From Theory to Practice: Design of Excavation Support

Richard J. Finno

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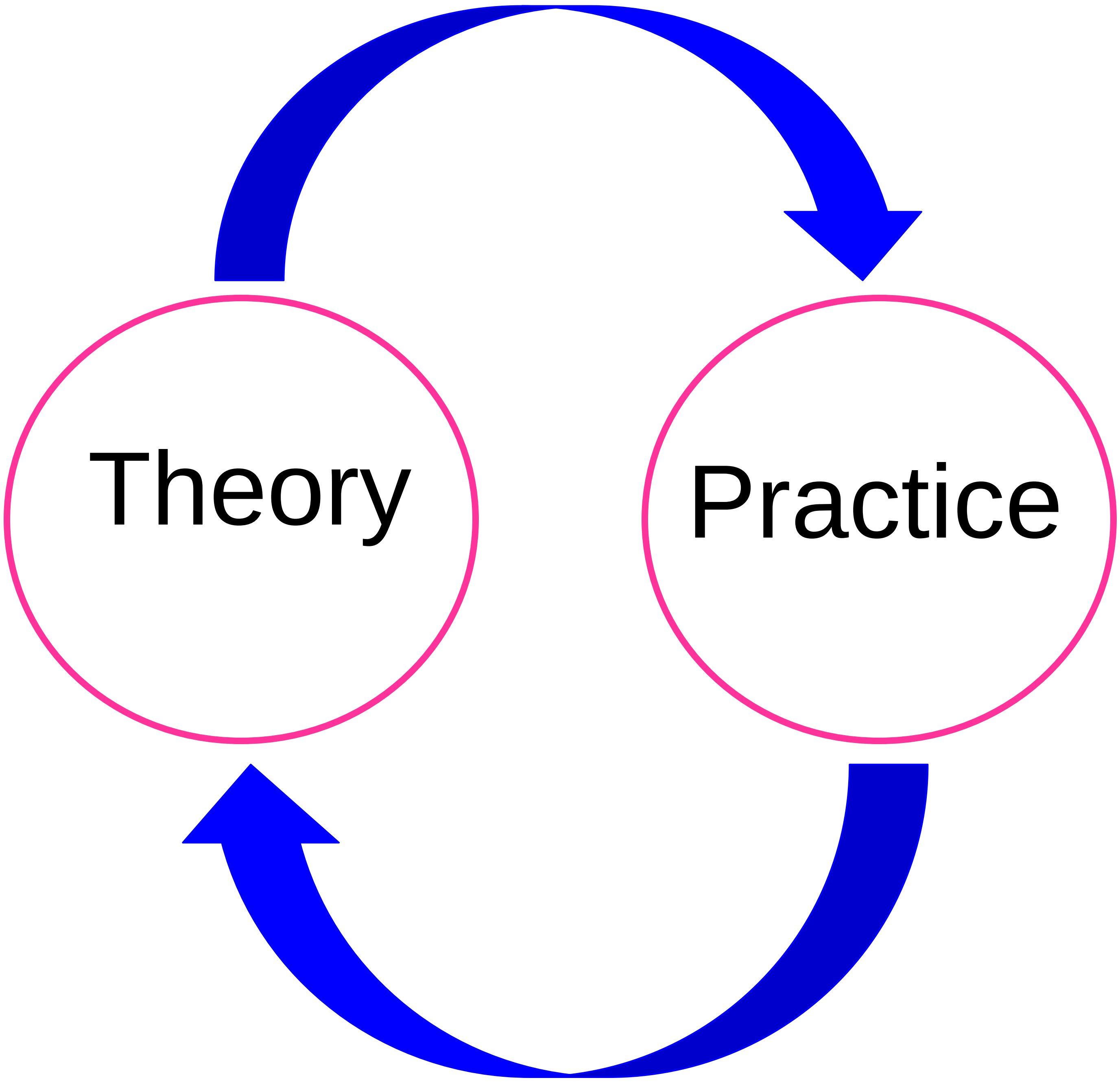

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Outline

- Fallacy in earth pressure calculations

  From theory to practice

  – Coulomb and Rankine limitations

  – Apparent earth pressure diagrams

  – Factors affecting loads in supports

  – Cross-lot vs tied-back ground anchors

- Serviceability: movement predictions

  From practice to theory and back again…

  – Precedent

  – FE simulations

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Fallacy in earth pressure calculations

Terzaghi (1936)

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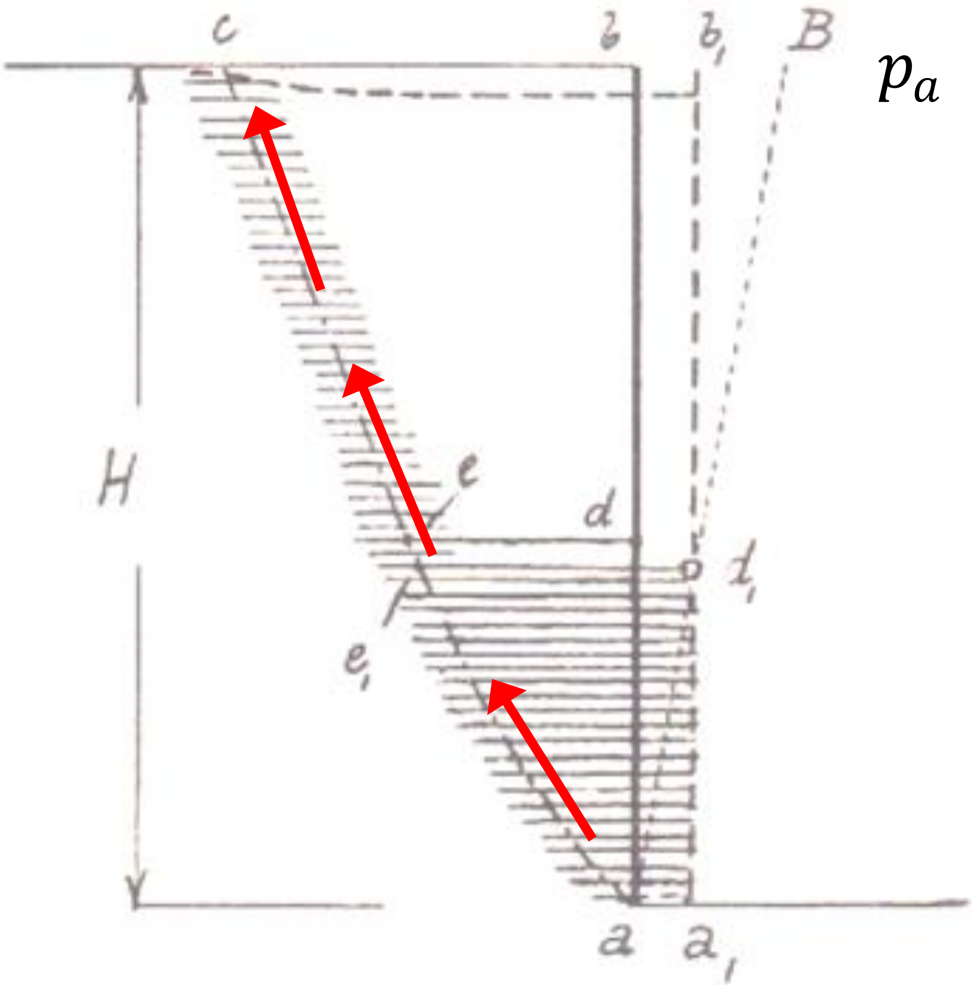
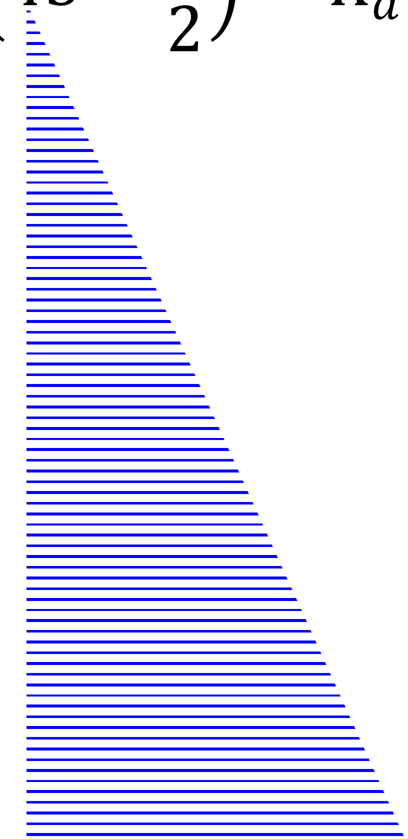
Experience did not match Coulomb or Rankine earth pressure distributions for retained sands



