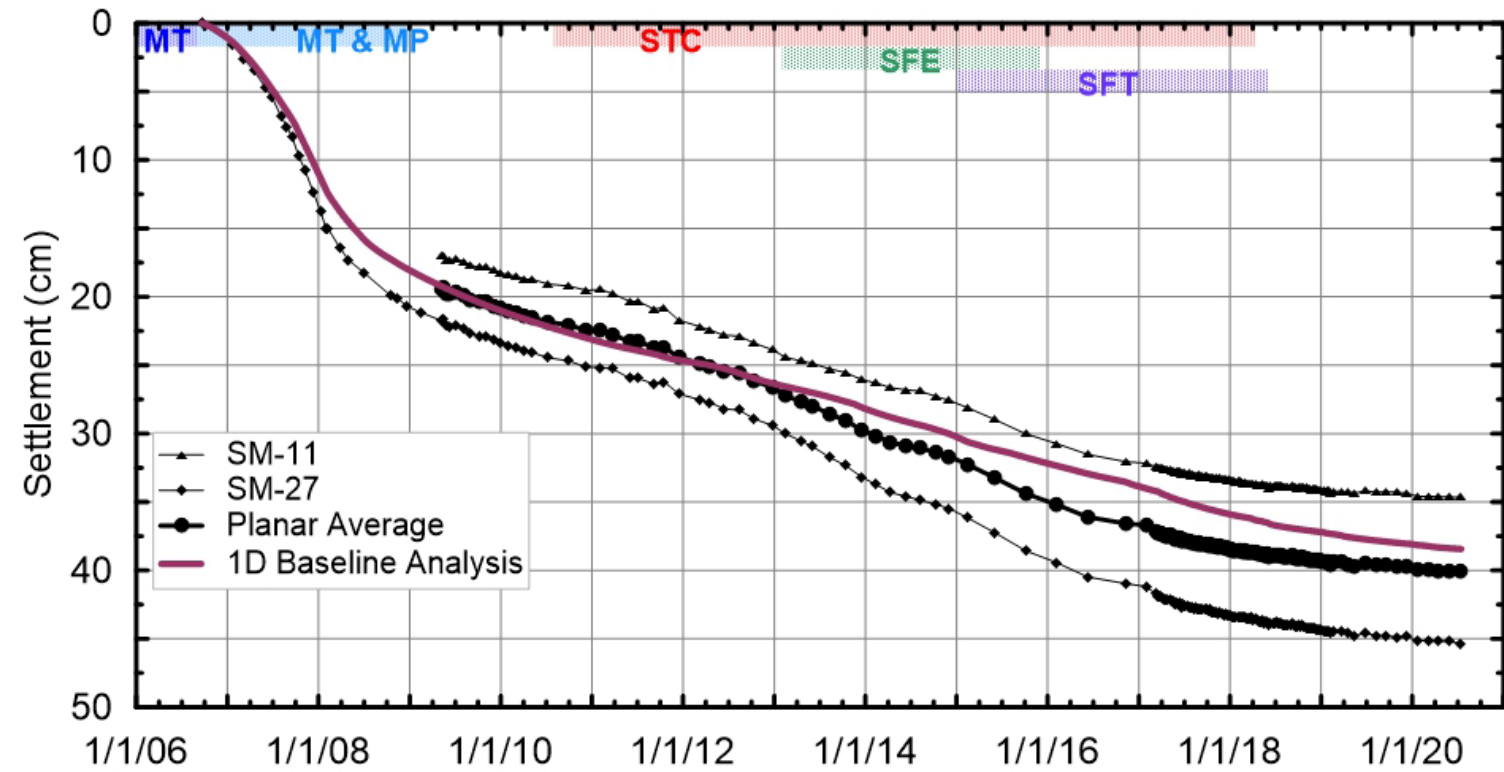
# 3D Results

## Settlement



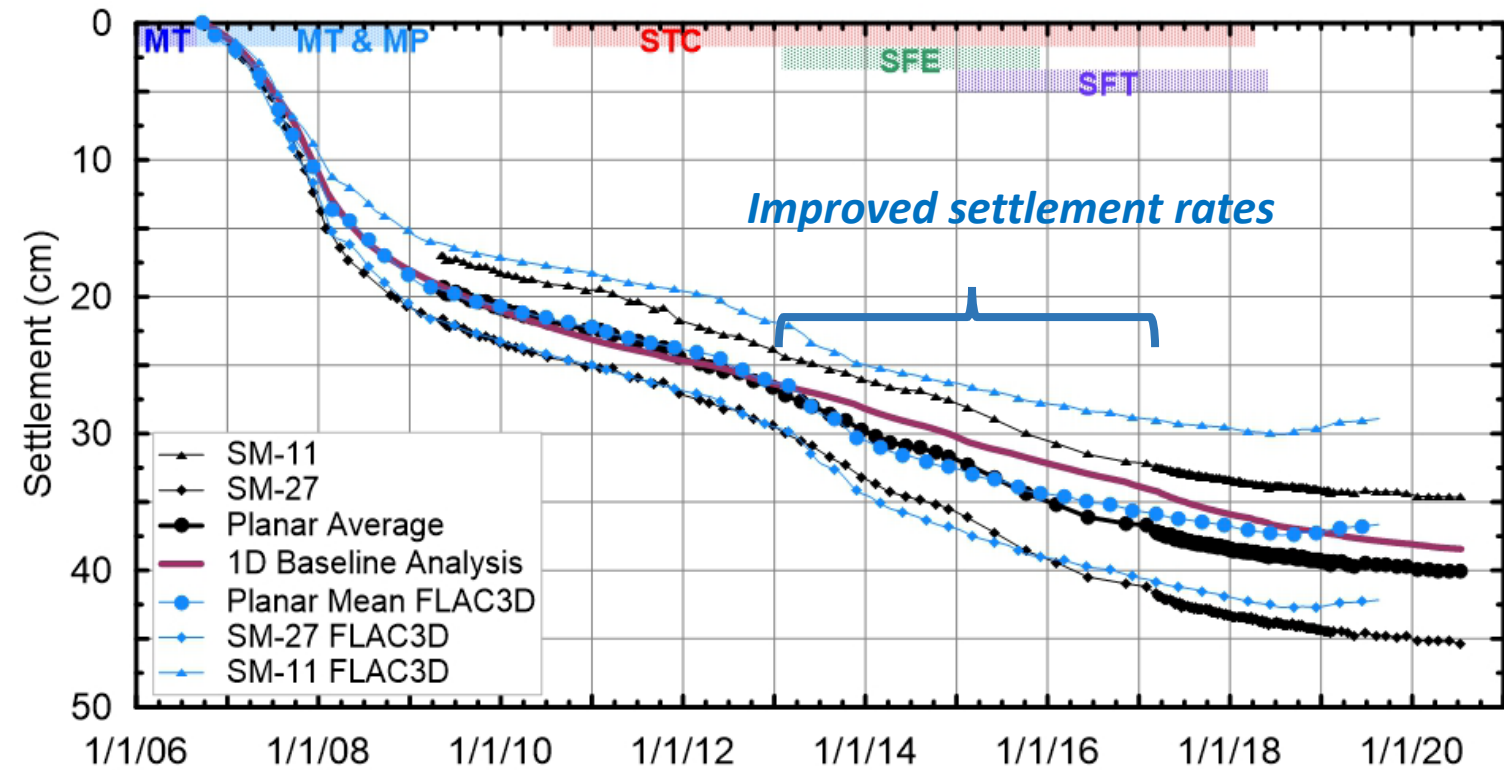
# 3D Results

## Settlement



# 3D Results

## Settlement

