# Predicting ground movements adjacent to braced excavations

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# Outline

- Establishing acceptable movements
- Predicting deformations
- Constitutive model considerations
  - Why small strain stiffness?
- FE model for site
  - Computed results
  - Comparison of Gur with Go

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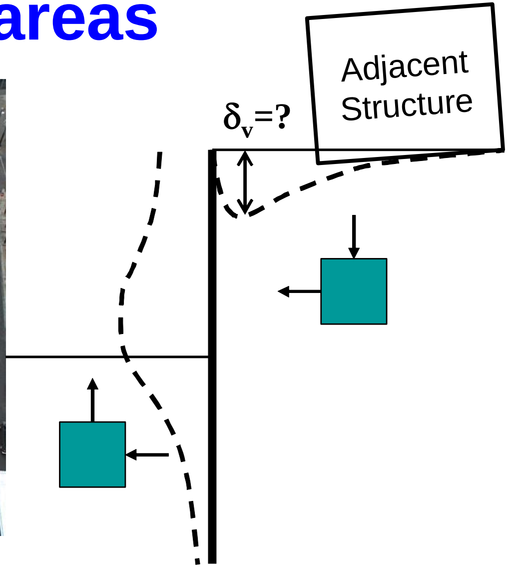
# Design objective for excavations in urban areas




**Prevent damage to urban infrastructure and minimize cost escalations – Serviceability rather than limit state governs**

**Stiffness based design of support system**

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# Allowable movements

- Set by regulatory agency
- Assess damage potential
  - Several methods to assess damage potential exist
  - Most relate damage to cracking of architectural details or load-bearing masonry walls
  - Wide range of limits can be calculated depending on building to be protected
  - Need estimate of movement distribution from wall

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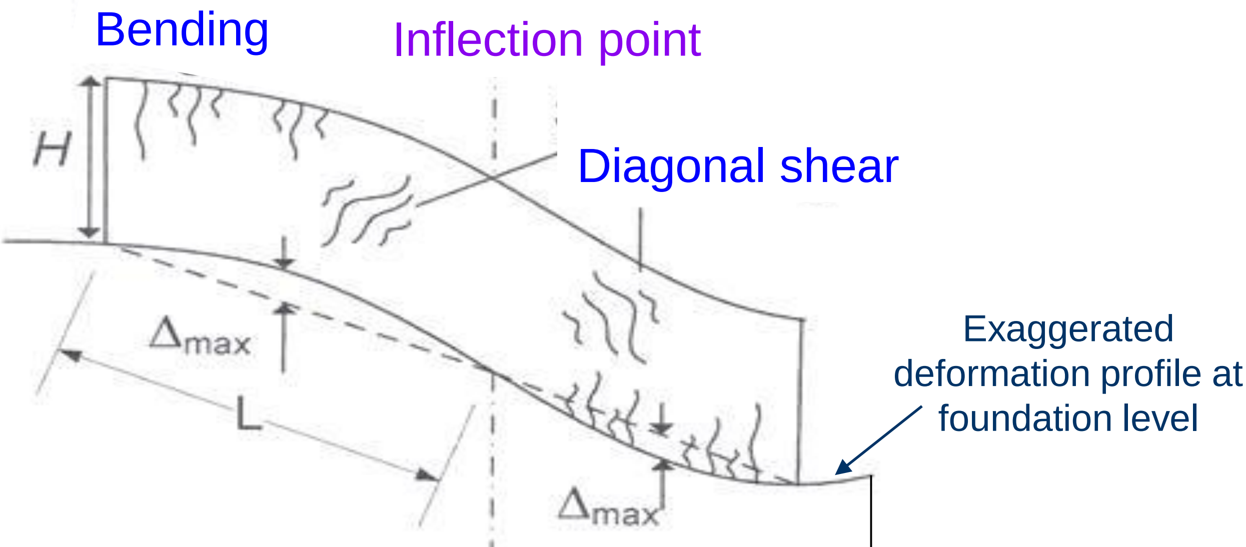
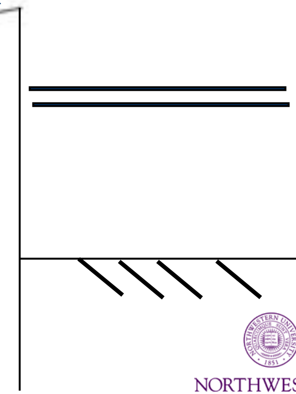
# Settlements, cracking and damage




Deflection ratio, $\Delta_{max}$ /L



Most models represent buildings as a beam and damage is defined in terms of cracking

# Movement predictions

- Magnitude depends on soil conditions, retention system stiffness, adjacent building and construction procedures
- Approaches
  - Precedent (approximate)
  - Numerical analysis
- Always verify in field – construction process has large impact on actual responses

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# How do ground movements develop?

- In response to stress reduction caused by excavation
- Other activities related to excavation and bracing process
  - Demolition of existing structures, foundation elements, utility removal
  - Wall installation
    - Densification of sands from vibrations
    - Displacements arising during installation
      - Slurry or secant pile wall
      - Sheet-pile wall
  - Foundation installation

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# Comments

Commercial codes can an account for

- Cycles of excavation and bracing
- Effects of past construction activities
  - Tunneling
  - Adjacent buildings

Not easily included

- Wall installation
- 3D effects
- Removal of existing foundations
- Installation of foundations

# Constitutive models

- A key factor in analysis
- Generally, selection depends on:
  - Purpose of analysis
  - Quality of data on which parameters are based
  - Type of information desired as outcome
- Soil is an incrementally non-linear material (e.g., Burland and Symes 1982; Jardine et al 1984; Callisto and Calebresi 1998; Clayton and Heymann 2001; Santagata et al 2005, Finno and Cho 2010)

For analyses where ground deformations are key output, need model with non-linear behavior, and preferably with small strain stiffness capabilities

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# Stress-strain characterization

Bender elements
Internal instrumentation

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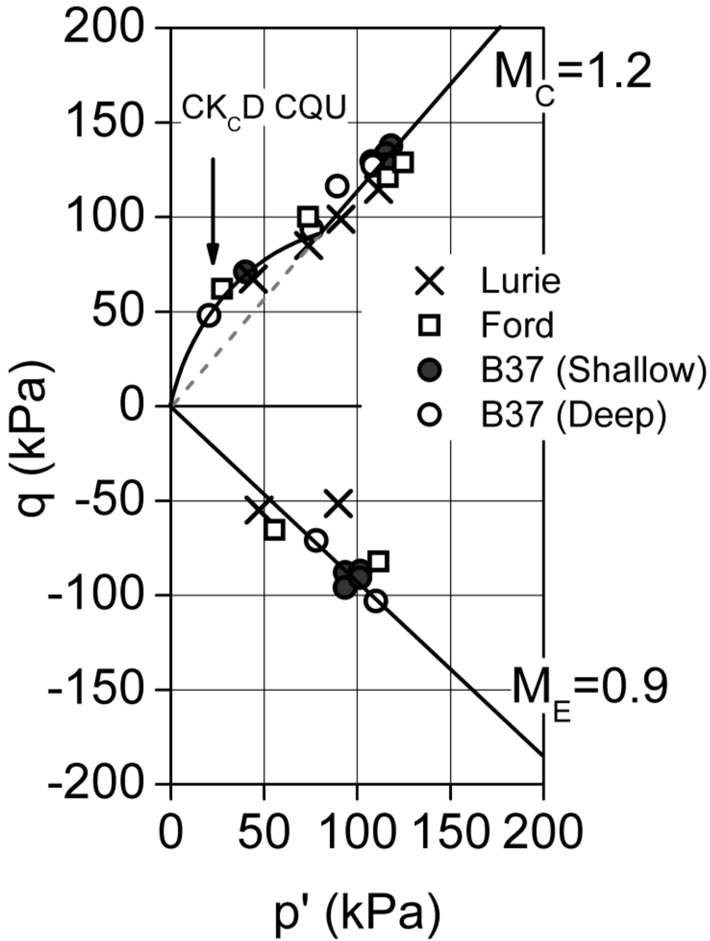
# Failure conditions

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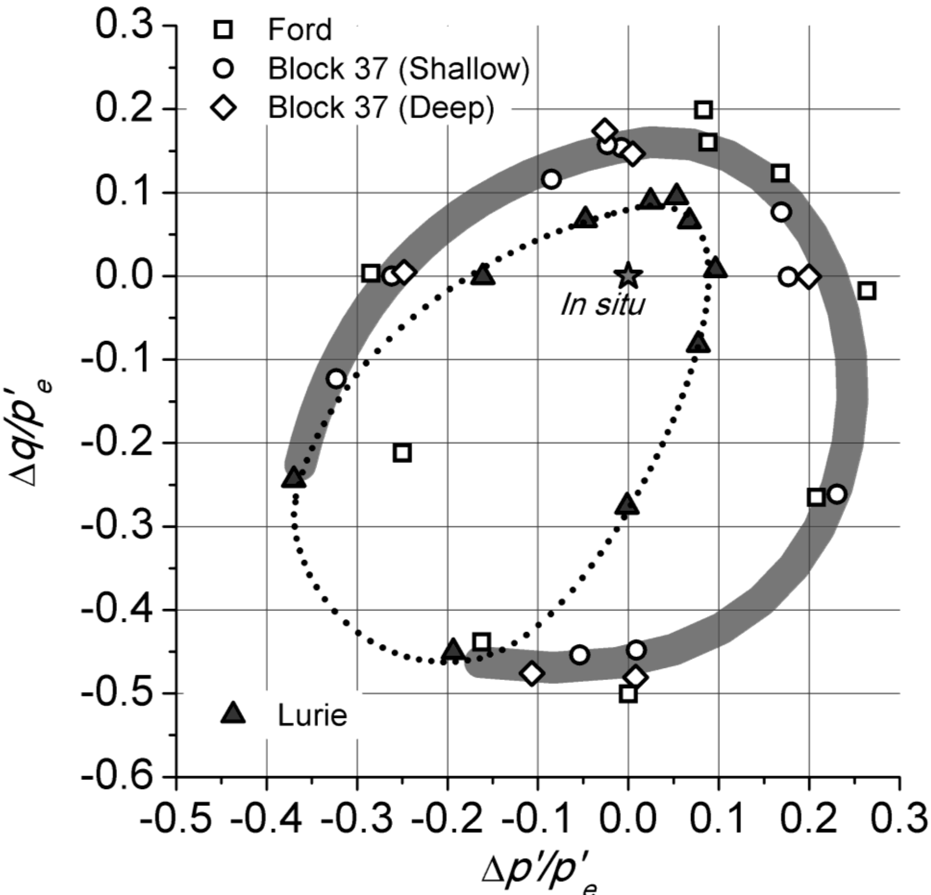
# Normalized yield surfaces




Difference: that occurred during saturation!