After Terzaghi (1936) Fig.4

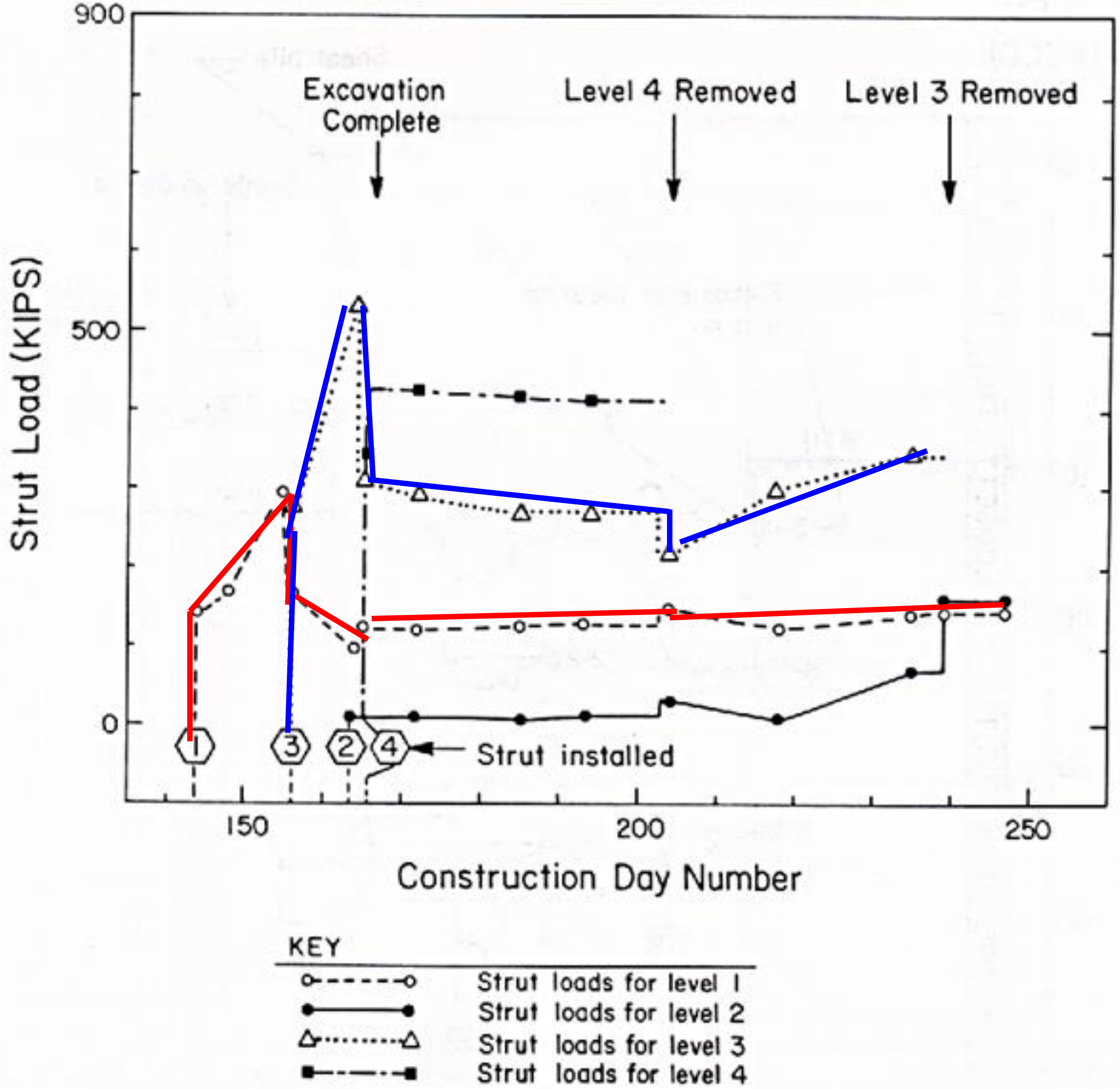
≠

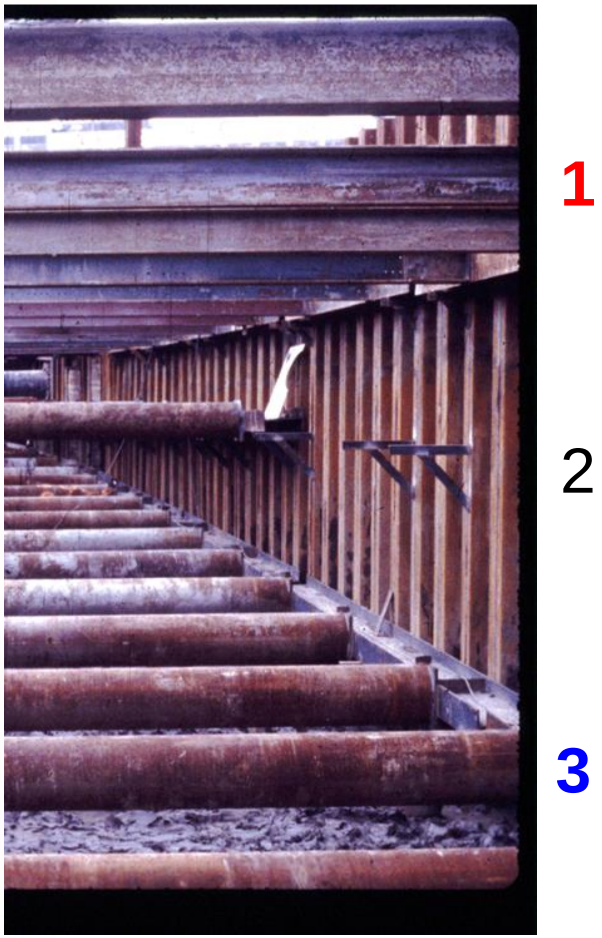
$$p_a = \gamma z \tan^2\left(45 - \frac{\varphi}{2}\right) = K_a \gamma z$$



Higher apparent stresses at top and lower at bottom of cut

Strut loads during excavation: HDR-4 project





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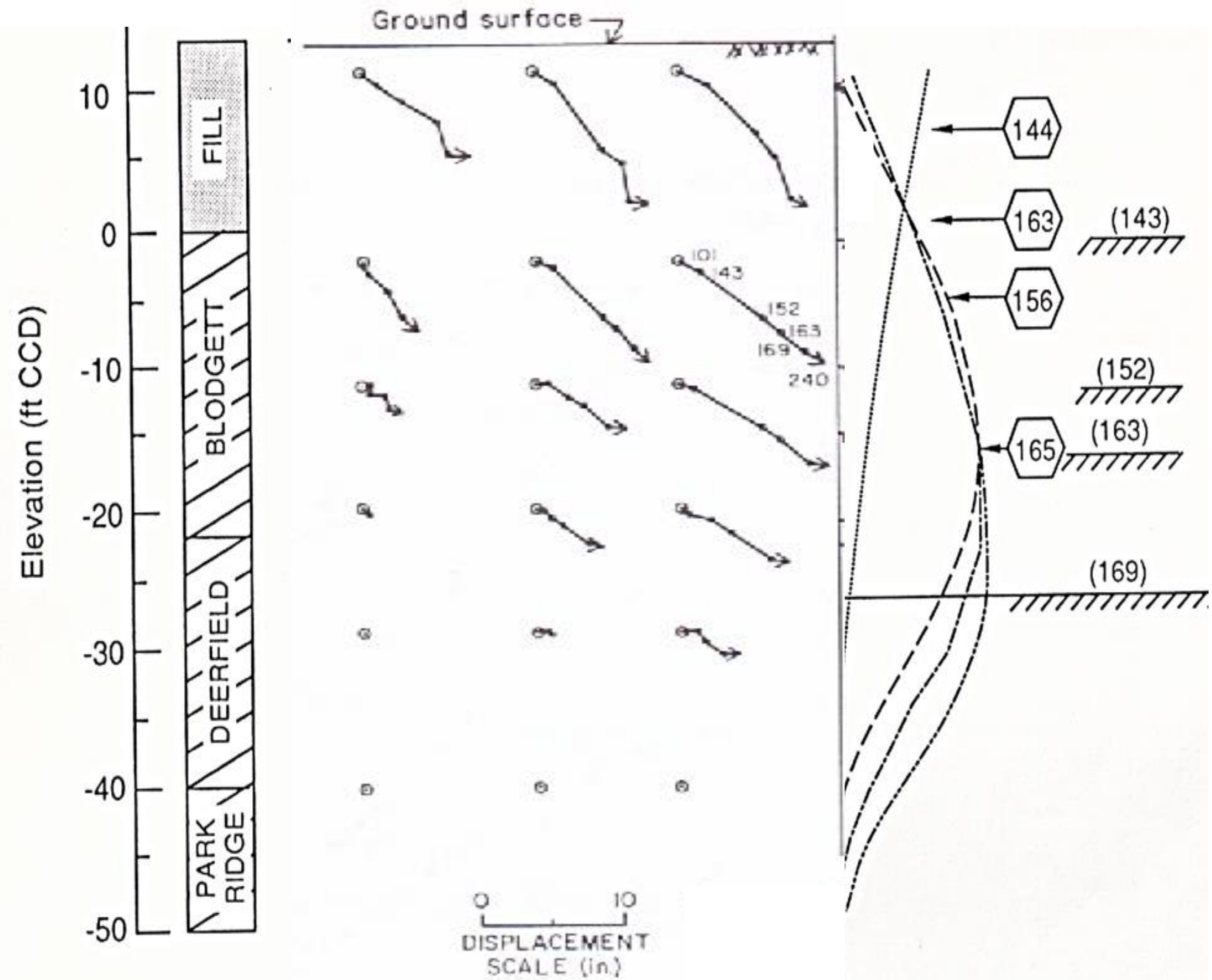
Deformations during excavation: HDR-4 project



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Apparent Earth Pressure Envelopes

- Measured loads in cross-lot braces
- For a given soil condition
  - At each excavation
    - Loads in each brace divided by tributary area
    - Selected maximum apparent pressure at each level
  - For all excavations, defined envelope of maxima
- Developed loading diagrams for sands, stiff clays and soft clays

Details found in PhD thesis by Flaate (1966)

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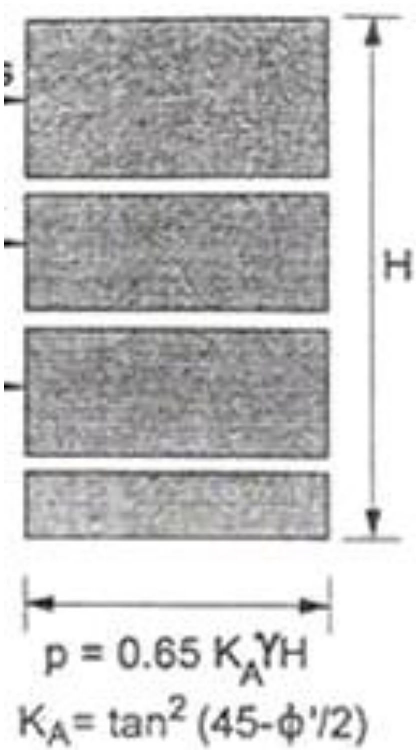
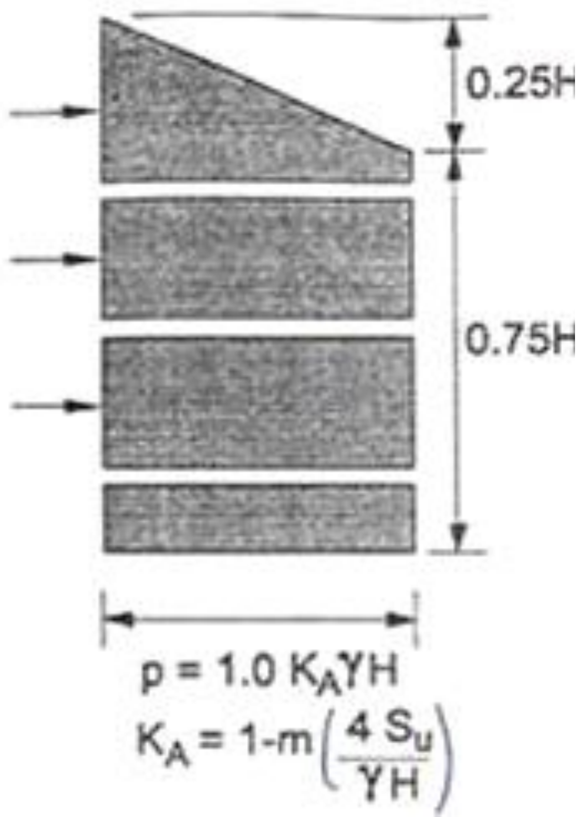
T&P Apparent Earth Pressure Envelopes