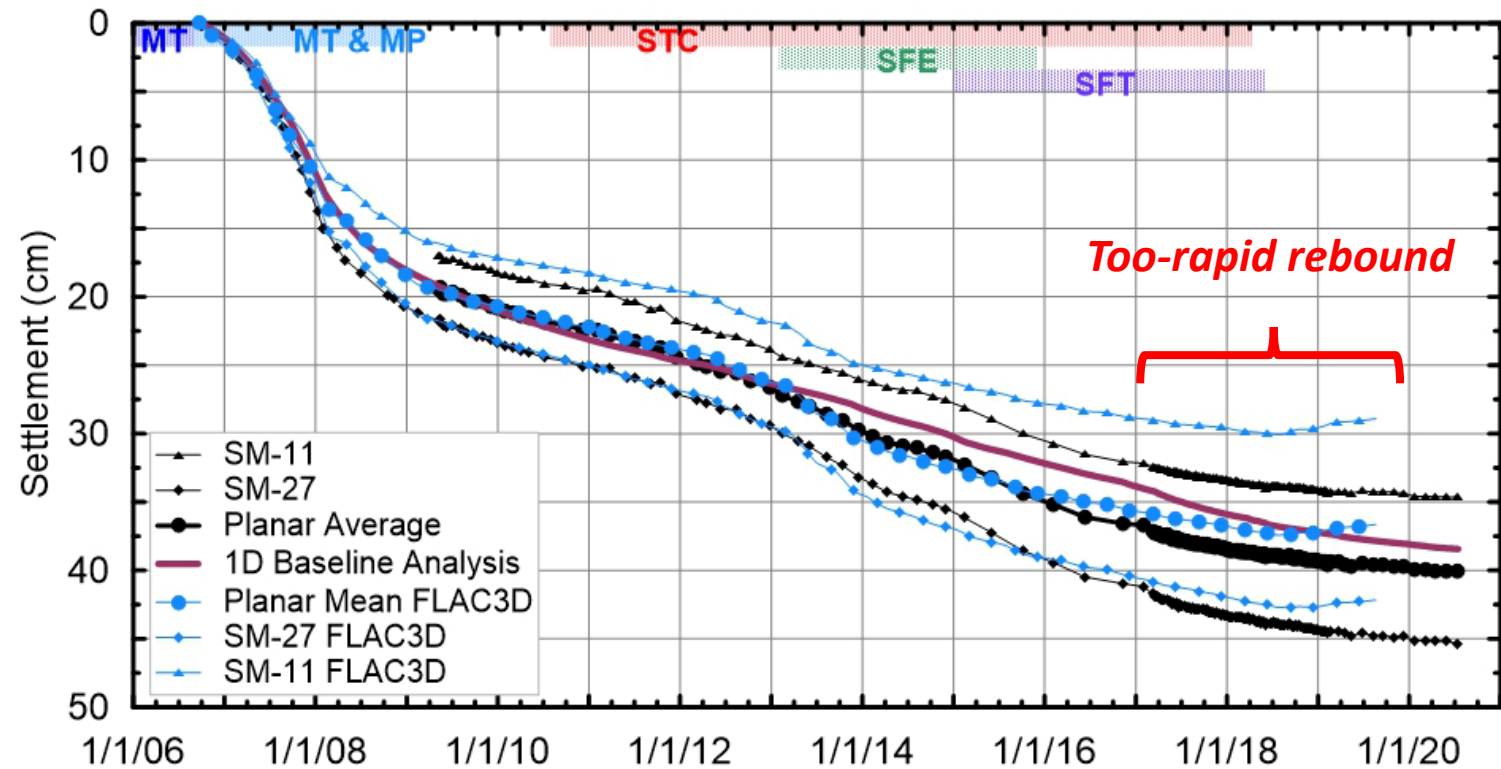




# 3D Results

## Settlement

- $U_{3D}=90\%$  (late 2011)
- $U_{3D}=100\%$  (late 4/2019)



# Outline

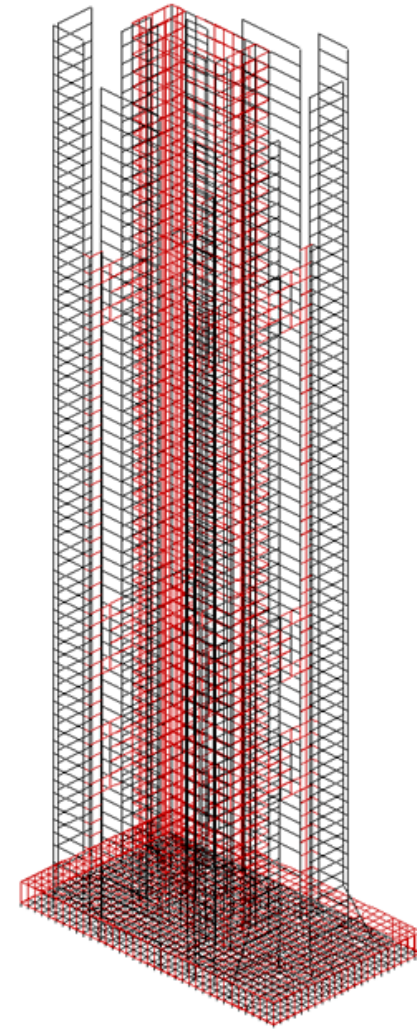
- Millennium Tower: why it matters
- Site conditions
- MT structure and construction timelines
- Foundation movement mechanisms
- Foundation performance
- Simulations
- **Status**
- Lessons learned