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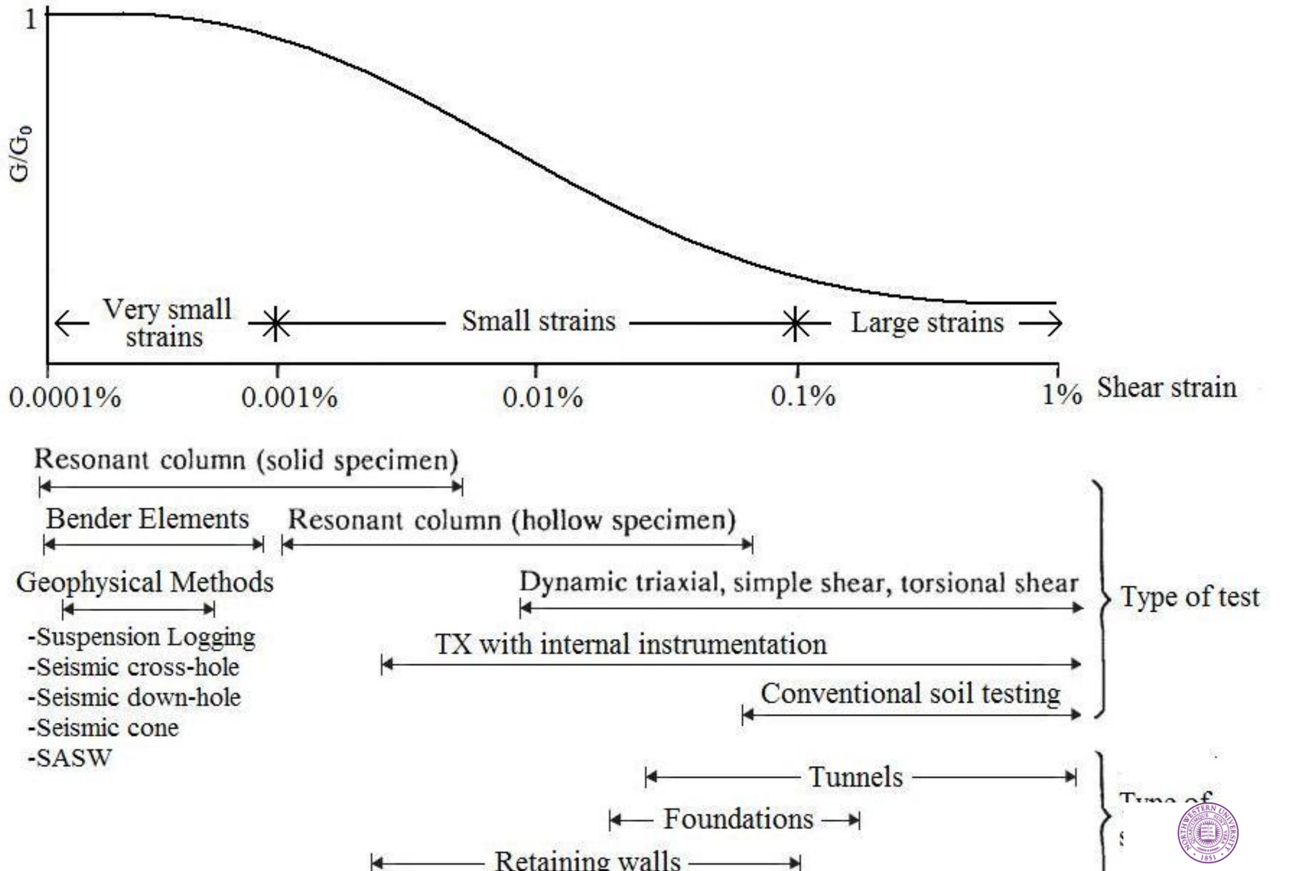
# Small strain stiffness




Designed to minimize movements

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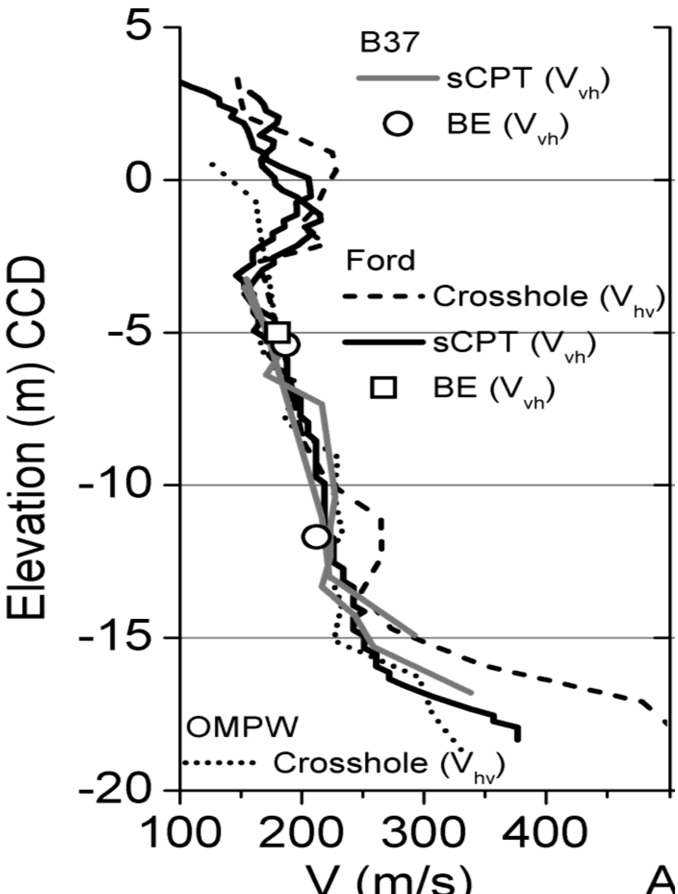
# Initial shear stiffness variations




Soft to medium clays with OC crust

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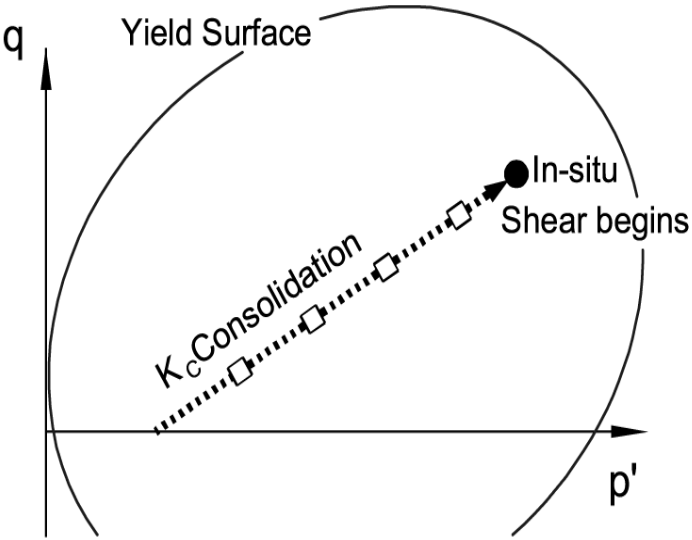
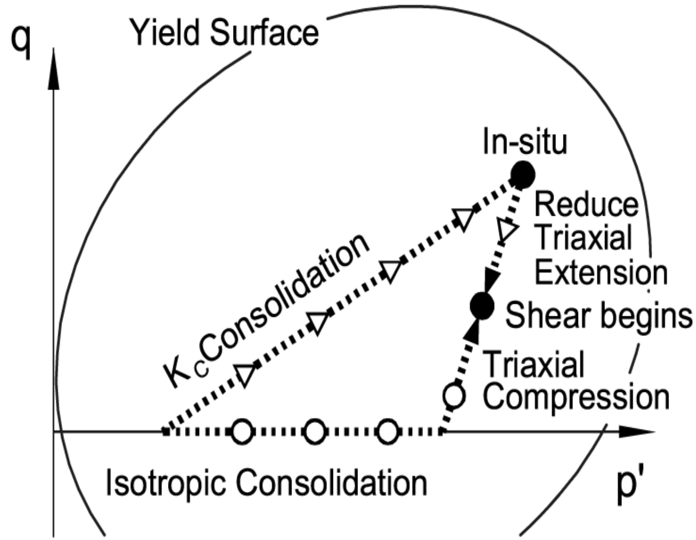
# Stiffness degradation is more complicated




Direction of loading

Recent stress history

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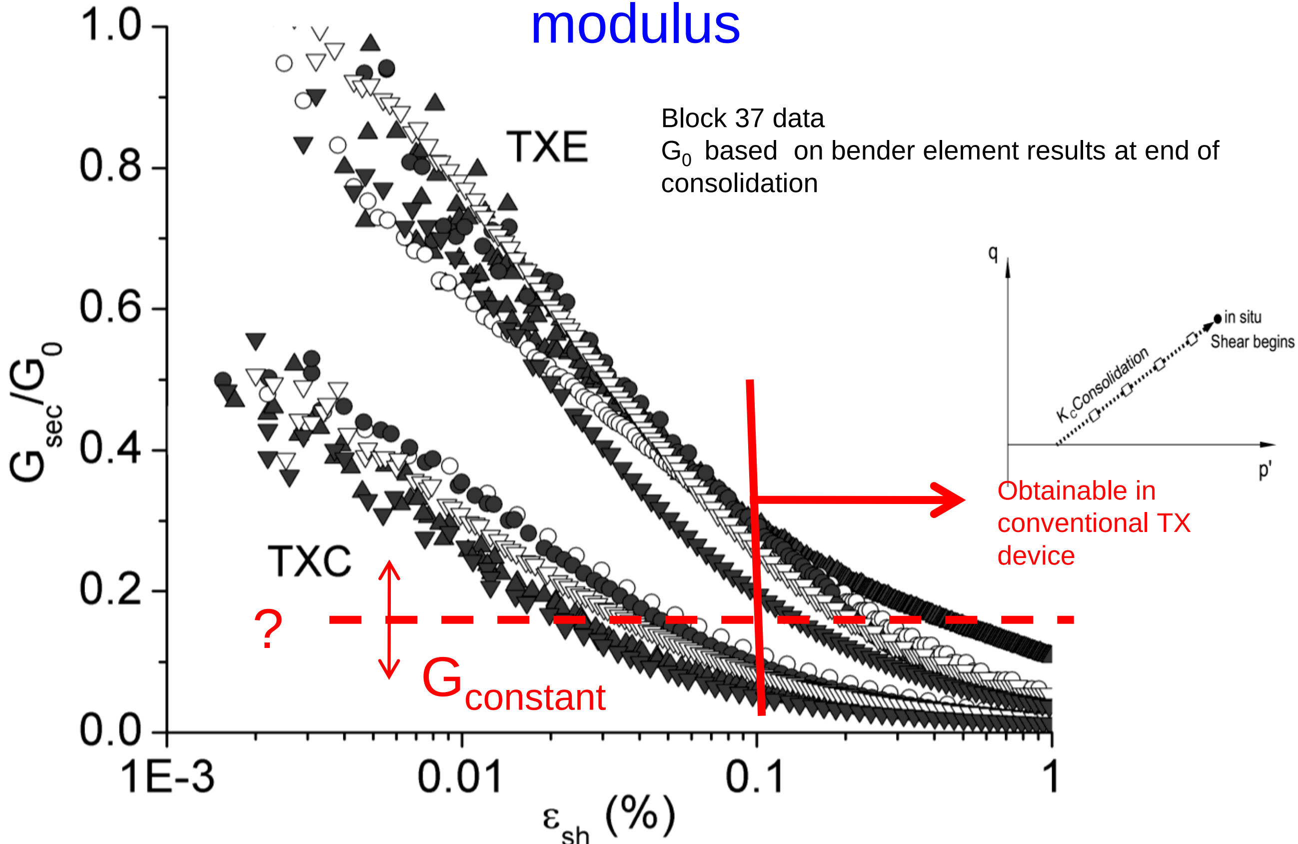
# Direction of loading - normalized secant shear modulus