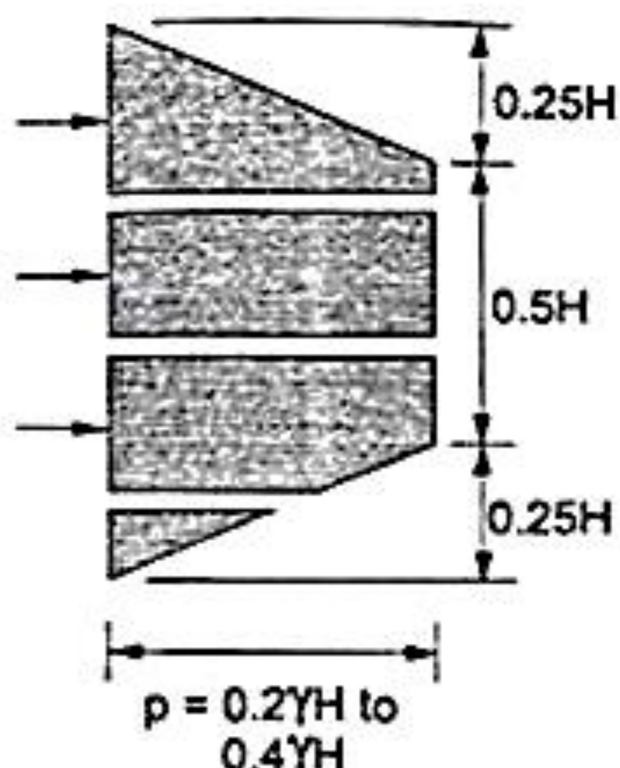
Sands



Soft to medium clays



Stiff clays



Factors affecting strut loads

- Earth and water pressures
- Workmanship
- Preloading
- Temperature

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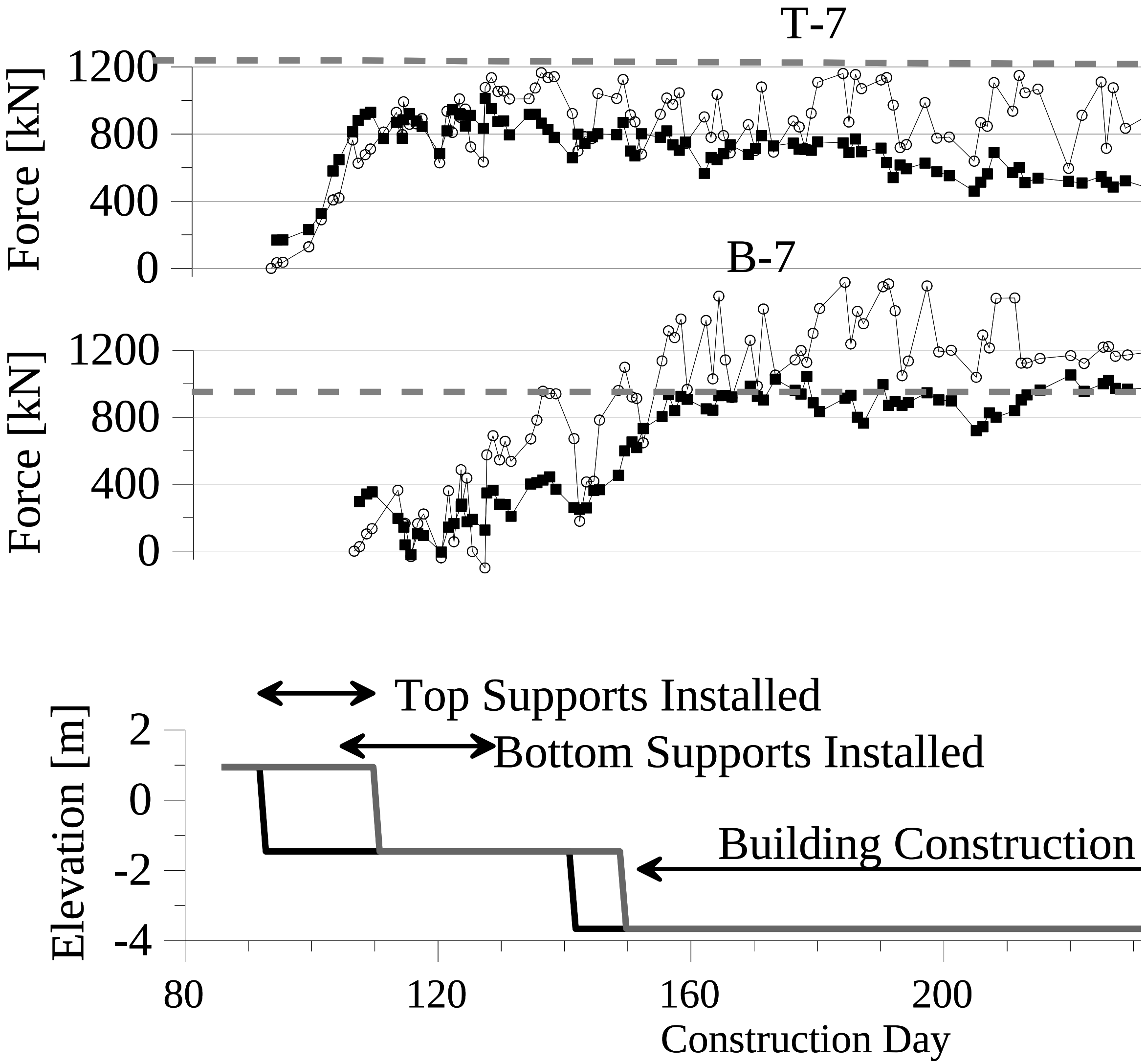
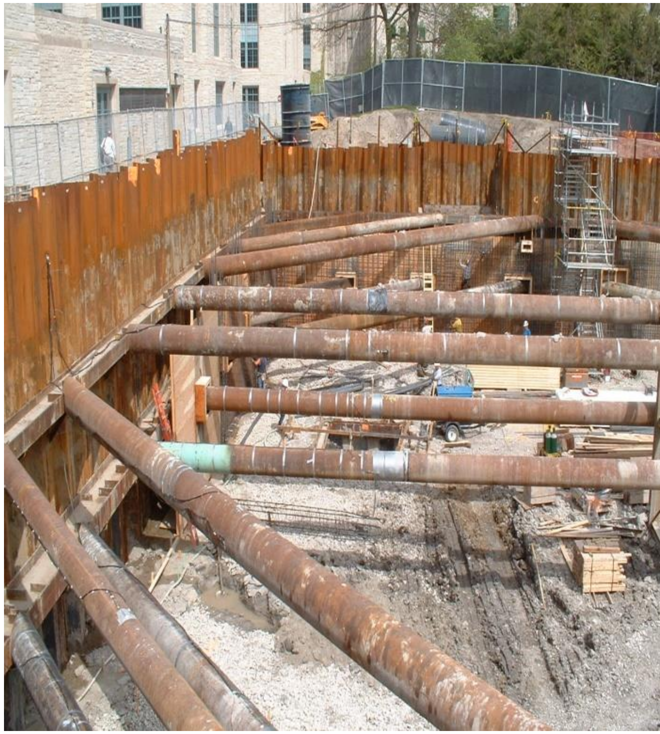
Effects of temperature on strut loads





Open circles – total force in member

Solid circles – temperature effects removed

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Cross lot brace vs Tied back ground anchor behavior

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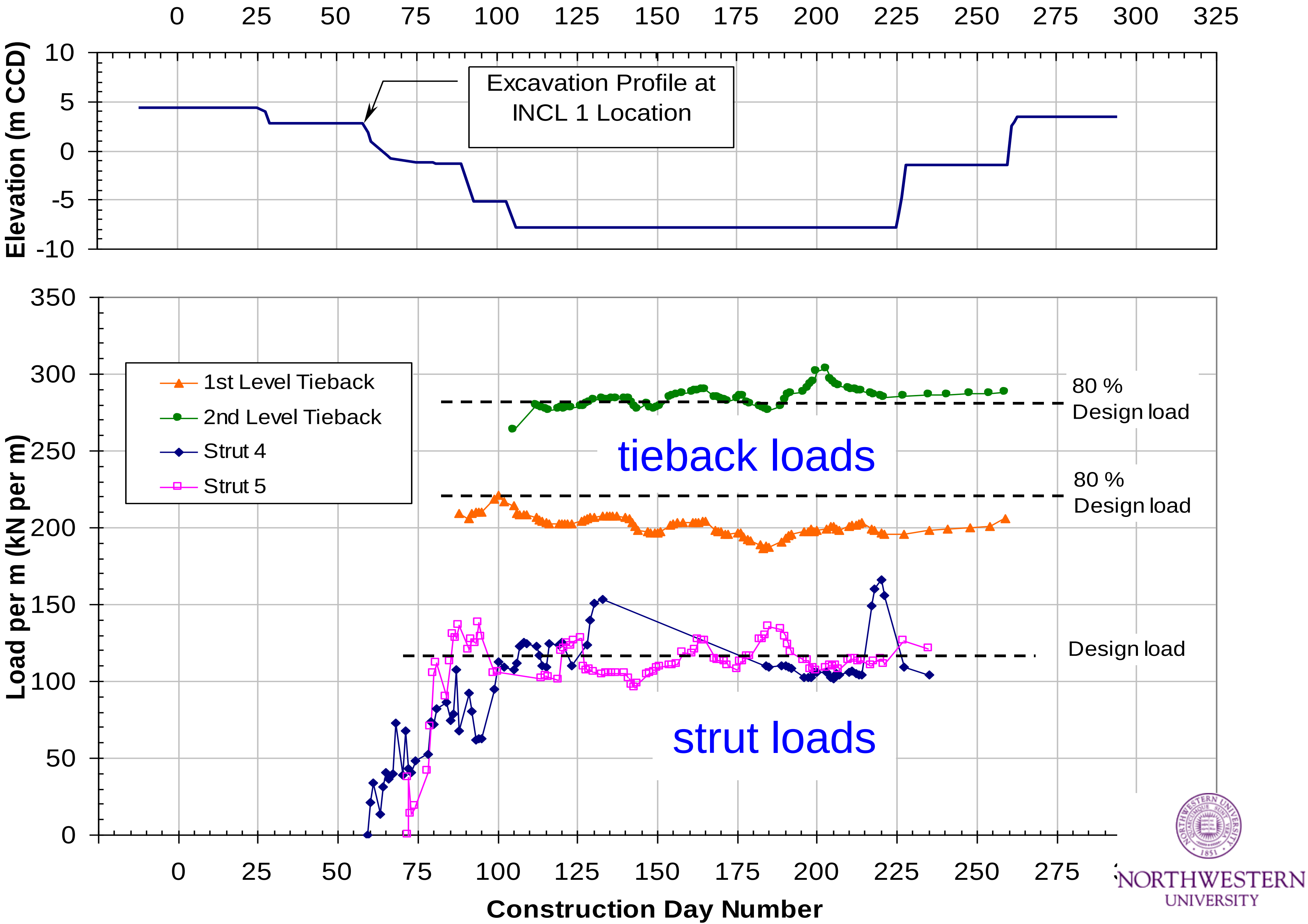
Cross lot brace vs Tied back ground anchor behavior



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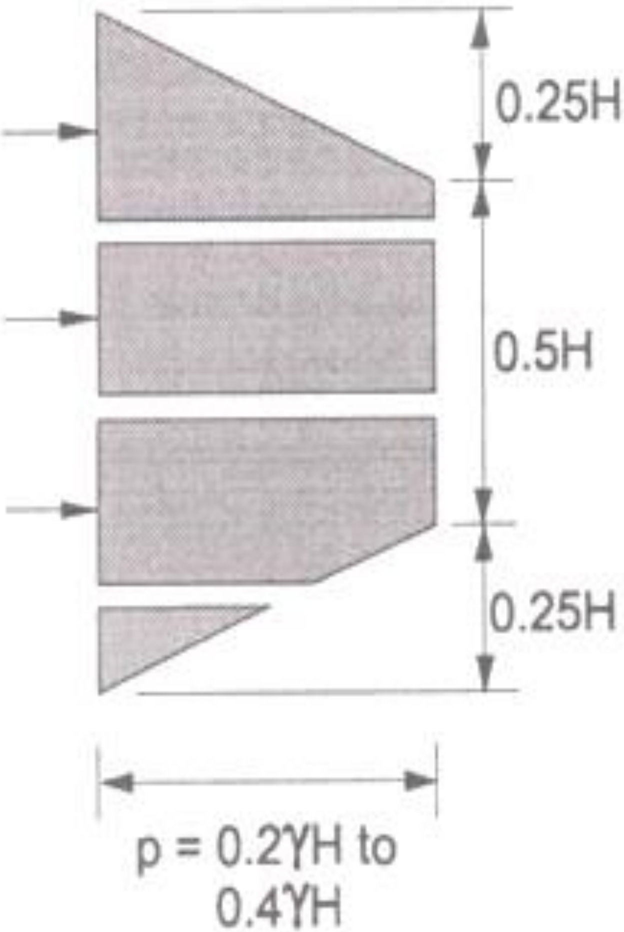
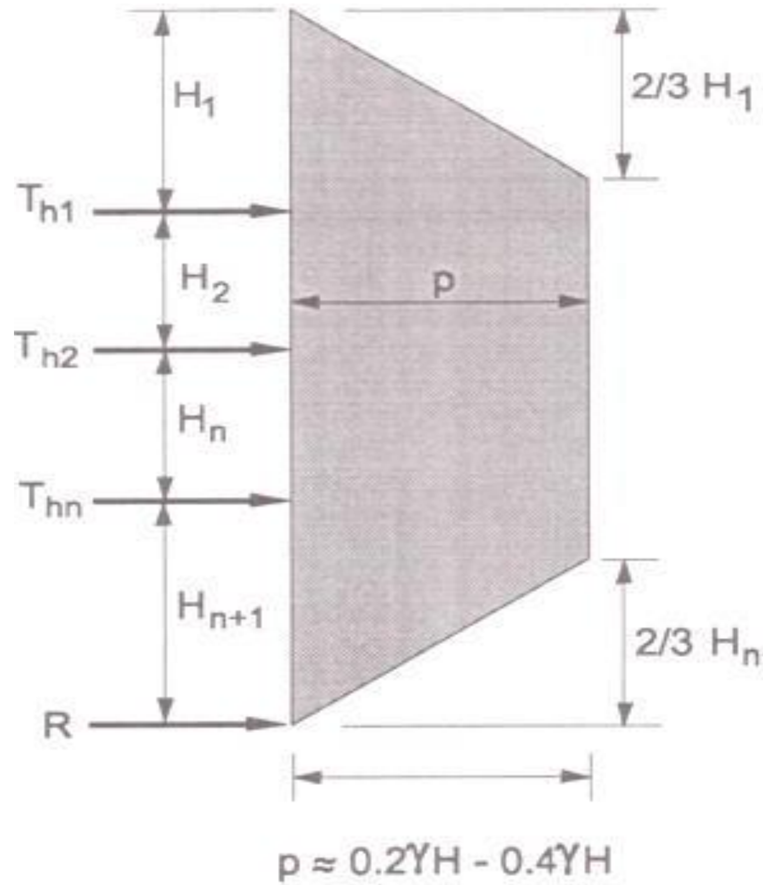
Anchor location affects lateral load distribution

Internally braced walls (T&P)



Tiedback walls (FHWA)



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Comments

- Apparent earth pressure (AEP) envelopes developed in response of observed differences between theory and field performance
- No numerical methods existed at time of development of AEP envelopes
- Finite element simulations are being used to design support systems without including temperature-induced loadings in cross-lot braces

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Serviceability

- Constraints in urban areas restrict magnitude of deformations
- Stiffness based design
- Need to develop design estimate of ground movements
  - Precedent
  - Numerical analysis

Iterations from practice to "theory"