# Status

## Structural analysis (SGH):

- Tower “seismic response considering settlement is essentially the same as that neglecting it”

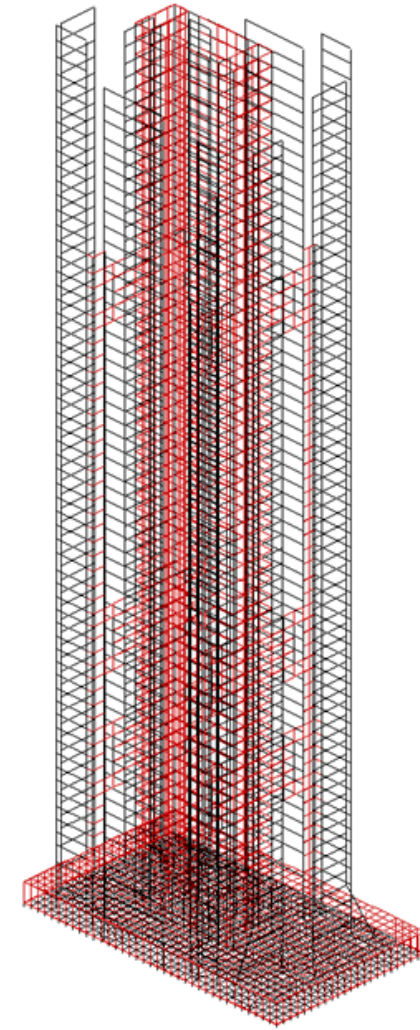


*Courtesy RO Hamburger*



# Status

Structural analysis (SGH):  
Retrofit not required



*Courtesy RO Hamburger*

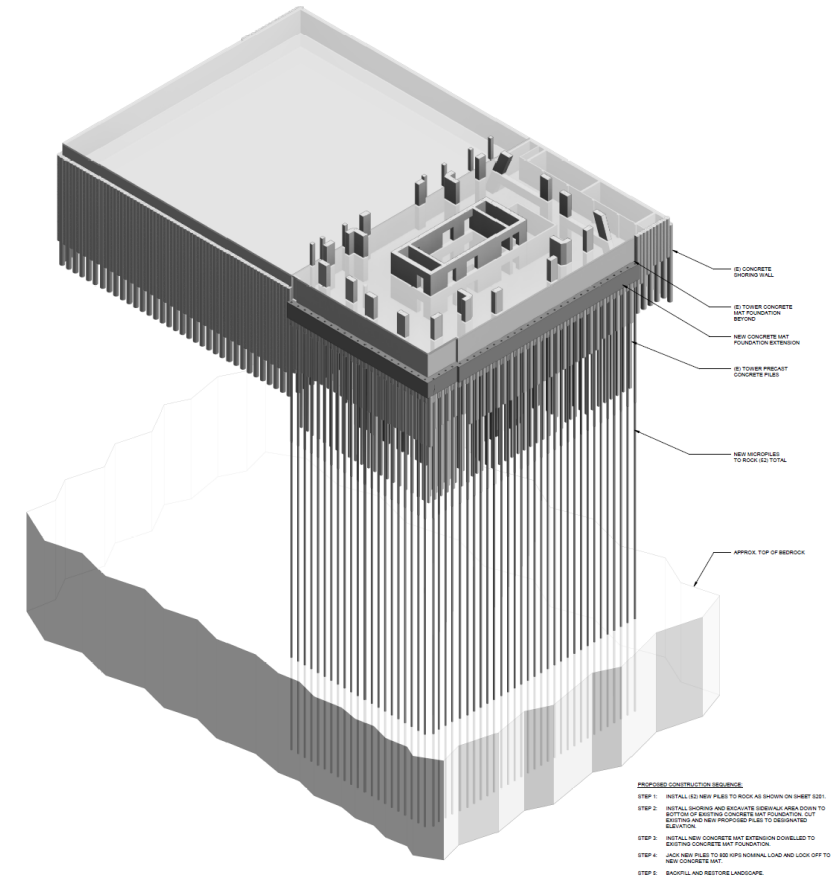
# Status

Structural analysis (SGH):