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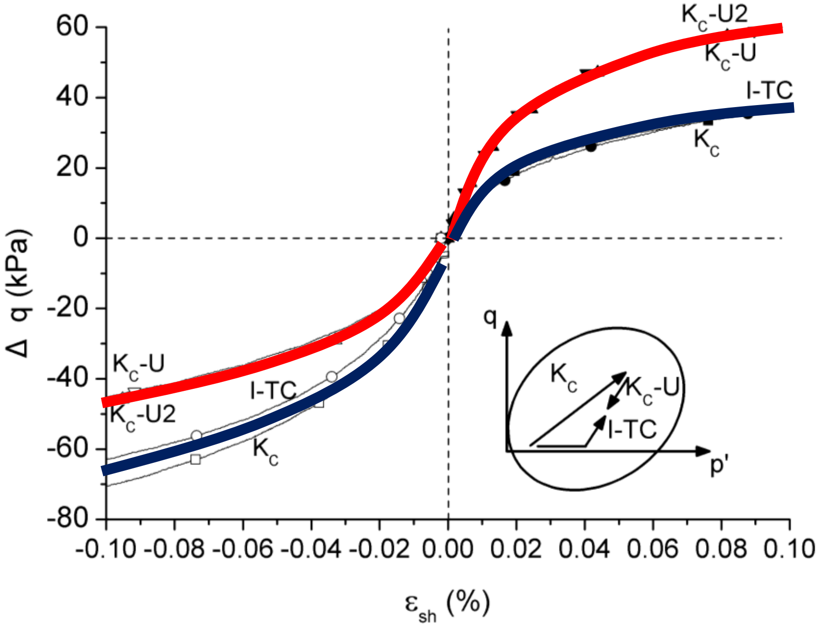
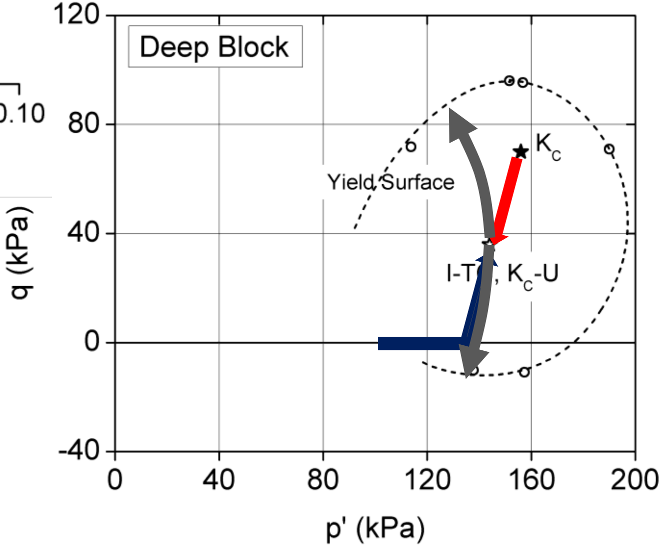
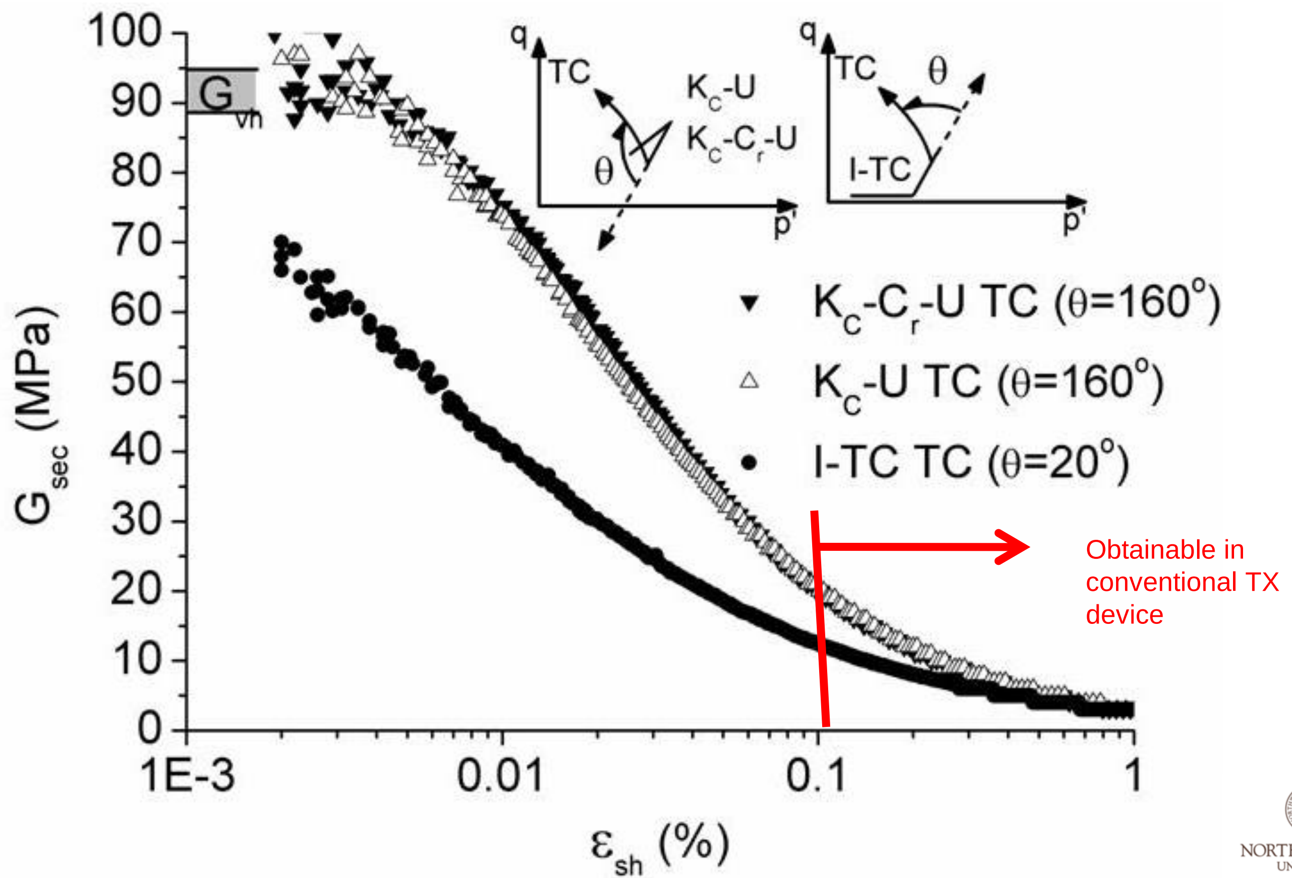



# Effects of recent stress history on stress-strain responses



# Recent stress history (a function of rotation angle) - normalized secant shear modulus

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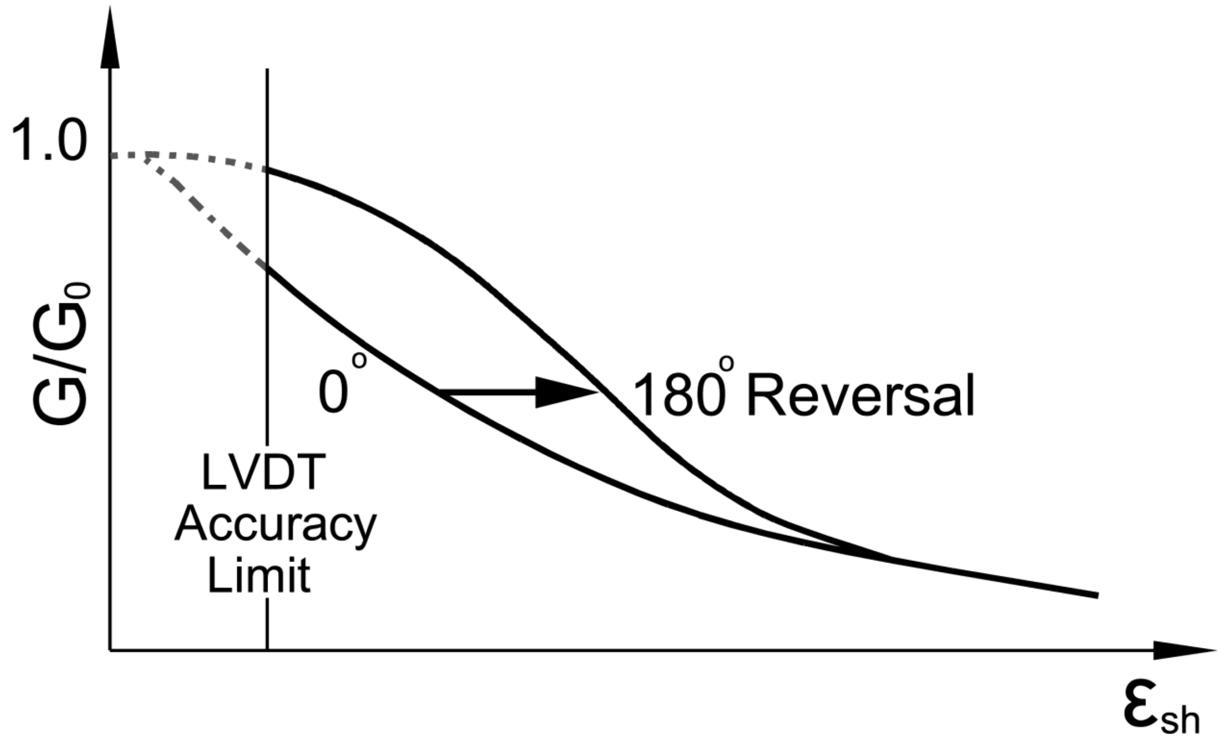
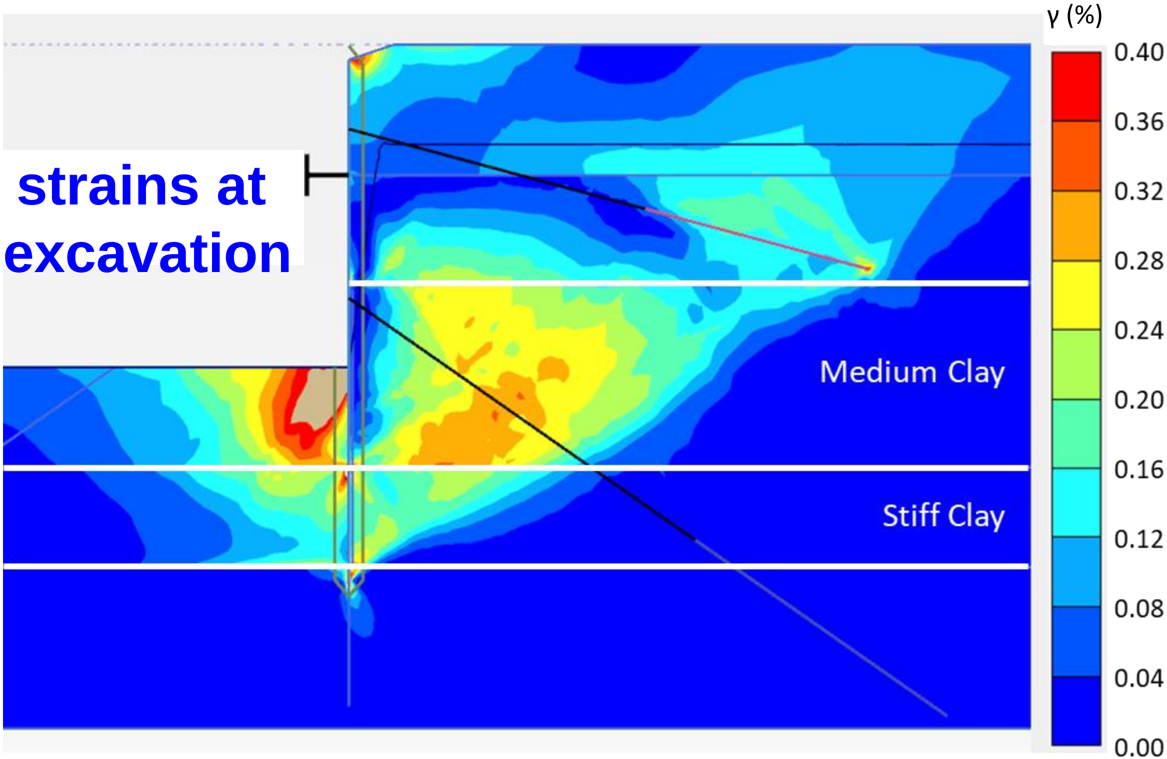
# Effects of recent stress history




Approach: can find Go in field but rate of degradation is more complicated. Use a degradation parameter as one that is optimized based on field performance data