Observations of deformations during excavation – maximum movements and bounds

Practice to “theory”

Finite element estimates of excavation-induced deformations: free field and “simple” constitutive models of soil behavior

“Theory” to practice

Observations of deformations during excavation – distributions of settlements

Practice to “theory”

Finite element estimates of deformations: construction simulation and more realistic constitutive models of soil behavior

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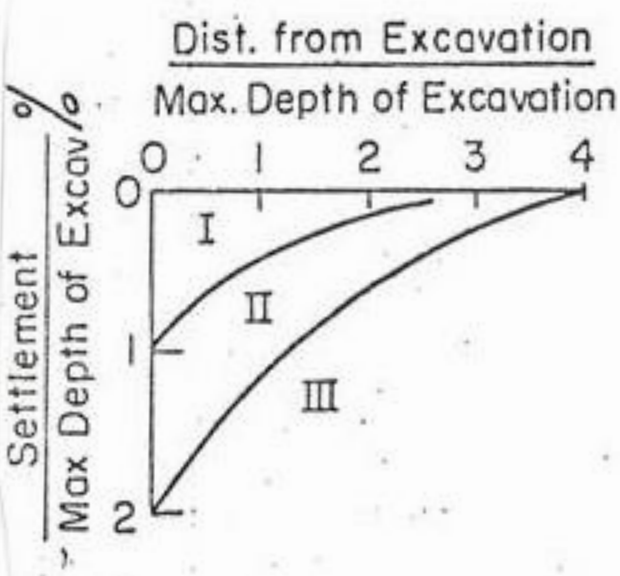
Observations of deformations during excavation – maximum movements and bounds

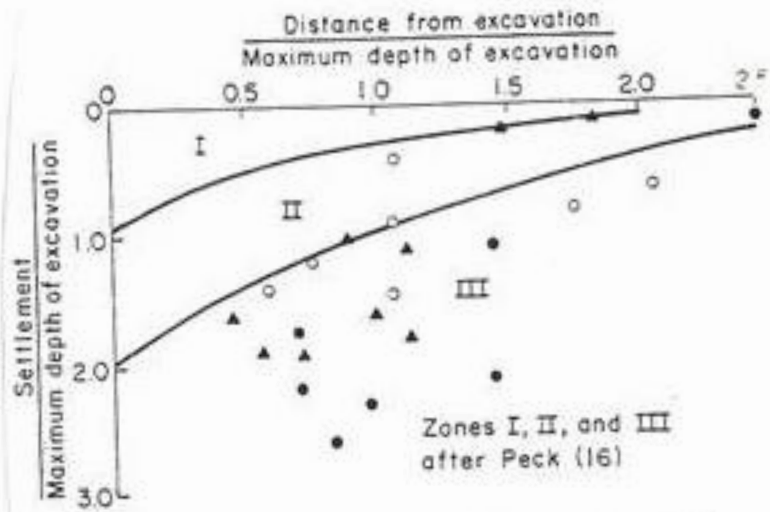
Empirical

- Peck (1969)
- Goldberg et al. (1975)
- Clough and O'Rourke (1990) ~ lateral wall movement and settlement
- Long (2001)
- Kung (2008)

Peck (1969) diagram



Lateral Distribution of Settlements Behind Excavation



Case	Symbol	Max. depth ft (m)	Support	Special problems
1	▲	45 (14)	Slurry wall, 3 levels of rakers	Pumped fines from base of caissons
2	●	28 (8.5)	Soldier piles & lagging, 1 level of rakers	Soil squeeze during caisson construction
3	○	26 (8)	Slurry wall, 1 level of struts	Soil squeeze during caisson construction

Zone I: Sand and clay with average workmanship

Zone II: Very soft to soft clay with limited depth below b/cut

Zone III: Very soft clay to large depth below cut

Examples of performance data that does not fall within Peck diagram limits

Goldberg, Jaworski and Gordon (FHWA 1972)

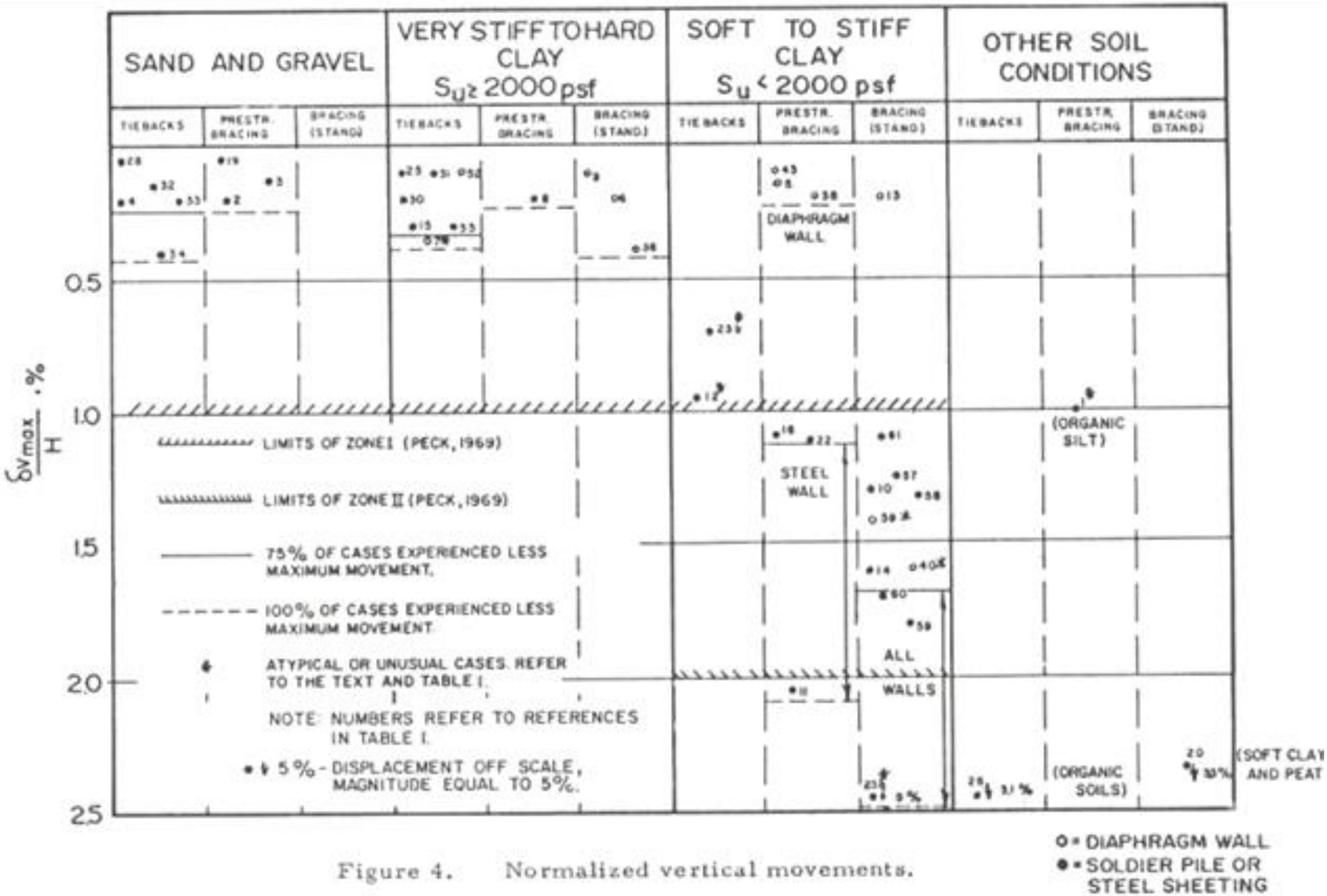
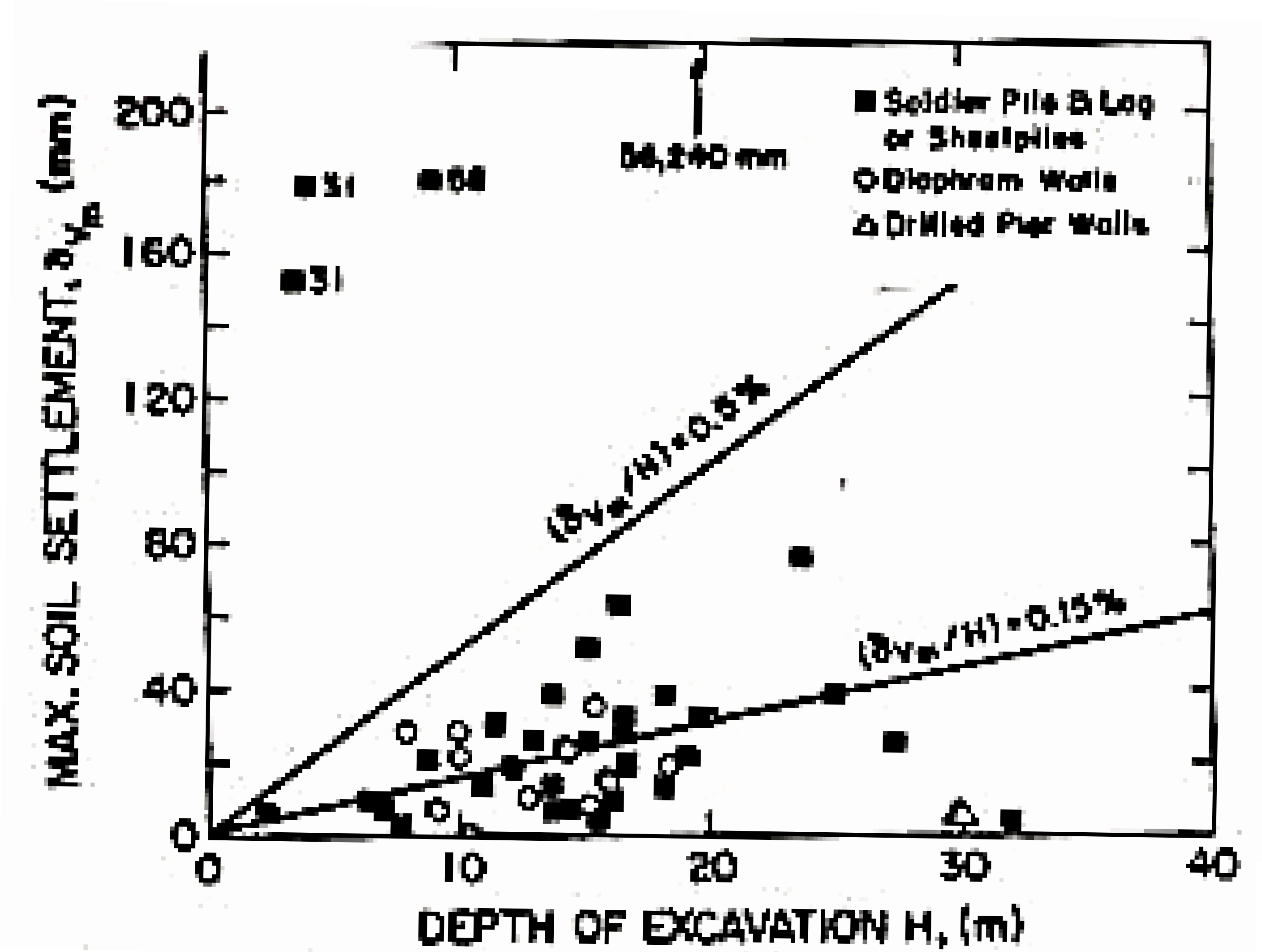


Figure 4. Normalized vertical movements.