Retrofit not required

Retrofit underway to address stigma-related losses

- Perimeter piles (N and W sides)



*Courtesy RO Hamburger*

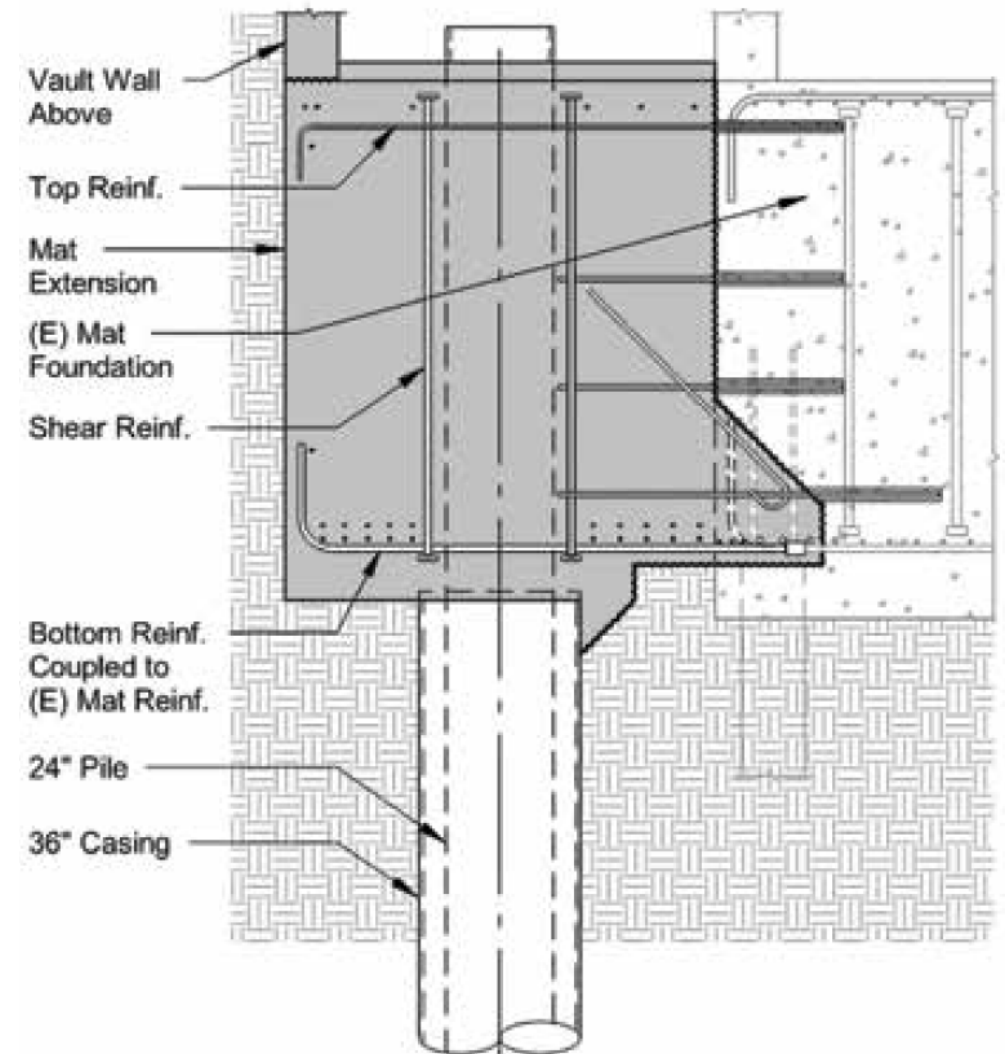
# Status

Structural analysis (SGH):