# Shear strains at end of excavation



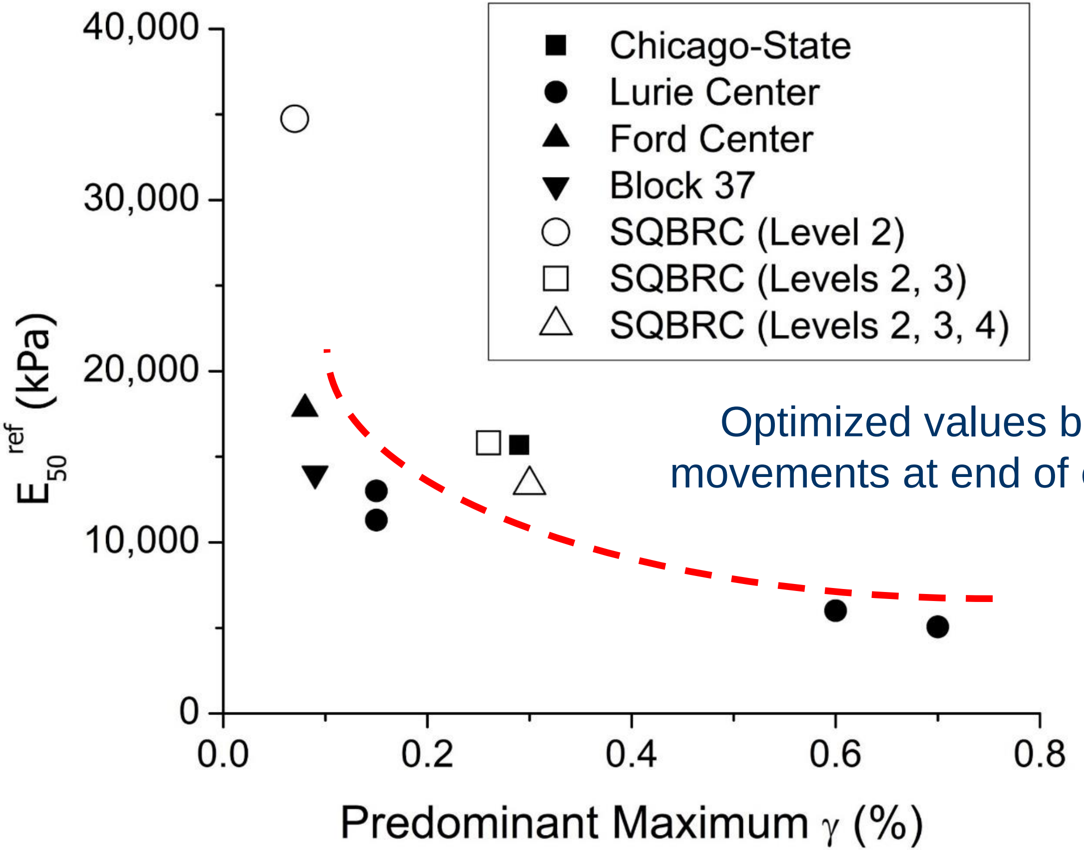

Lateral displacements near wall dominated by $\varepsilon_H$ max

Settlement distribution depends on all strain levels

Variable moduli (e.g. elasto-plastic model) can be used to compute lateral movements near wall

Small strain non-linearity and dilatancy must be included for settlement distributions

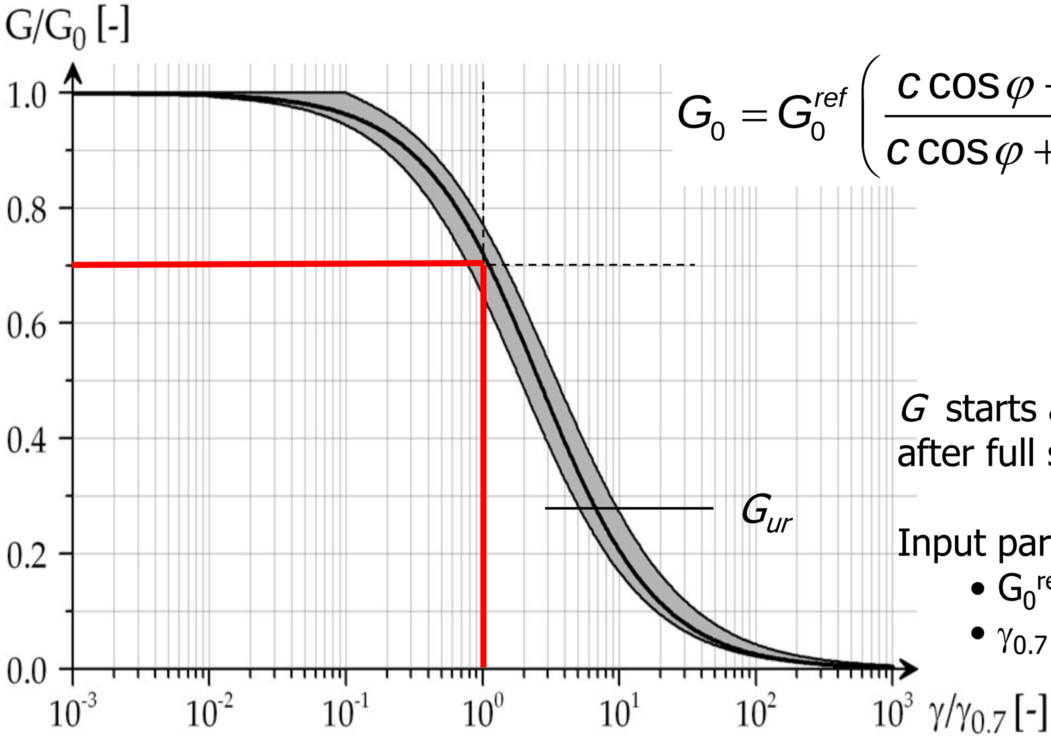
# HS model: no small strain stiffness




Optimized values based on movements at end of excavation

# Small-strain stiffness in the HSS model

Strain(path)-dependent elastic overlay model:




$$G_0 = G_0^{ref}\left(\frac{c\cos\varphi - \sigma_3 \sin\varphi}{c\cos\varphi + p^{ref}\sin\varphi}\right)^m$$

*G* starts again at $G_0$ after full strain reversal

Input parameters of HSSmall:

- $G_0^{ref}$
- $\gamma_{0.7}$

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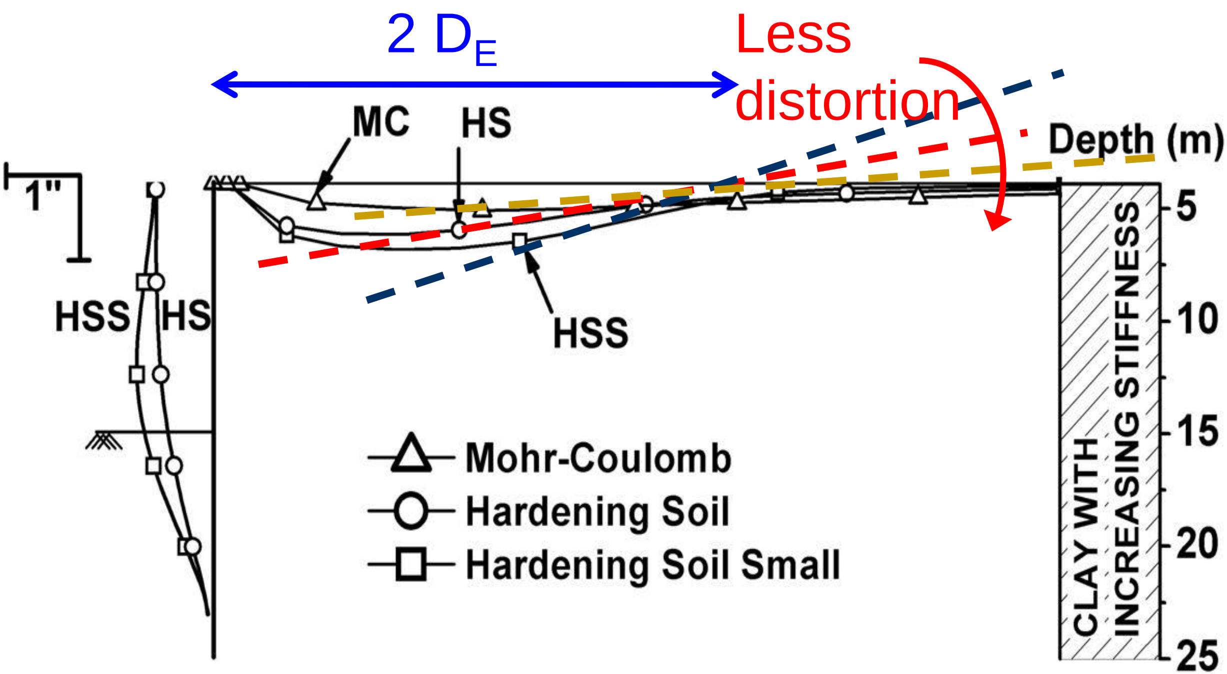
# Effect of constitutive model on computed deformations




MC – underpredicts max. settlement and distortion but overpredicts extent of movements: true for any model with constant elastic modulus. Non-linear model required

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# Monitoring – all can be automated

- Responses of adjacent structures/utilities
  - Optical survey points
  - Tilt meters
- Ground response
  - Optical survey points
  - Inclinometers
- Support system
  - Strain gages and load cells

  (temperature effects)
- Construction progress
- Locate instruments where model can predict response and where most information can be obtained from the data

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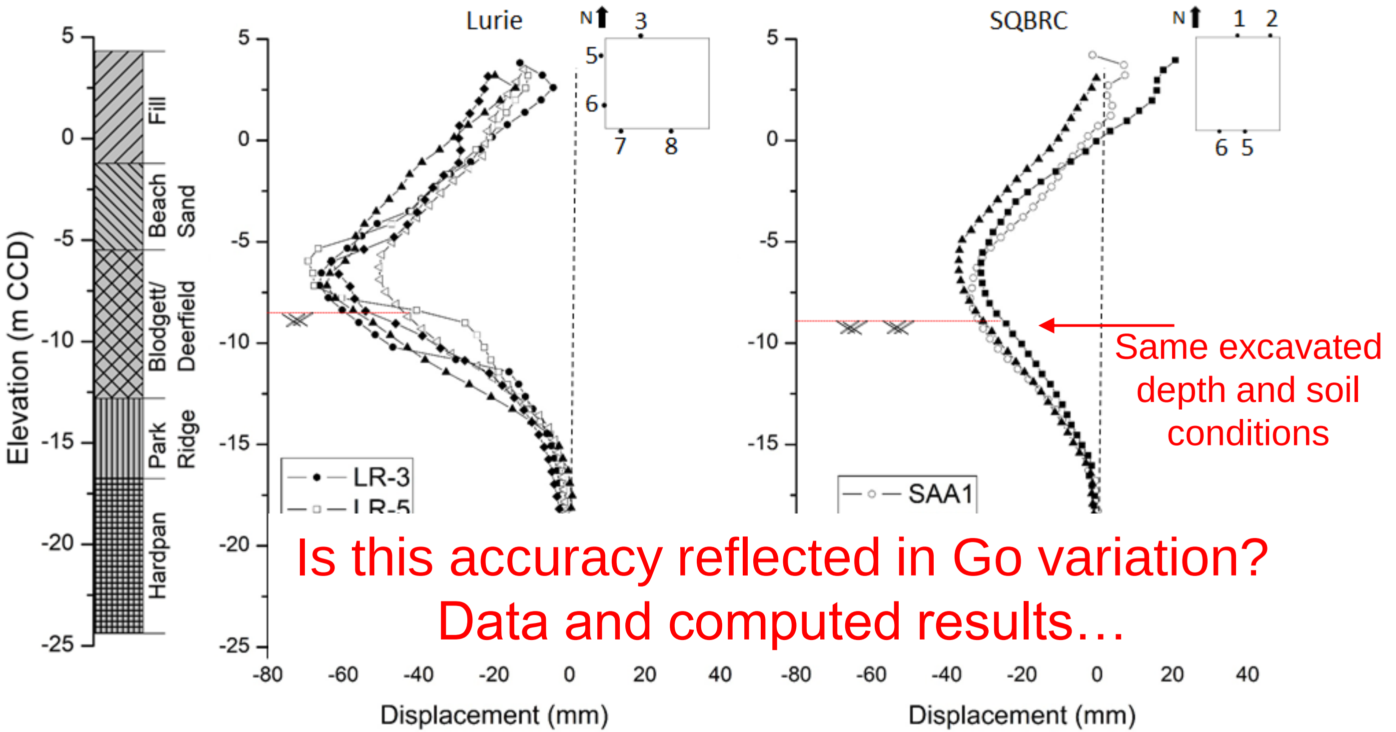
# “It’s tough to make predictions, especially about the future”

Yogi Berra, Hall of fame catcher for the NY Yankees and philosopher

# Expected accuracy in "uniform" conditions
(SQBRC and Lurie Center)




Is this accuracy reflected in Go variation?
Data and computed results…

Lateral wall movements at end of excavation

One can expect to be able to predict lateral wall deformations, at best, with an accuracy of ±15 % of the maximum value.