Maximum settlement vs Depth of excavation (Clough and O'Rourke 1990)



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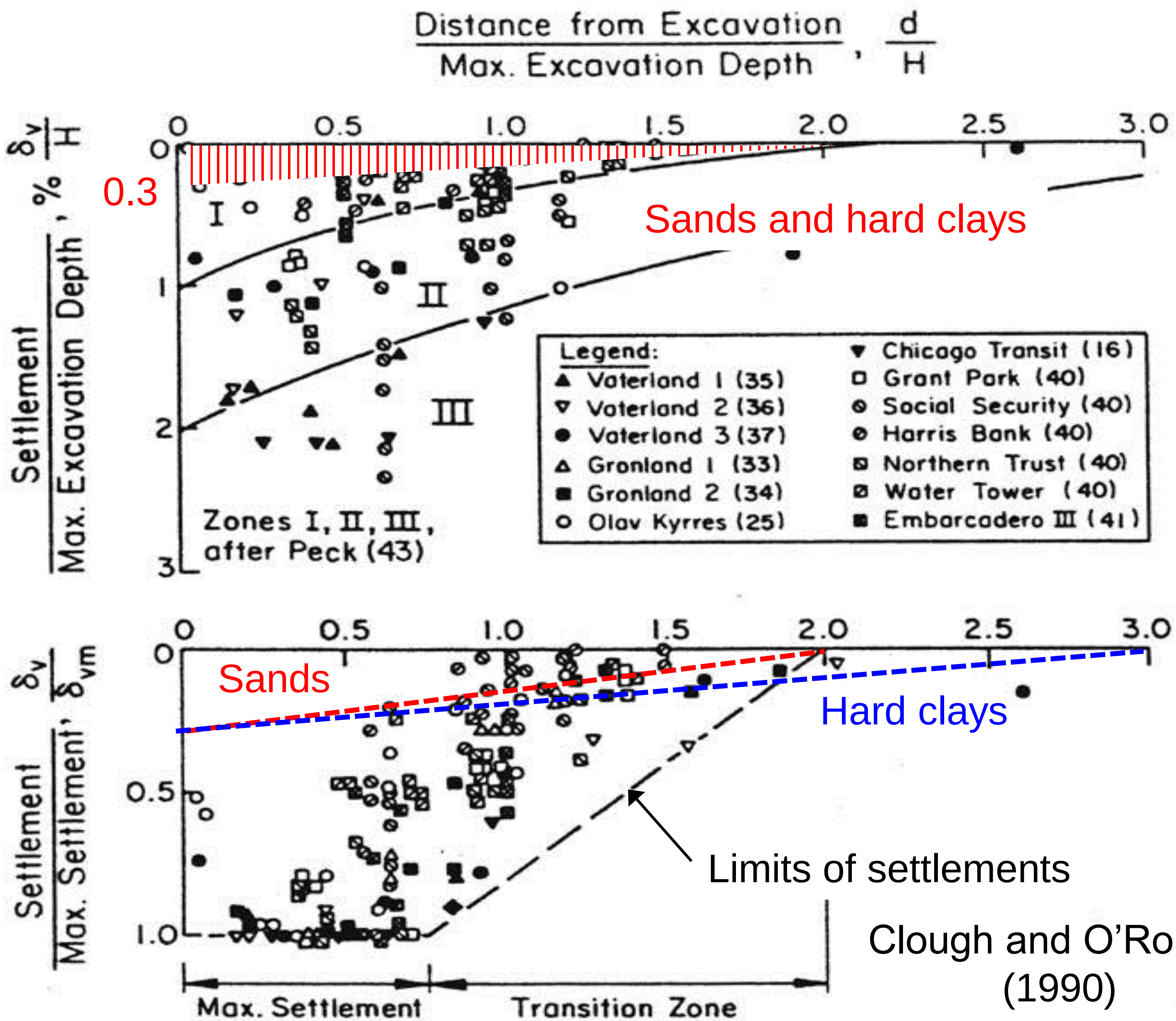
Normalized movements: soft clays



Clough and O'Rourke (1990)

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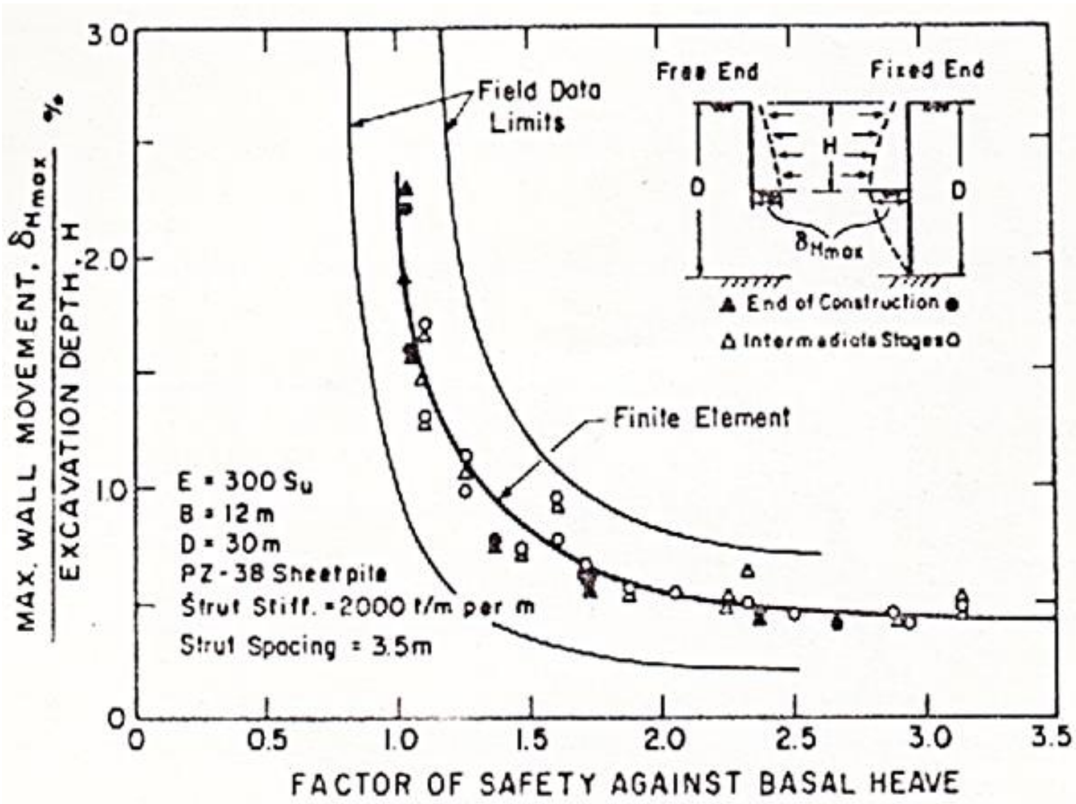
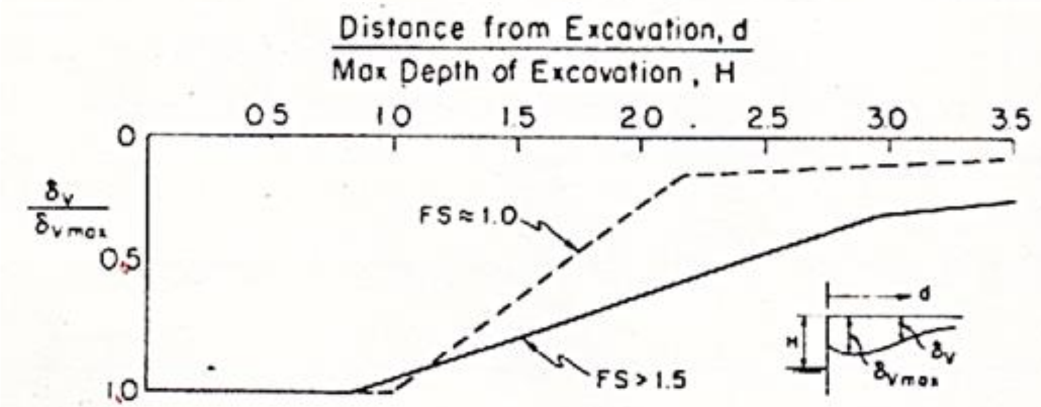
Finite element estimates of excavation-induced deformations: free field and “simple” constitutive models of soil behavior





Adjust values for effects of

- wall stiffness
- strut stiffness
- depth to underlying firm layer
- excavation width
- strut preload
- modulus multiplier, m

Mana and Clough (1981)

$$\delta_{Vmax} = (0.6 - 1.0)\ \delta_{Hmax}$$

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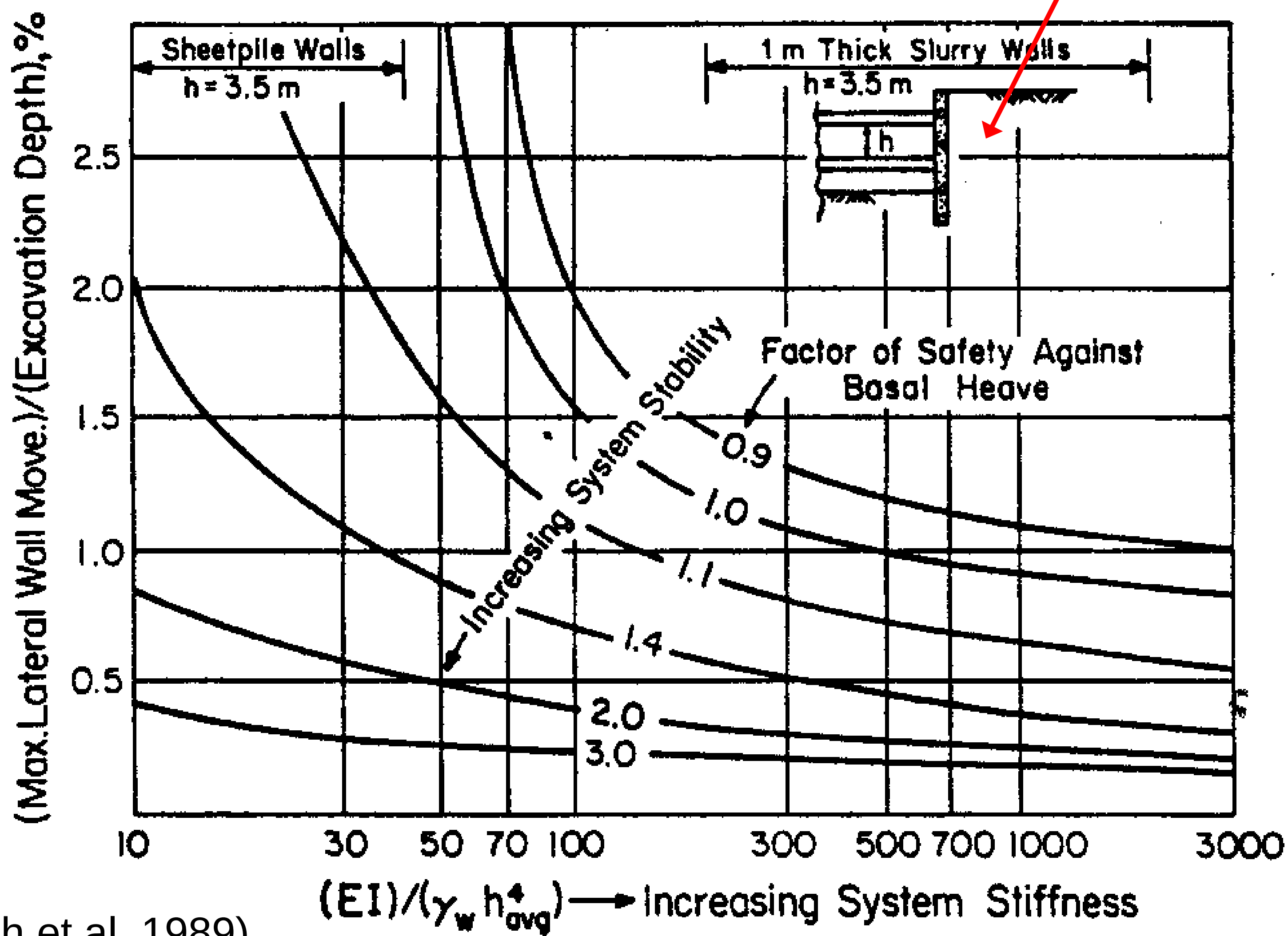
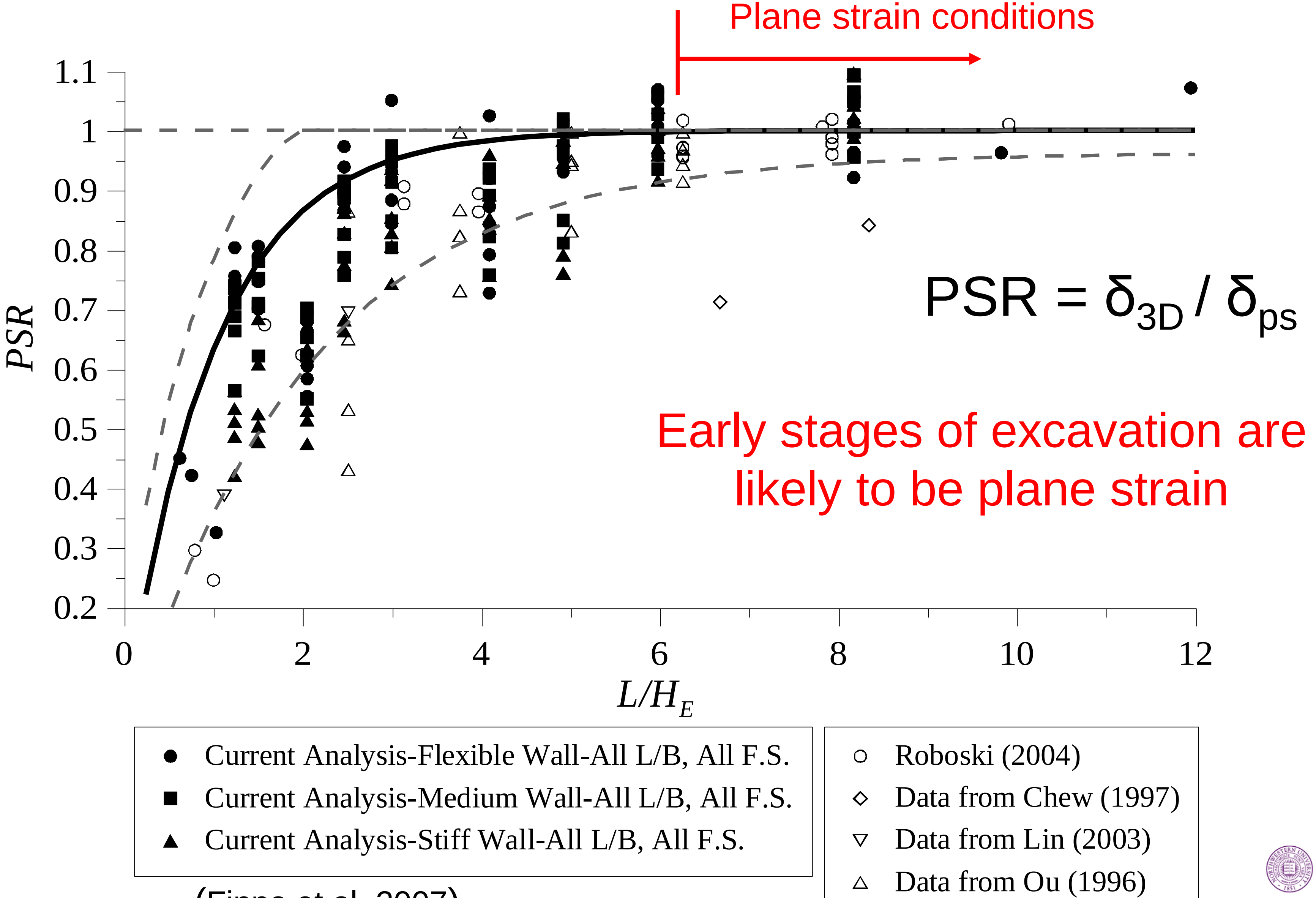
Estimate maximum lateral wall movement in clays