Retrofit not required

Retrofit underway to address stigma-related losses

- Perimeter piles (N and W sides)
- Mat extension



*Hamburger et al. (2021)*



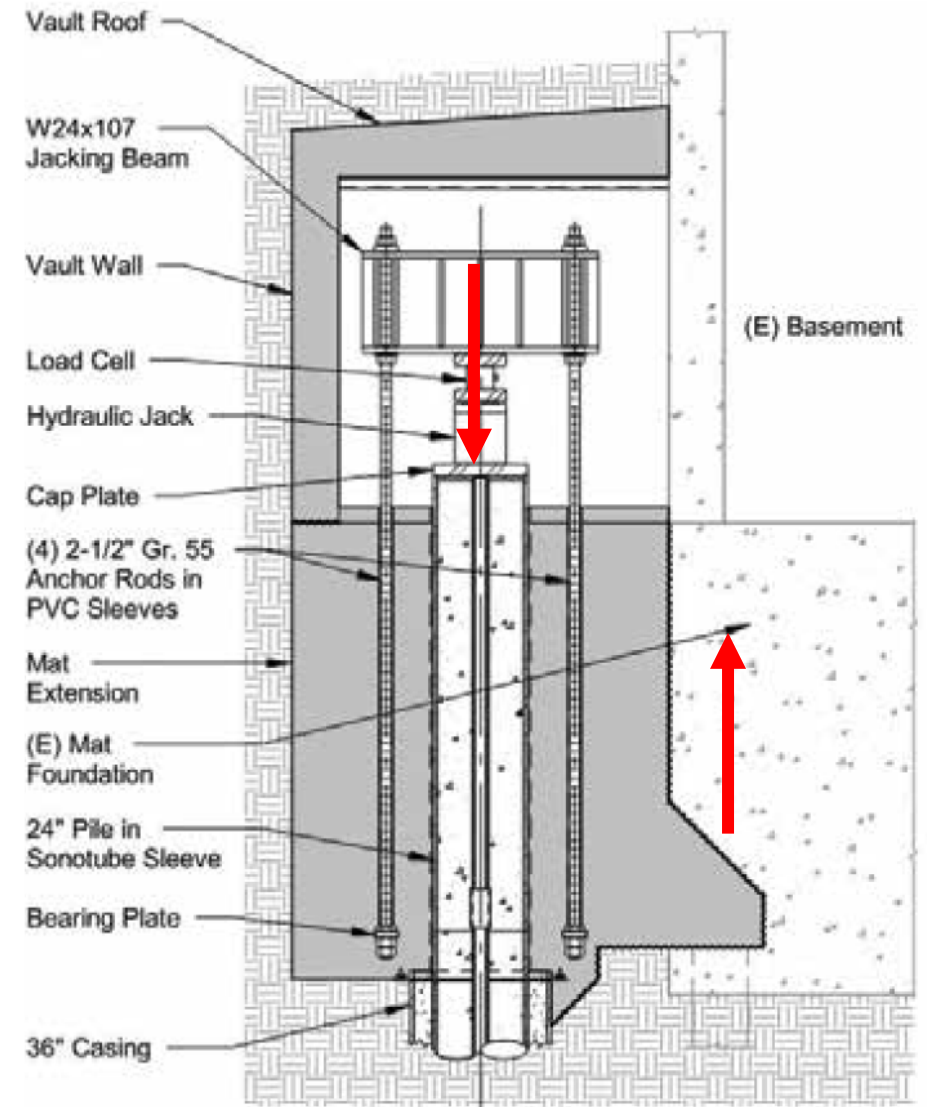
# Status

Structural analysis (SGH):

Retrofit not required

Retrofit underway to address stigma-related losses

- Perimeter piles (N and W sides)
- Mat extension
- Jack piles, to transfer 18% of building load (later reduced)



*Hamburger et al. (2021)*

# Outline

- Millennium Tower: why it matters
- Site conditions
- MT structure and construction timelines
- Foundation movement mechanisms
- Foundation performance
- Simulations
- Status
- **Lessons learned**



# Lessons Learned

Be cautious in application of precedent

Multiple consequential episodes of volumetric and shear deformation in OBC layer

MT foundation sensitive to stress perturbations in OBC due to its nearly normally consolidated state over  $\sim 10$  m depth interval

Volumetric deformations are the dominant contributor to settlements

Original and re-activated deformations are predictable,  $\therefore$  could be anticipated during design and mitigated

## ***More Information***

Secondary compression: Wagner, N, M Largent, JP Stewart, C Beyzaei, D Murphy, J Butkovich, JA Egan (2021). [Stress history-dependent secondary compression of San Francisco Bay region Old Bay Clays](#), *J. Geotech. Geoenv. Eng.*, **147**, 04021045.

Case history: Stewart, JP, N Wagner, D Murphy, J Butkovich, M Saqui, H Nouri, H Curran, D Maffioli, JA Egan (forthcoming). Foundation settlement and tilt of Millennium Tower in San Francisco, California, *J. Geotech. Geoenv. Eng.*, <https://doi.org/10.1061/JGGEFK/GTENG-10244>.