# What is adaptive management?

- Quantitatively evaluate performance of a system based on observations
- Use observations to update performance predictions
- Plan project so alternative procedures can be applied depending on observed performance – a design approach for stiffness based designs
- "Automated observational approach"

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# Key elements of adaptive management

- Identify control parameters (inclinometer data supplemented by settlement data)
- Prediction method ~ finite element method
- Observations must be reliable, accurate and obtained in a timely fashion
- Constitutive model must have capability to replicate behavior that is observed
- Assume differences in observed and computed responses are due to soil responses
- Contingency options must be planned in design stage

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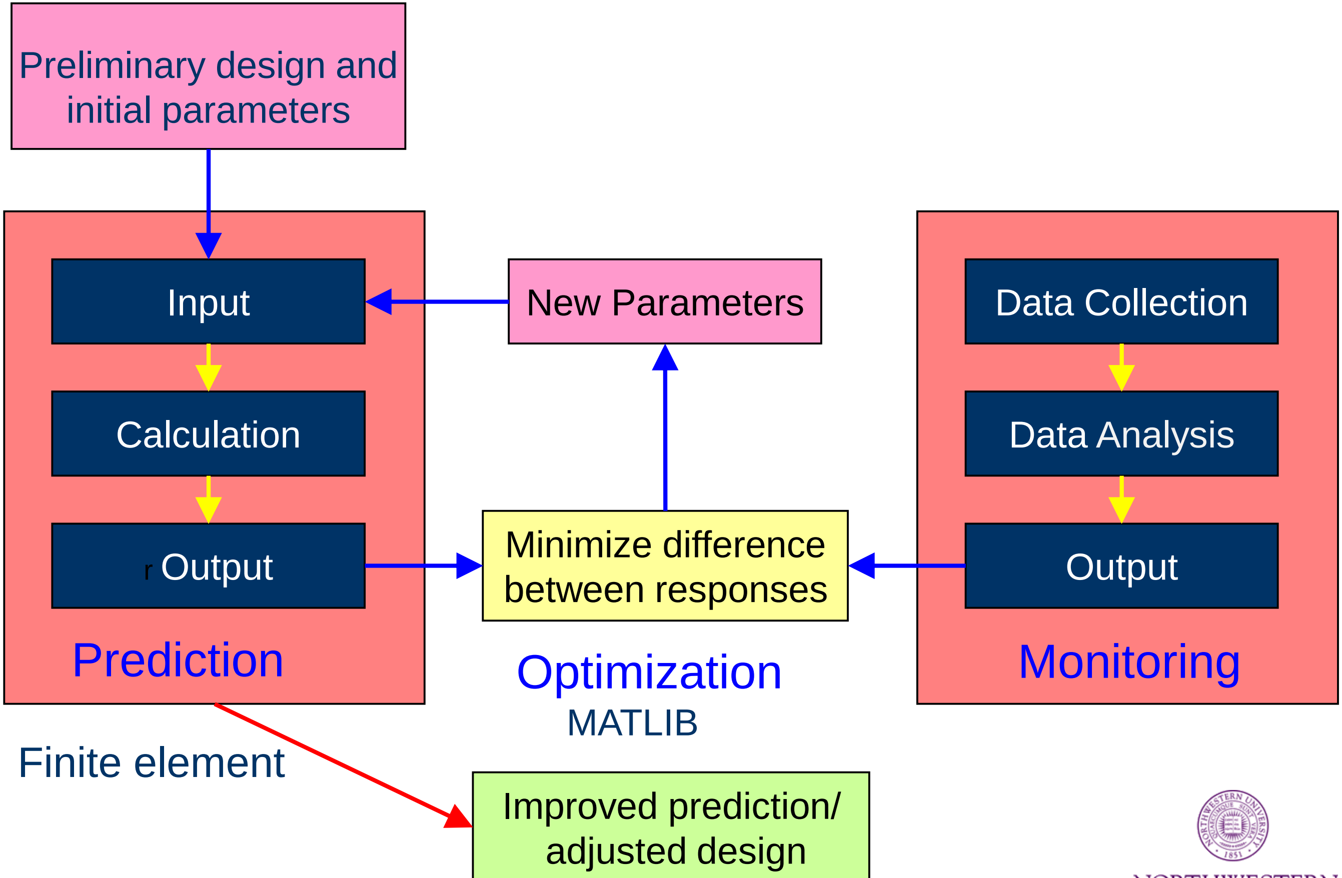
# Integrated System

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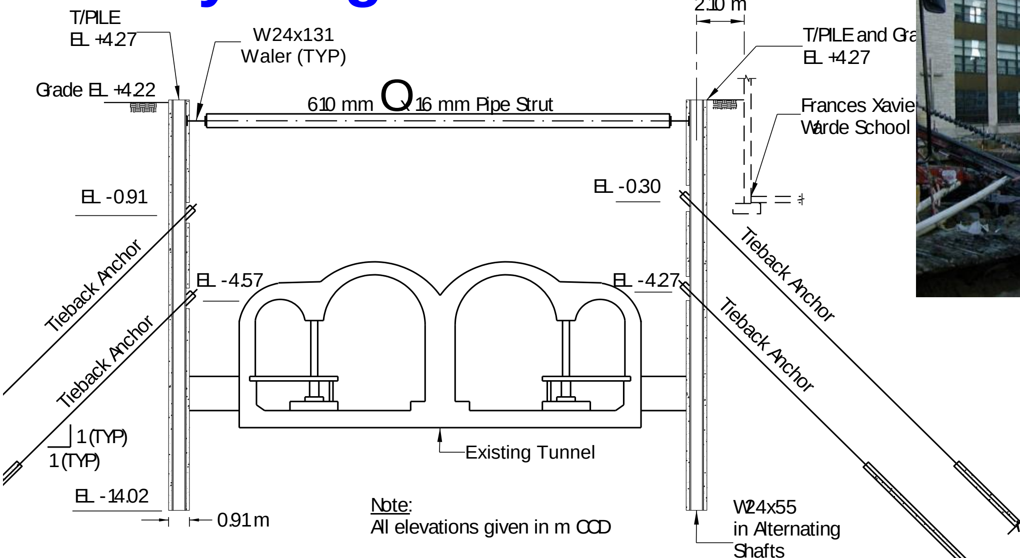
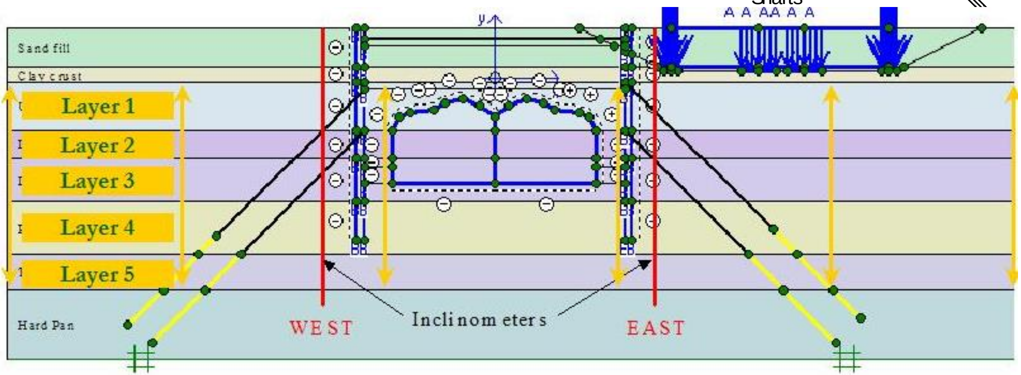
# Optimize parameters at early stage of excavation




Numerical analyses:

Plaxis

UCODE/MATLAB

Hardening soil model

Optimized $E_{50}^{ref}$ of softer clays

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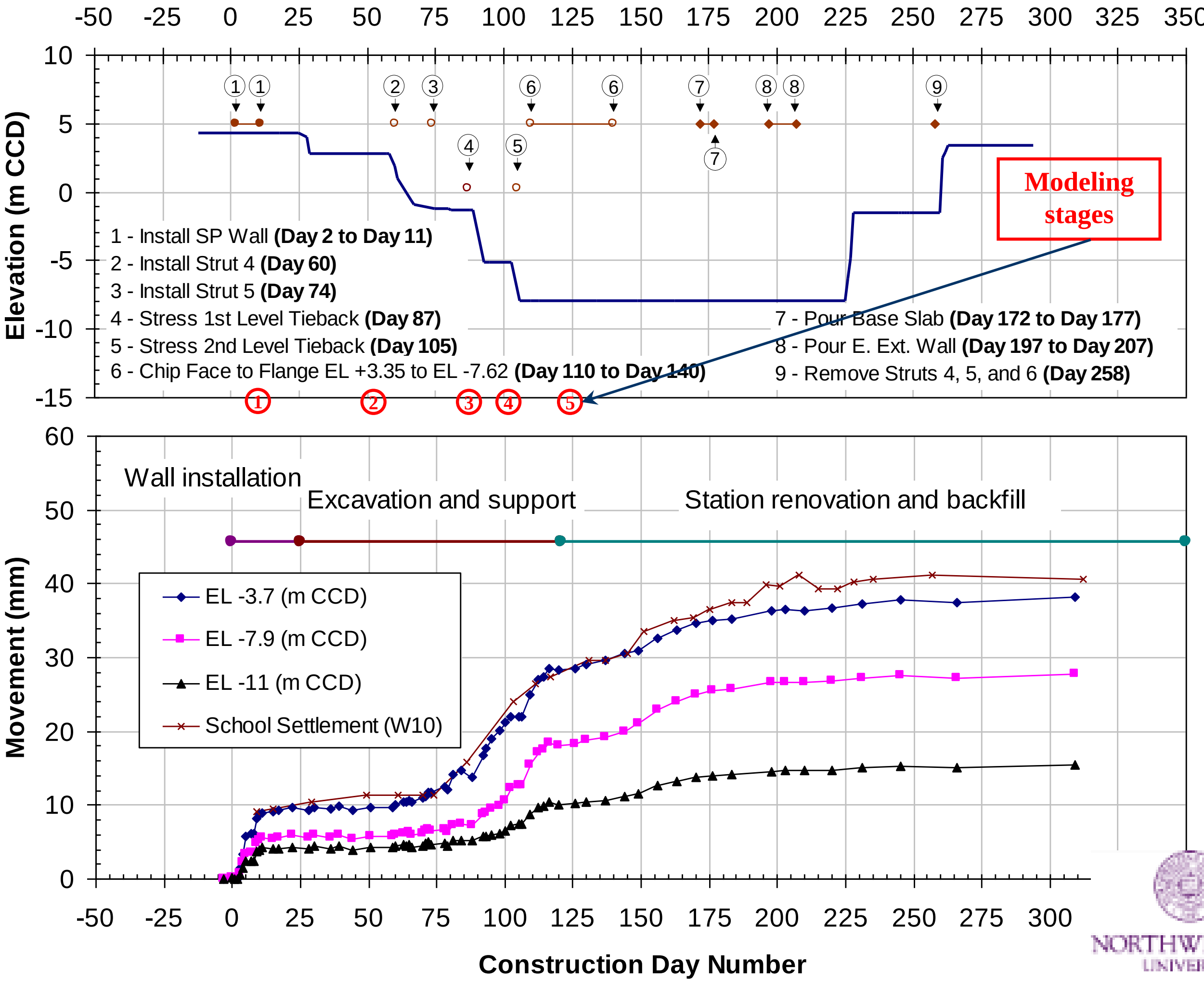