Free field movements



(Clough et al. 1989)

Adjustments if conditions are not plane strain



(Finno et al. 2007)

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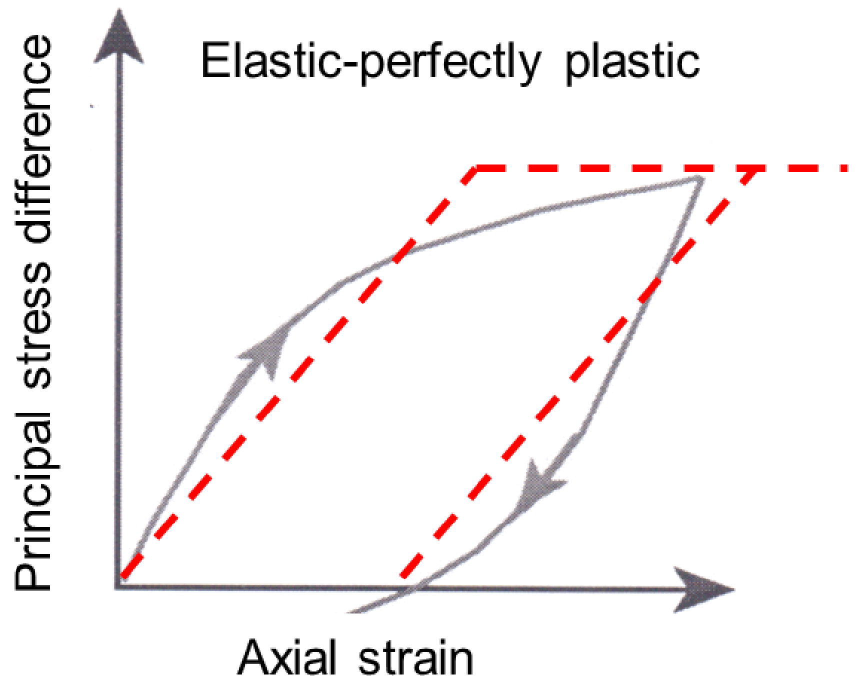
Assumed stress-strain responses



Mises elastic-perfectly plastic model
2 elastic parameters and failure parameters
For undrained loadings on clay and Mohr Coulomb failure criteria:

$\phi = 0$, $c = S_u$

$E = m\, S_u$, $v \approx 0.5$

Implications of assumed constitutive responses

- Linear elastic and elasto-plastic models underpredict maximum settlement behind wall and overpredict extent of settlement trough
- Approach is to compute maximum lateral wall movement and estimate maximum vertical settlement ~ 60 to 100% of maximum wall movement per Mana and Clough (1981)

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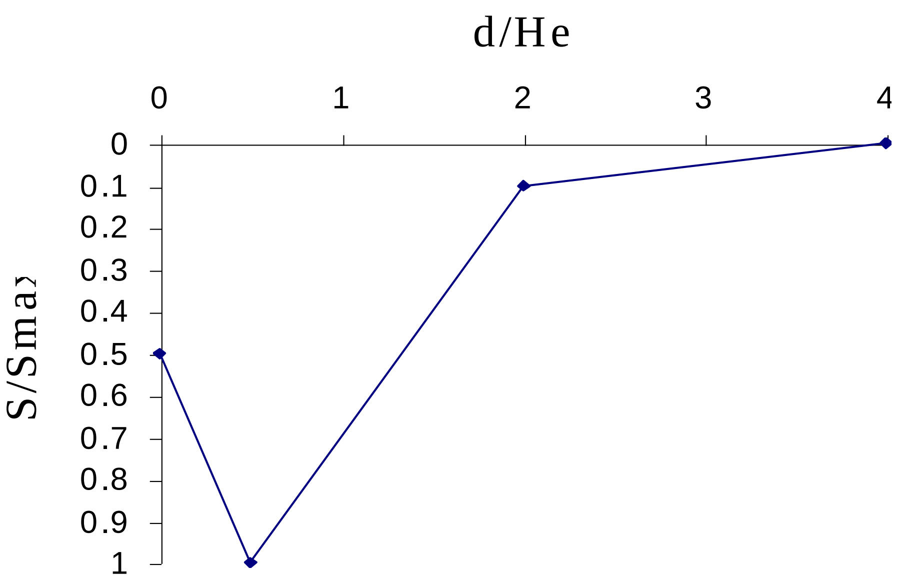
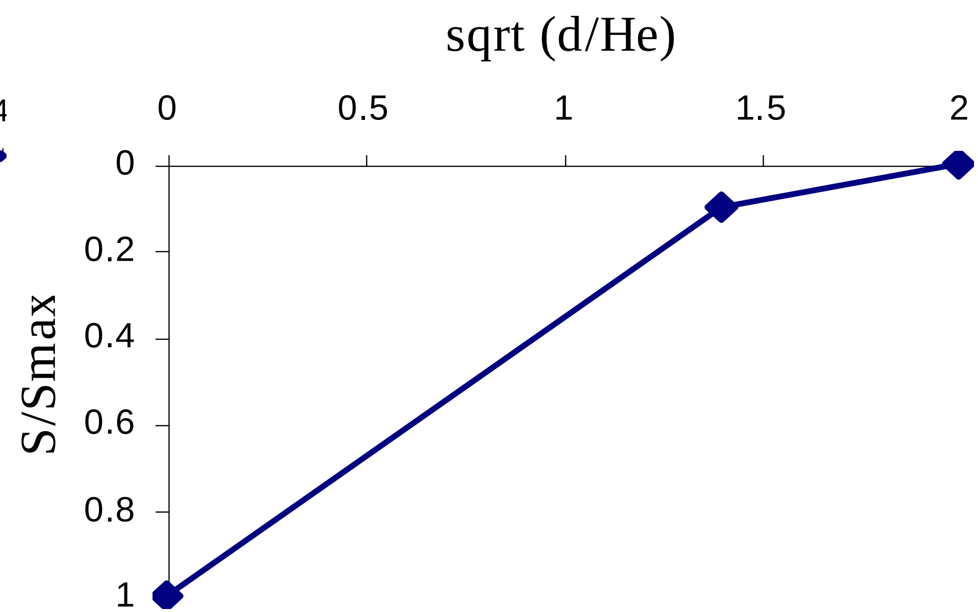
Observations of deformations during excavation – distributions of settlements

Settlement distribution – (Hsieh and Oh 1998)



“small” cantilever movements



“large” cantilever movements

Extents of settlement in Clough and O’Rourke charts are not distributions of settlements