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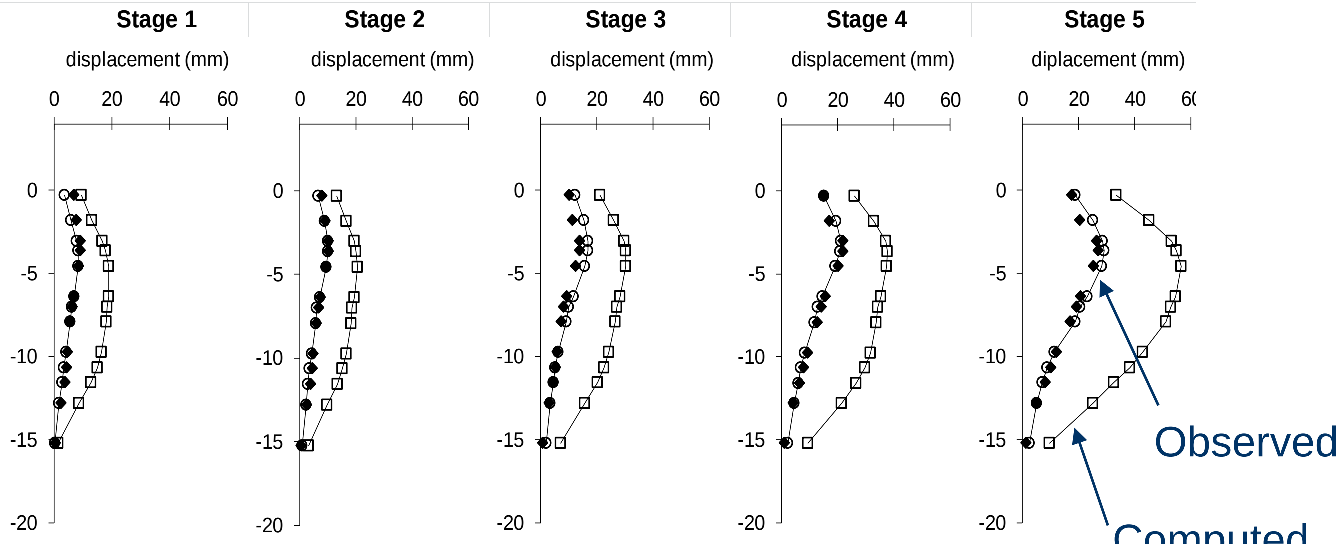
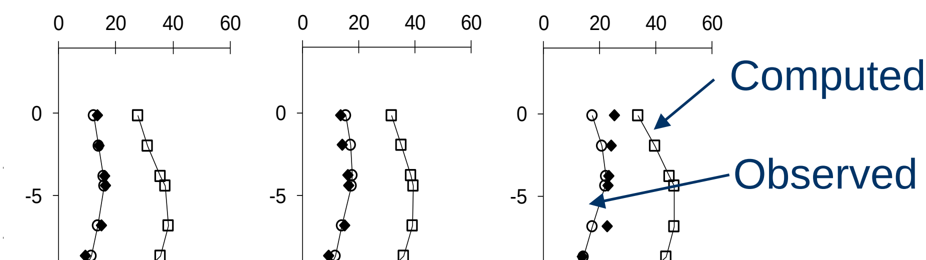
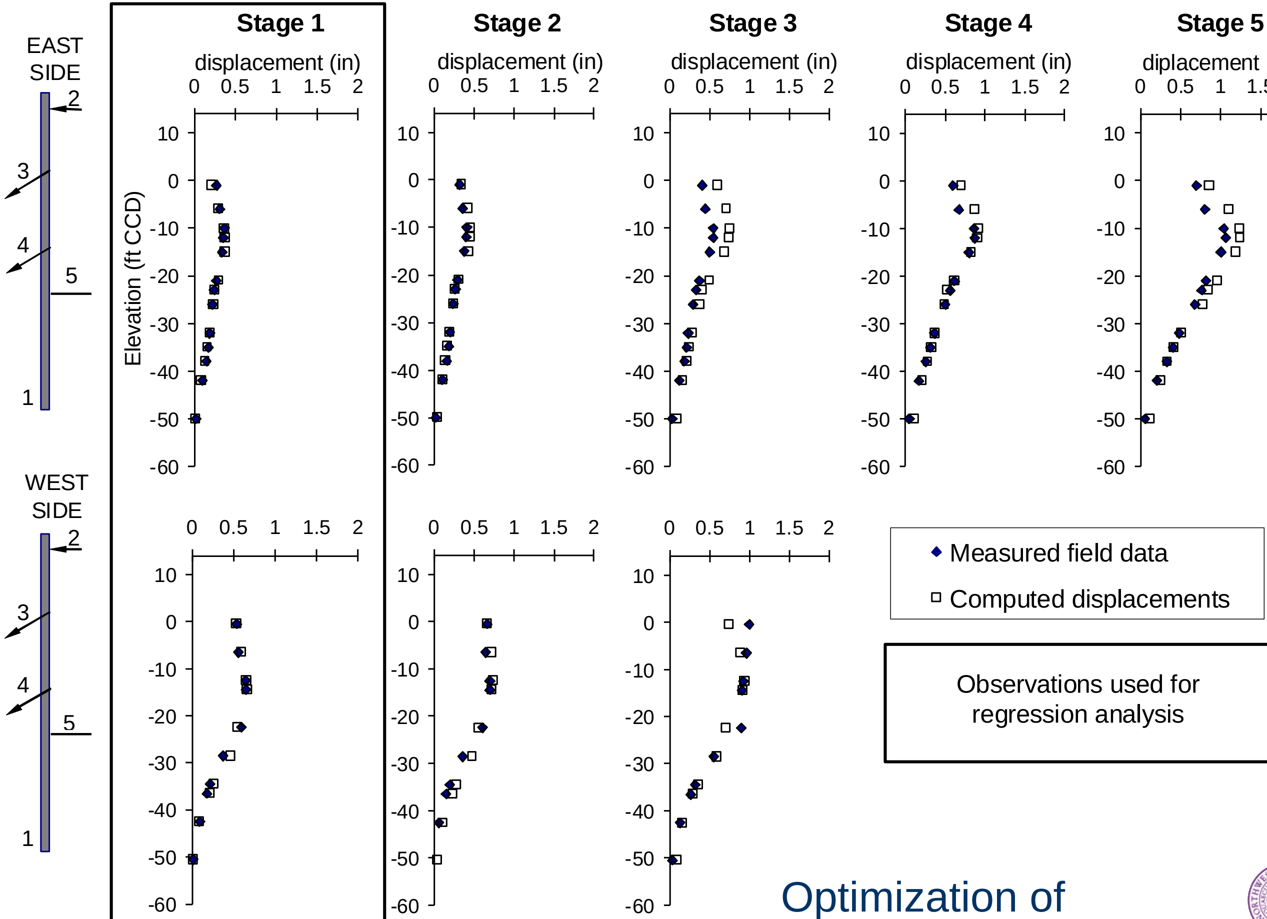
# No optimization




Soil parameters based on laboratory tests




# Optimization of data from stage 1

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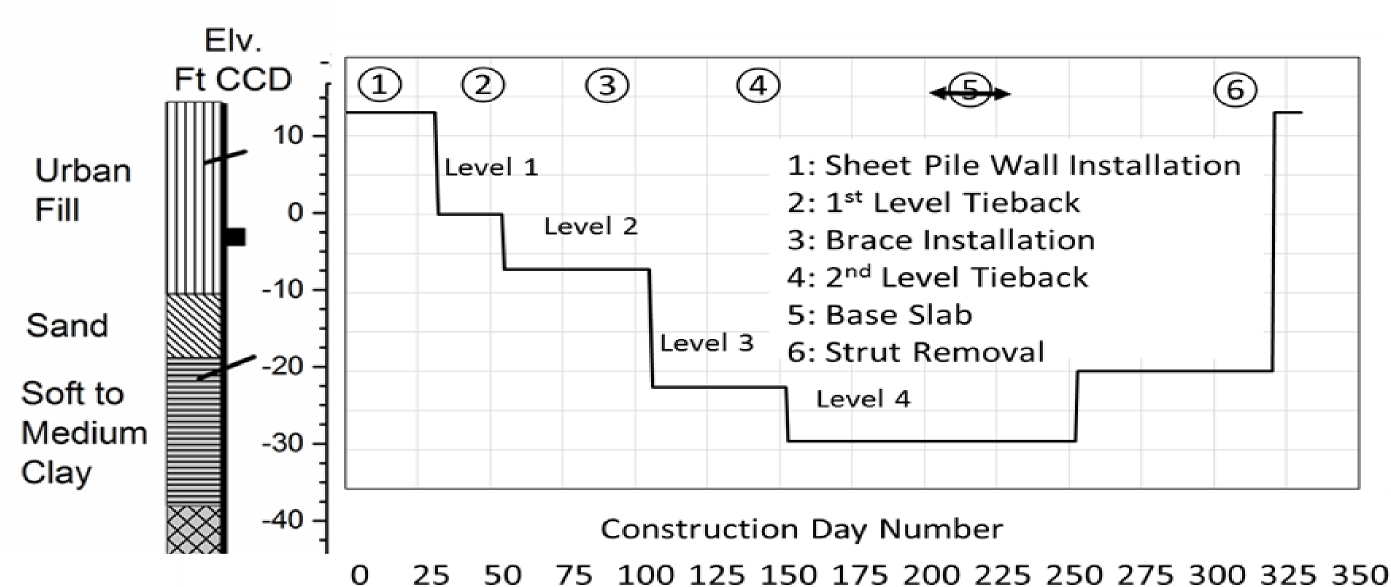
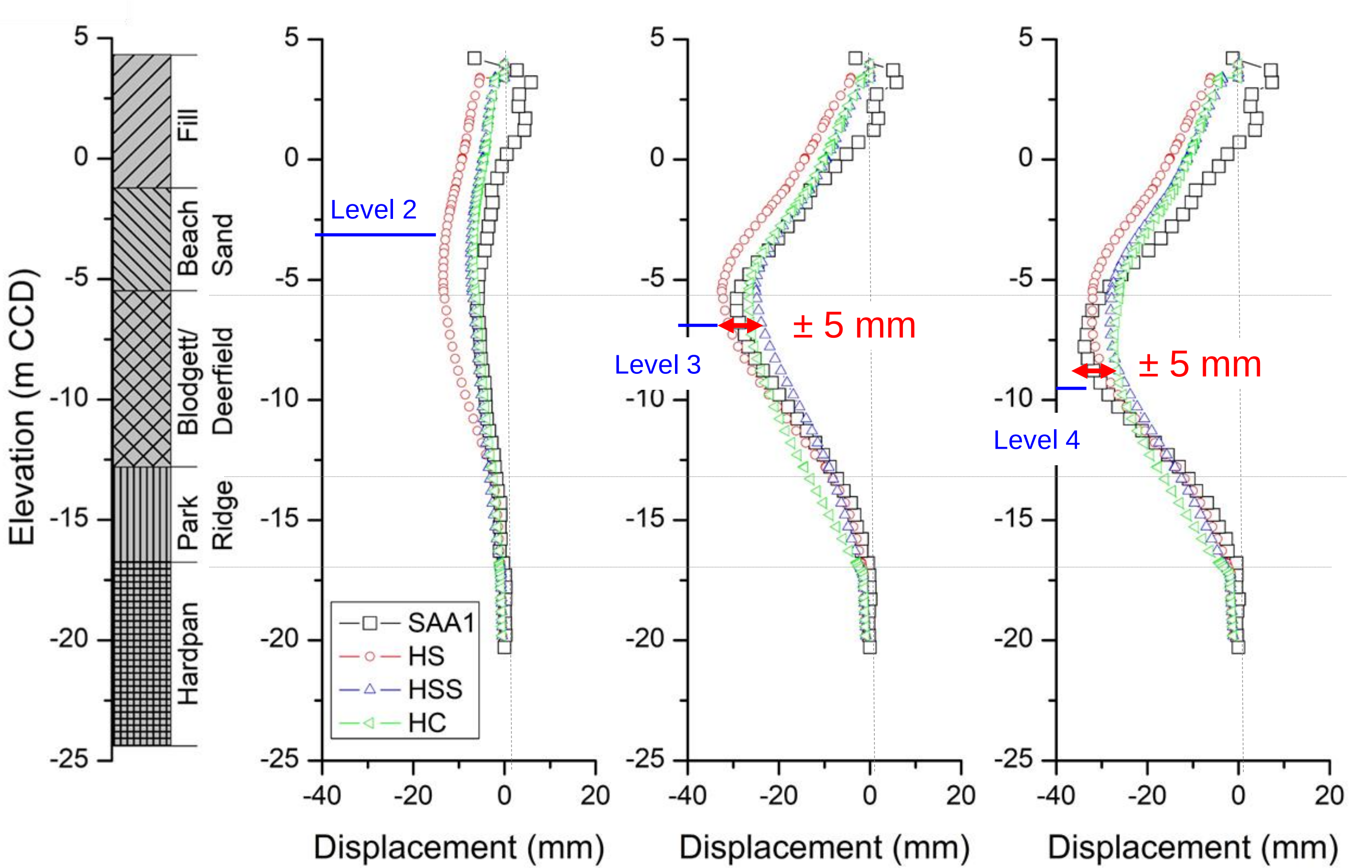
# Use of parameters optimized at other projects in same geology