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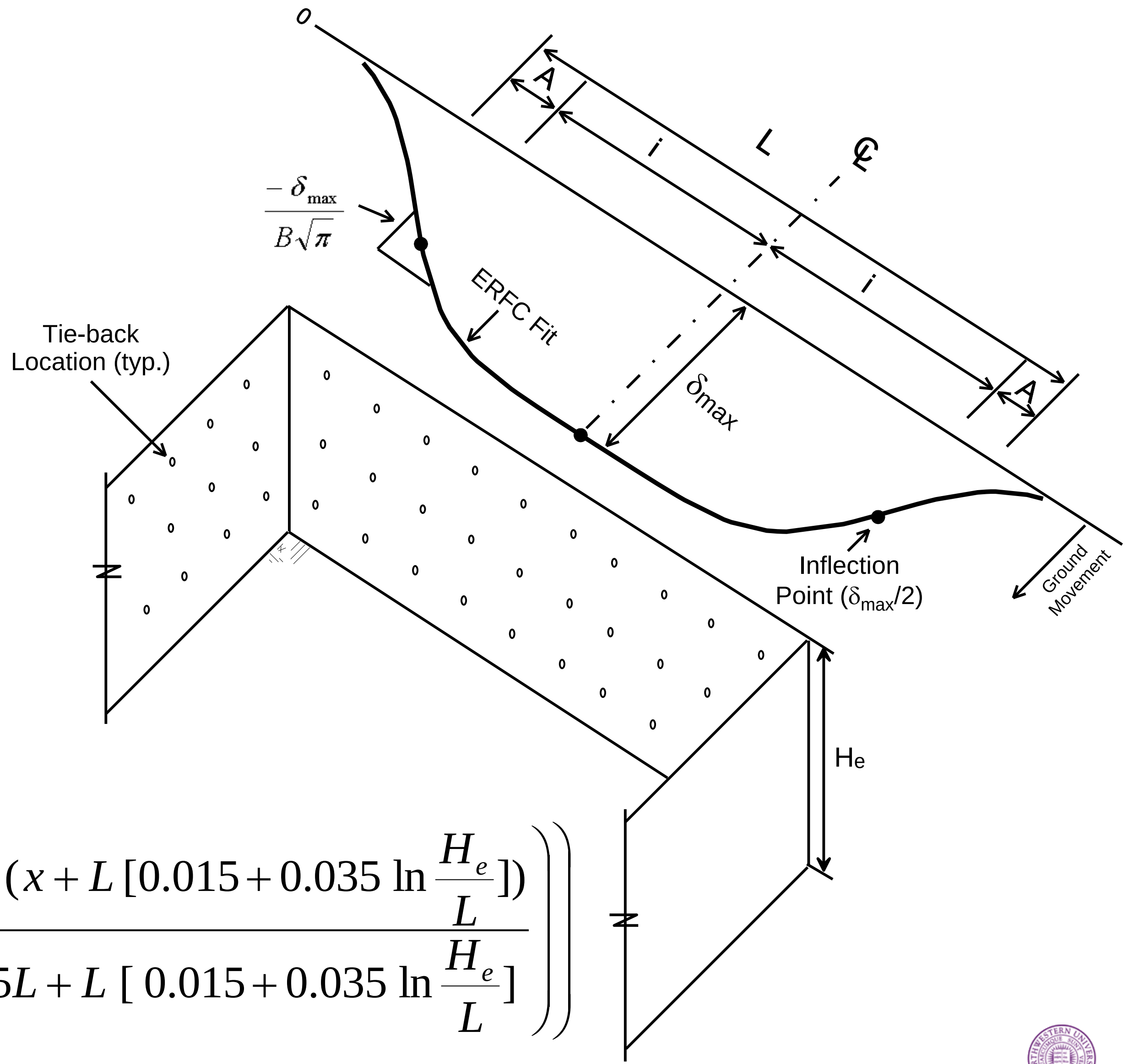
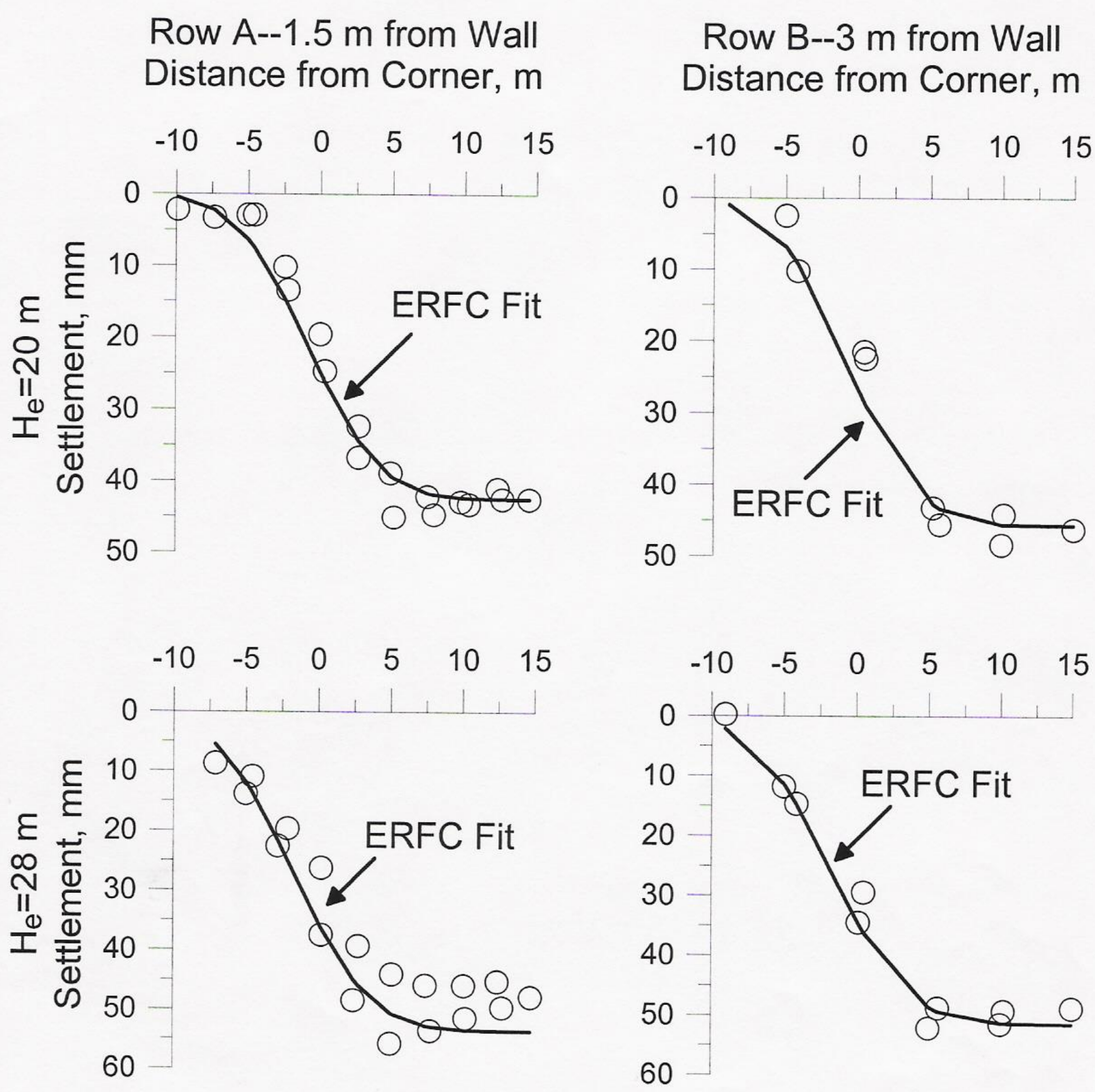
Movements parallel to wall



$$\delta(x) = \delta_{\max}\left(1 - \frac{1}{2} * erfc\left(\frac{2.8(x + L\,[0.015 + 0.035\,\ln\frac{H_e}{L}])}{0.5L + L\,[\,0.015 + 0.035\,\ln\frac{H_e}{L}]}\right)\right)$$

Note: Roboski and Finno (2005) original publication contained typo



Excavation in Toyko – Takagi et al. (1984)

Example of fit of complimentary error function

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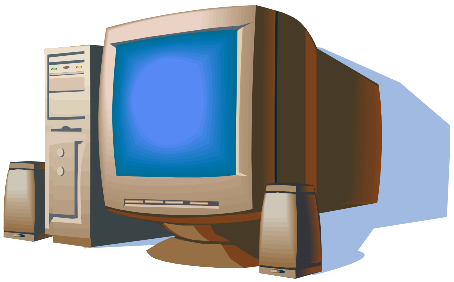
Finite element estimates of deformations: construction simulation and more realistic constitutive models of soil behavior



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Construction

FE procedures

Constitutive modeling

Instrumentation

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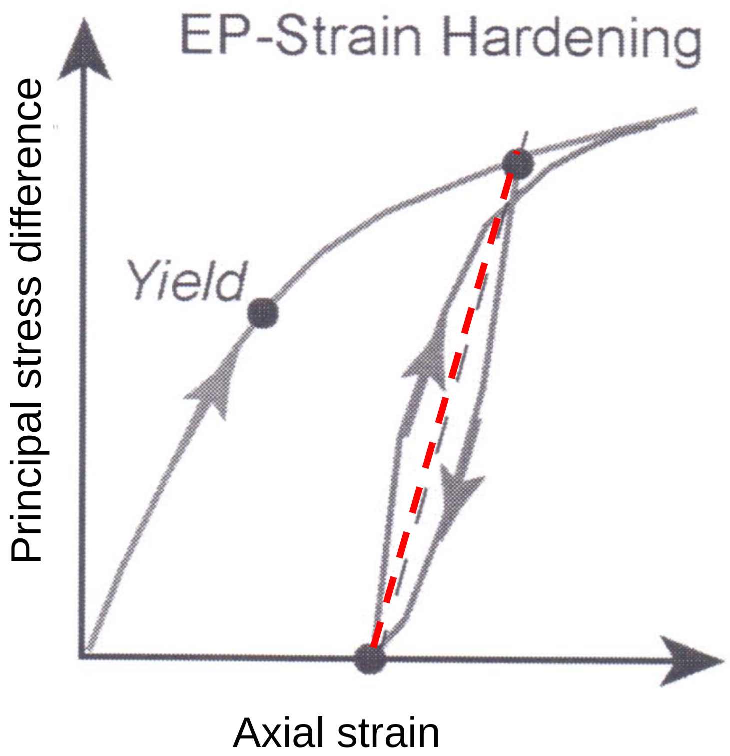
Types of stress-strain models



All plasticity models have failure criteria, yield surface(s), flow rule(s) and hardening law(s)

Commonly employed in commercial finite element codes:
Modified Cam-Clay
Hardening Soil Model (many similarities to Duncan-Chang model but in plasticity framework)

Either more parameters or assumptions regarding soil behavior required
Stiffness at small strains underestimated

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Stress-strain characterization – incremental non-linearity

Bender elements
Internal instrumentation

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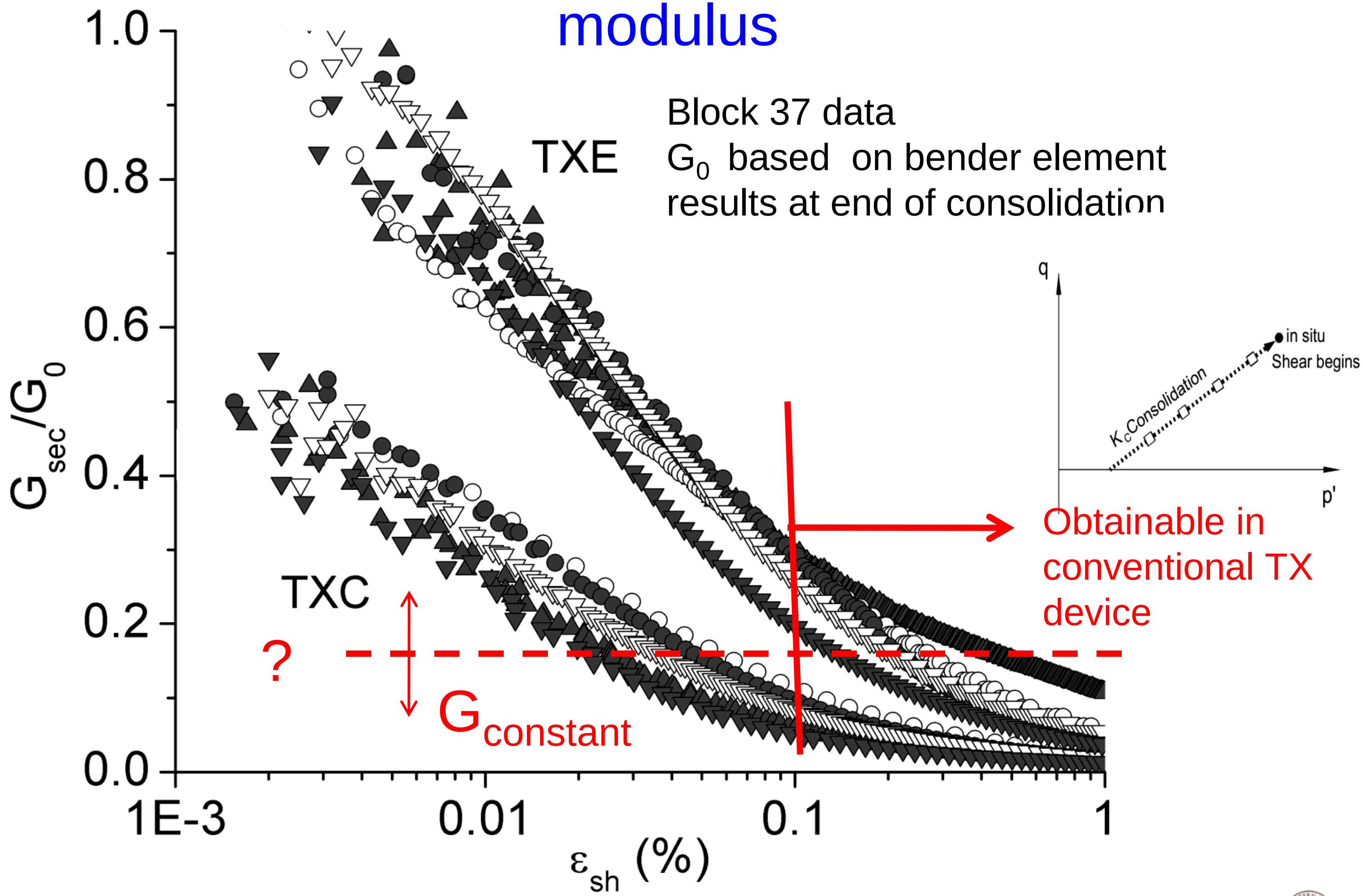
Direction of loading - normalized secant shear modulus



Data from Finno and Kim (2012)