- Three soil models
  - Hardening soil (Schanz et al 1999): Chicago-State, Ford and Lurie Centers excavations
  - Hardening soil small (Benz (2007): Block 37 excavation
  - Hypoplasticity clay (Masin 2014): Laboratory data from block samples taken from Ford and Block 37 excavation
- Applied to SQBRC excavation with computed results compared to observed wall deformations

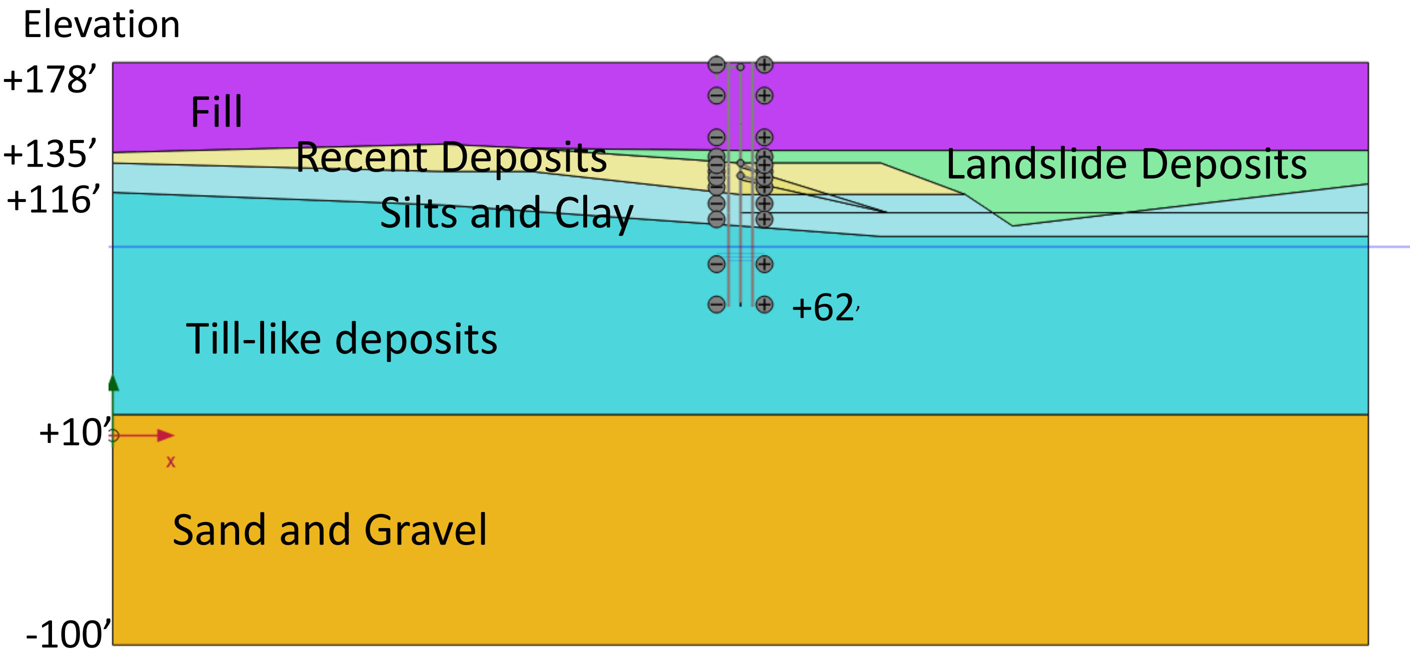
# SQBRC excavation



# Computed and observed lateral wall movements (parameters from previous excavations)



# Cross section at Pine Street

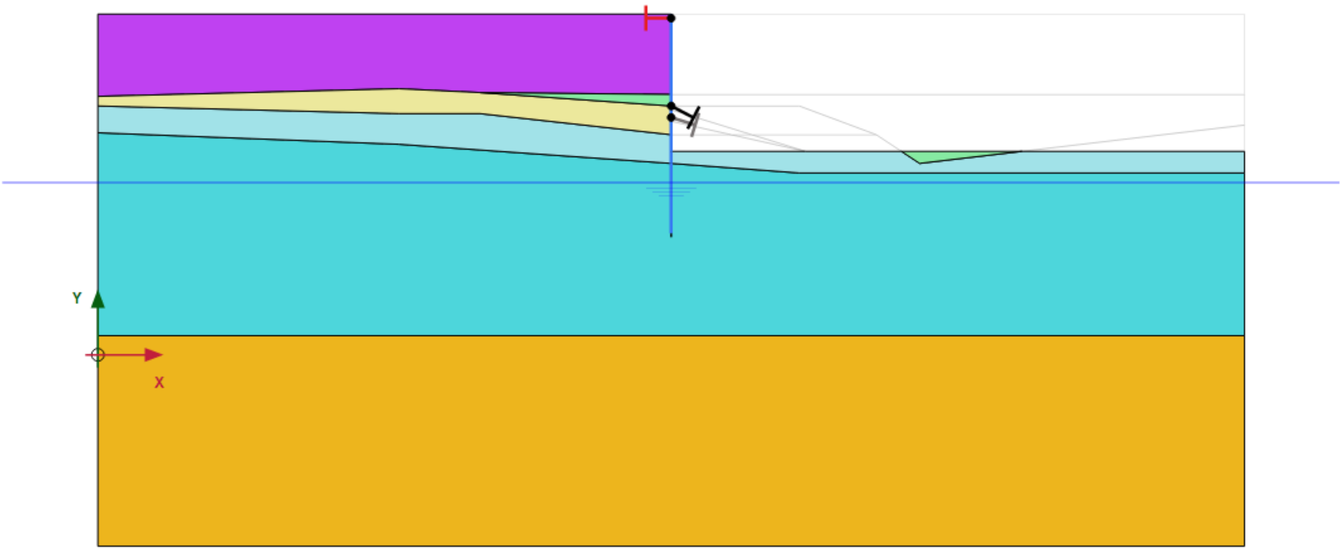



Both field studies and laboratory investigations will quantify magnitude and distribution of Go and its degradation with strain

Courtesy of GeoEngineers

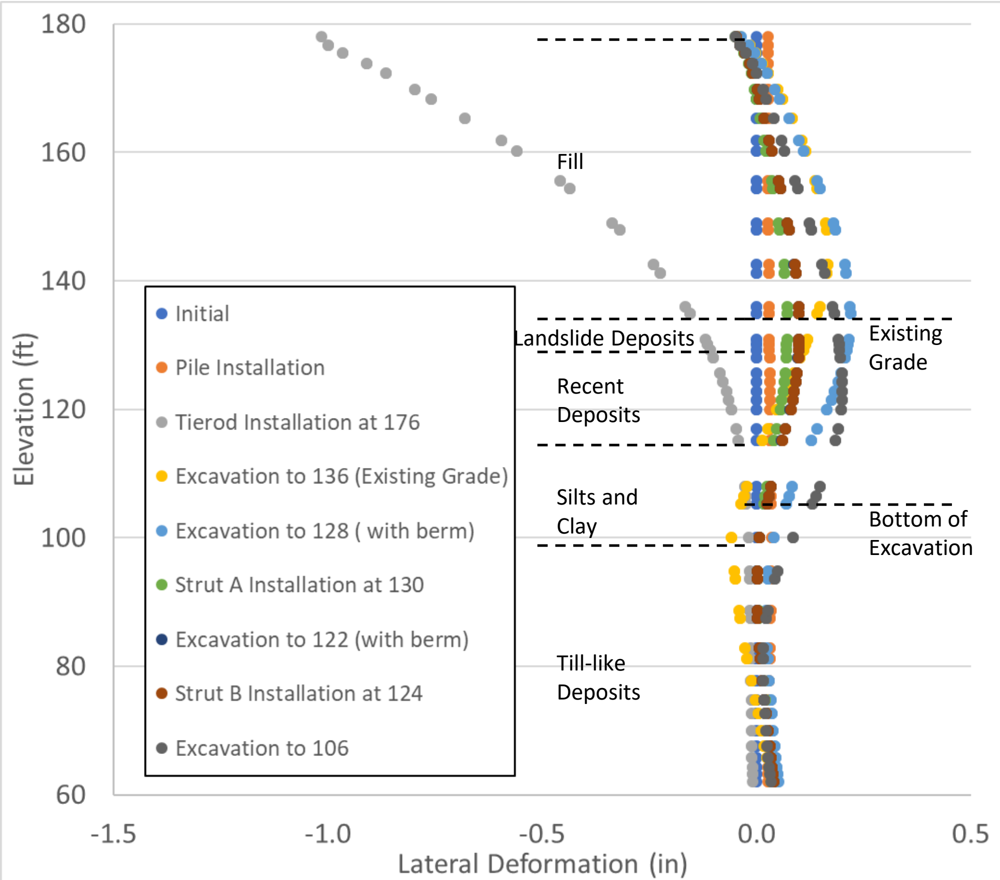
# Excavation sequence

Final Excavation




Courtesy of GeoEngineers

# Computed lateral wall deformations




Tierod pulls wall back significantly (1inch)

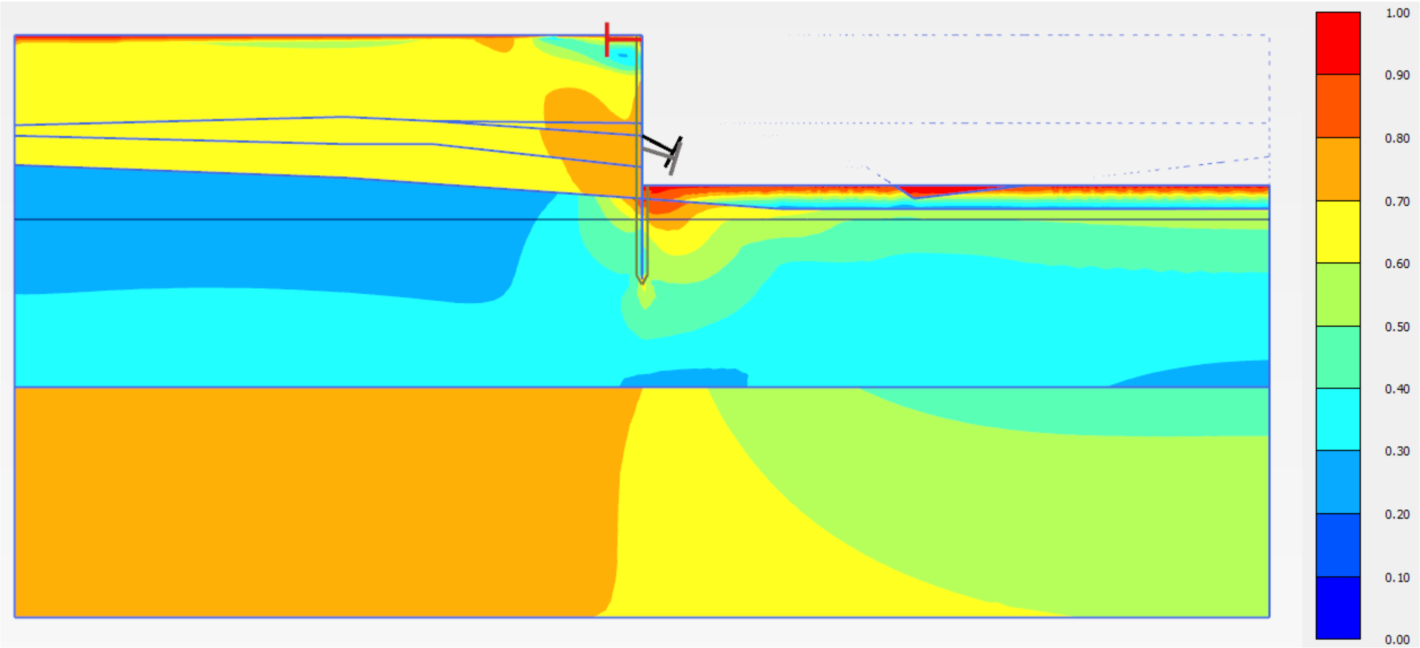
Strut A installation pulls back wall about 0.2 inch

Excavation to 122 (dark blue) and Strut B installation (dark red) are on top of each other

0.2 inch lateral deformation at final excavation

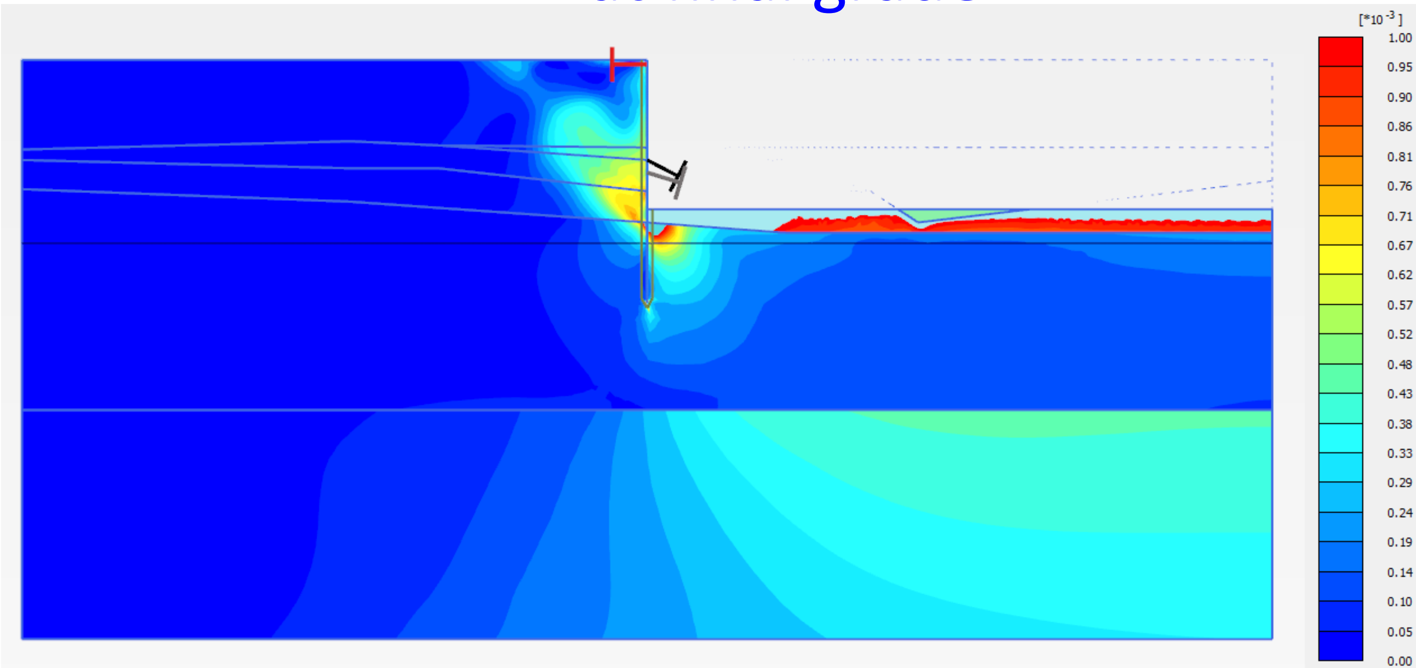
Courtesy of GeoEngineers

# Relative shear stress contour at final grade




Courtesy of GeoEngineers

# Deviatoric shear strain (invariant) contour at final grade




Maximum shear strain behind wall is 0.07 to 0.08%

Courtesy of GeoEngineers

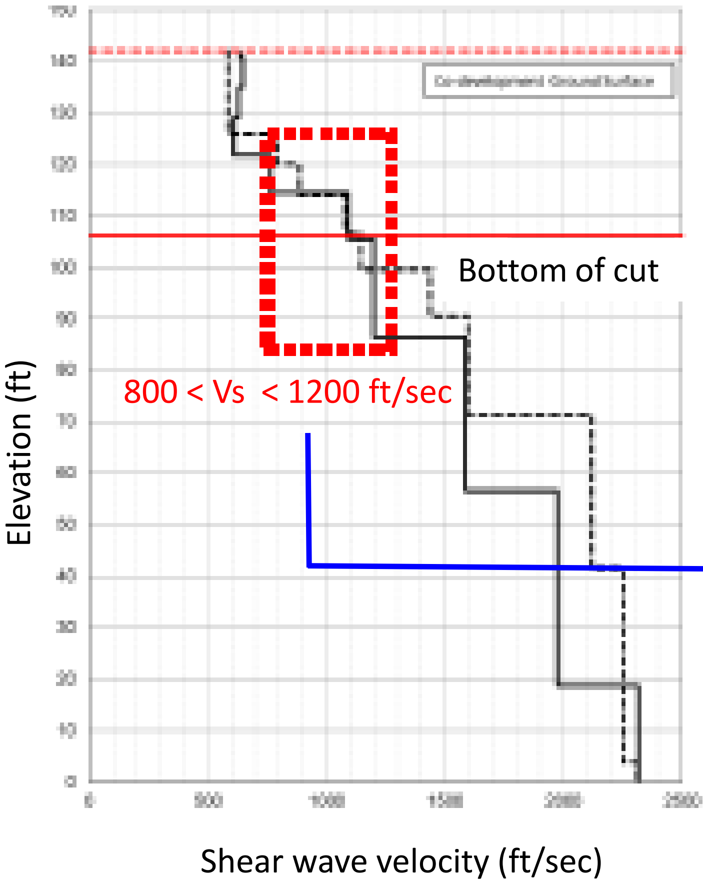
# HS model parameters:  Olive 8 project

| Parameter | Fill | Silty Sand | Clayey Silt | Dense Sand |
|---|---|---|---|---|
| $\gamma$ (pcf) | 125 | 130 | 125 | 130 |
| $\phi'$ (°) | 32 | 38 | 34 | 40 |
| $c'_{ref}$ (psf) | 100 | 200 | 200 | 0 |
| $K_0$ | 0.47 | 0.6 | 0.7 | 0.6 |
| $\nu_{ur}$ | 0.3 | 0.3 | 0.2 | 0.3 |
| $\psi$ (°) | 0 | 0 | 0 | 0 |
| $E_{50}^{ref}$ (psf) | 00,000 | 1,000,000 | 500,000 | 1,500,000 |
| $E_{oed}^{ref}$ (psf) | 500,000 | 1,000,000 | 700,000 | 1,500,000 |
| $E_{ur}^{ref}$ (psf) | 2,600,000 | 3,000,000 | 1,600,000 | 4,500,000 |
| $p_{ref}$ (psf) | 2,100 | 2,100 | 2,100 | 2,100 |

# HS model parameters: WSCC project

| Parameter | Fill | Recent Deposits | Landslide Deposits | Silts and Clay | Till-like Deposits | Sand and Gravel |
|---|---|---|---|---|---|---|
| $\gamma$ (pcf) | 125 | 125 | 125 | 130 | 135 | 130 |
| $\phi'$ (°) | 32 | 33 | 32 | 36 | 40 | 38 |
| $c'_{ref}$ (psf) | 0 | 0 | 0 | 200 | 200 | 100 |
| $K_0$ | 0.47 | 0.46 | 0.47 | 0.41 | 0.7 | 0.38 |
| $\nu_{ur}$ | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| $\psi$ (°) | 0 | 0 | 0 | 0 | 0 | 0 |
| $E_{50}^{ref}$ (psf) | 500,000 | 543,000 | 500,000 | 800,000 | 2,500,000 | 950,000 |
| $E_{oed}^{ref}$ (psf) | 500,000 | 543,000 | 500,000 | 800,000 | 4,400,000 | 1,110,000 |
| $E_{ur}^{ref}$ (psf) | 1,500,000 | 1,630,000 | 1,500,000 | 2,400,000 | 7,500,000 | 1,900,000 |
| $p_{ref}$ (psf) | 2,100 | 2,100 | 2100 | 2,100 | 500 | 500 |

# Comparison of Gur values to Go




HSS model

$$G_0 = G_0^{ref}\left(\frac{c\cos\varphi - \sigma_3\sin\varphi}{c\cos\varphi + p^{ref}\sin\varphi}\right)^m$$

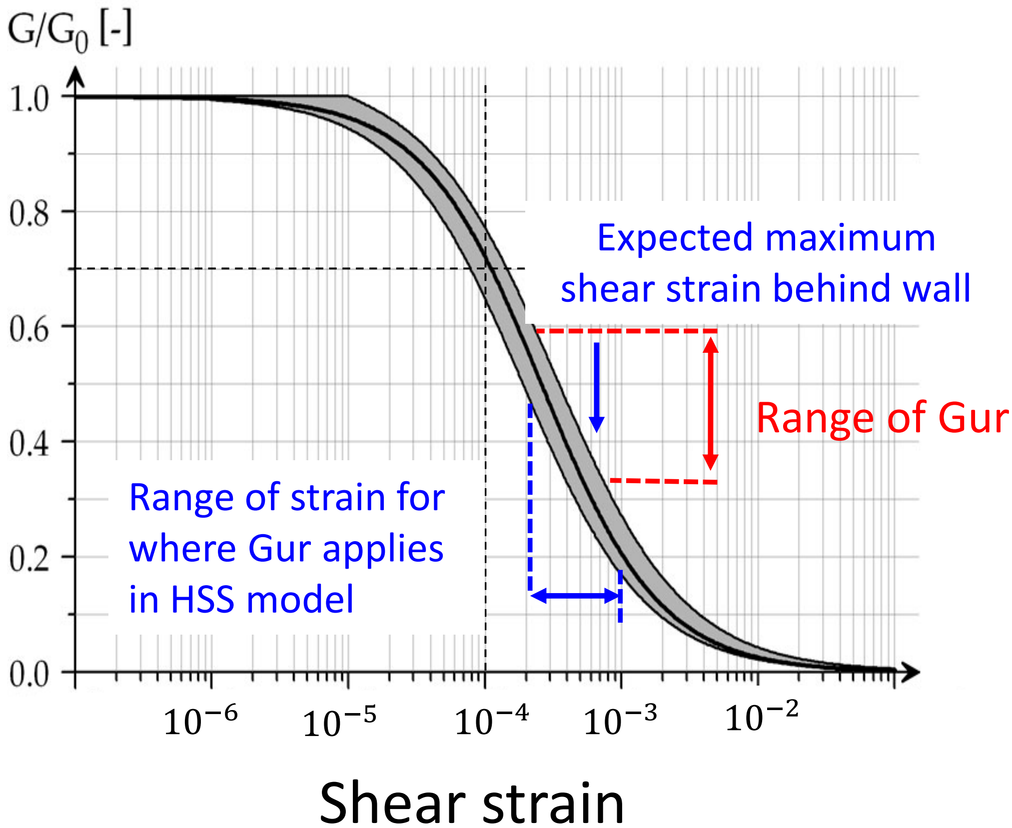
For range of effective stresses and HS soil properties:

1560 < Gur < 2150 ksf

2600 < Go < 5,800 ksf

Data from GeoEngineers

# Need for use of small strain stiffness



# Concluding remarks

- Deformations of wall will be determined primarily by small strain stiffness and its degradation
- Laboratory and field data will quantify magnitude and degradation of G
- Go variability will be directly determined in field
- Will variability of Go correspond to variability in observed lateral wall movements?
    - In both numerical results and inclinometer data

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