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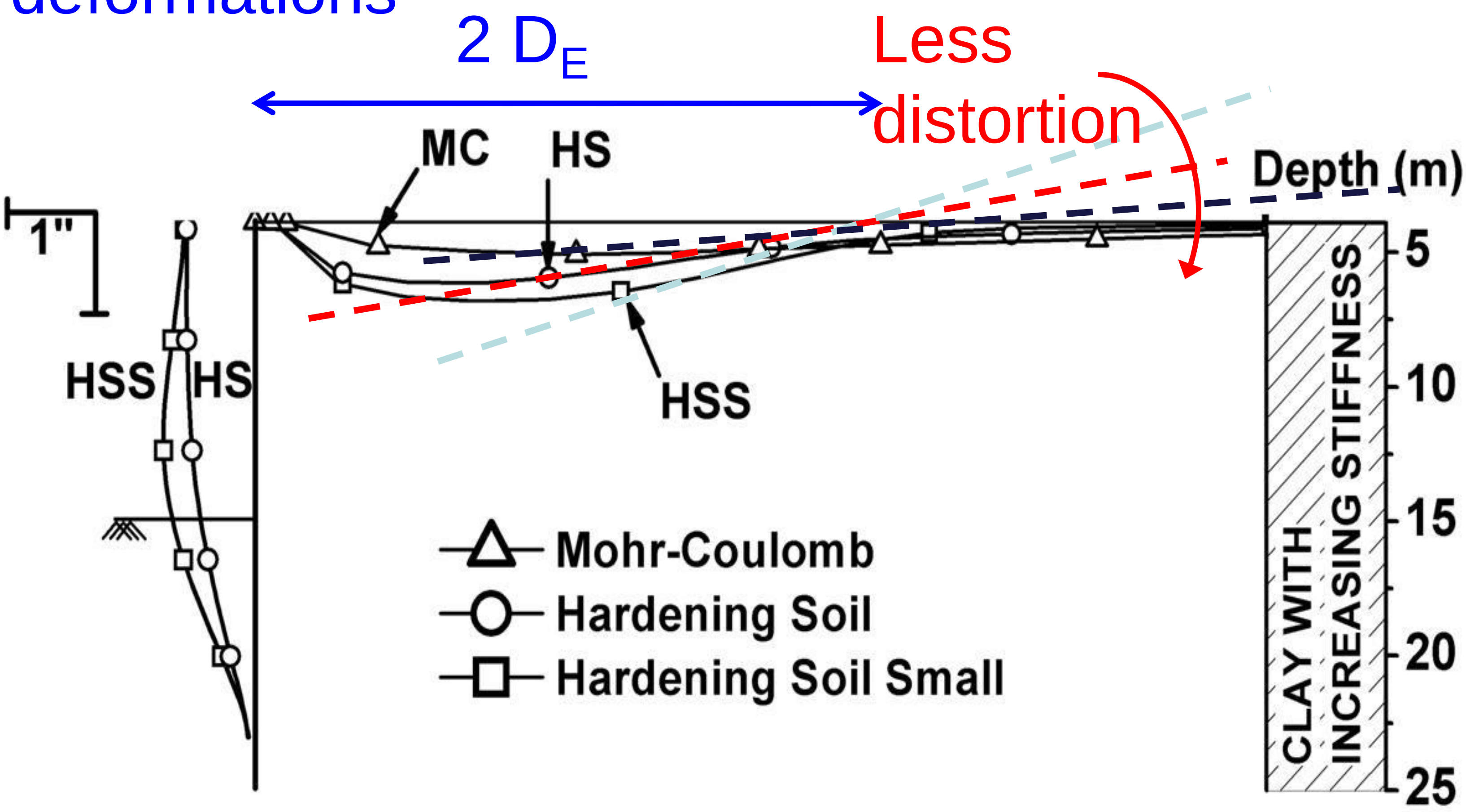
Effect of constitutive model on computed deformations



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

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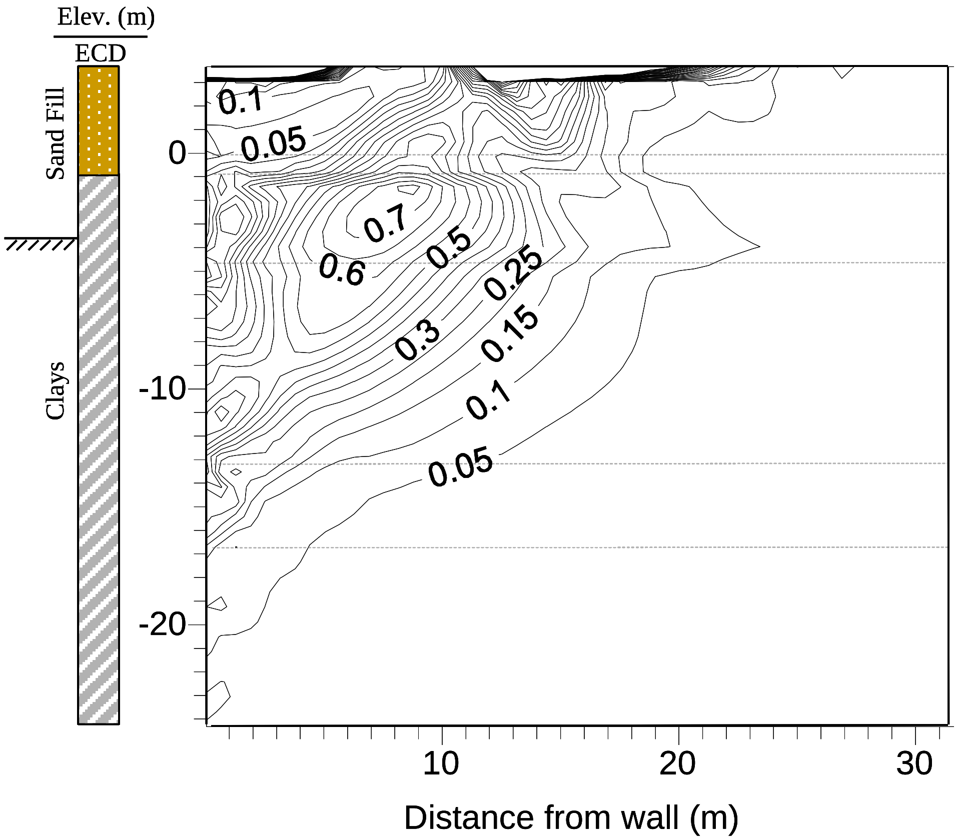
Shear strains for 10 m cut



57 mm lateral wall movement

Lateral displacements near wall dominated by ε_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

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Movements from causes other than excavation and bracing cycles

- Removal of existing foundations
- Wall installation
  - Densification of sands from vibrations (Clough and Chameau 1980)
  - Displacements arising during installation
    - Slurry or secant pile wall (Clough and O'Rourke 1990 and Finno 2010)
    - Sheet-pile wall (Finno et al. 1988)
- Deep foundation installation (Lukas and Baker 1978)
- Concrete shrinkage during top-down construction (Arboleda and Finno 2015)

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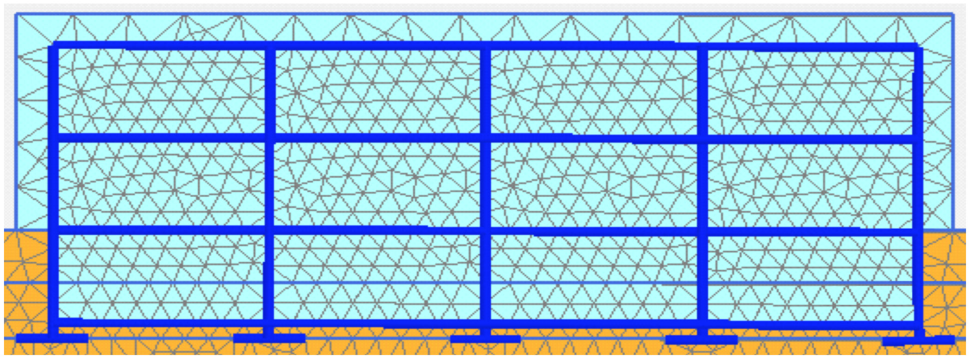
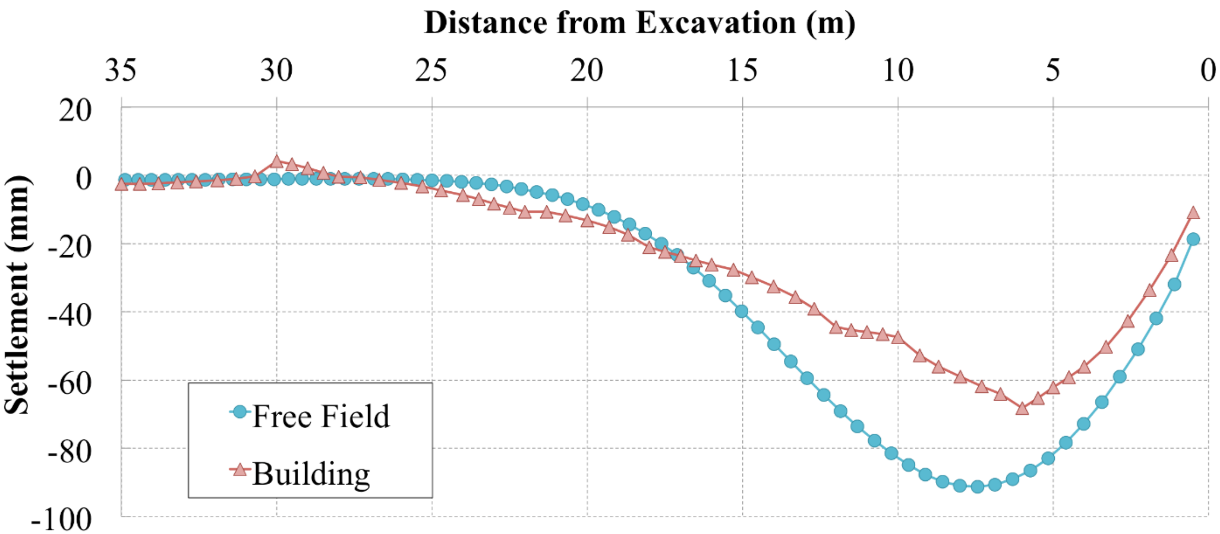
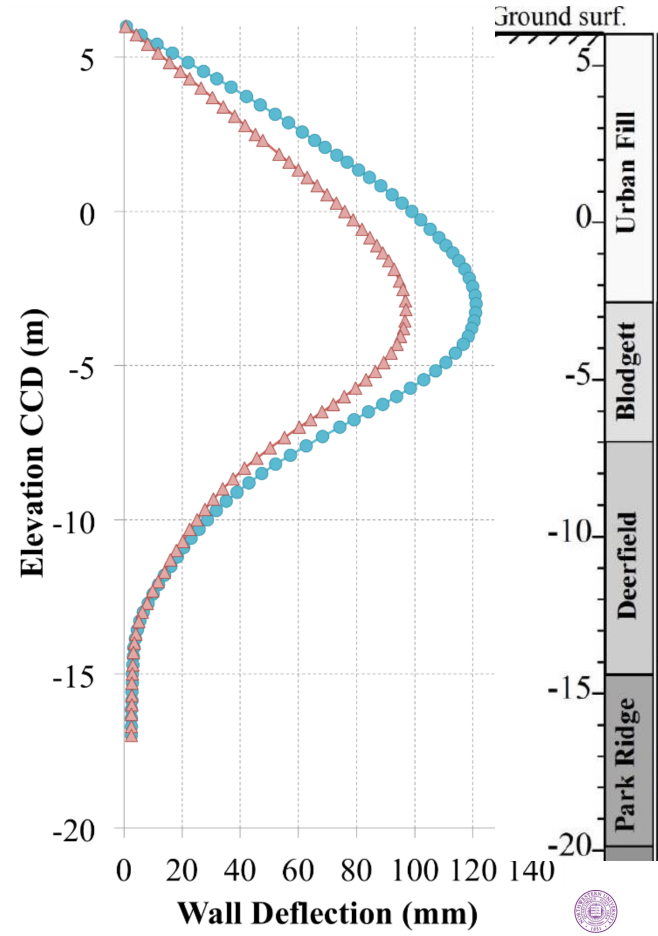
Presence of building adjacent to excavation affects movements







25% reduction of maximum free field settlement

two factors: lower stress from basement stiffness of building

Concluding remarks

- Cycles of practice (precedent) and theory/ numerical analyses have defined the state-of-the- art of deep excavation design
- Use of precedent provides *estimates* of support loads and deformations
- Numerical procedures can consider expected construction procedures explicitly – although constitutive responses and details and sequences of construction difficult to predict in design stage

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Concluding remarks

- Monitor, monitor, monitor….
- Going through the process of making predictions of ground movements is an excellent approach to design of supported excavations
- Optimum choice of support systems may be one that allow movements to slightly damage adjacent structures; then include bid item to repair

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It is what your learn after you know it all that counts

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