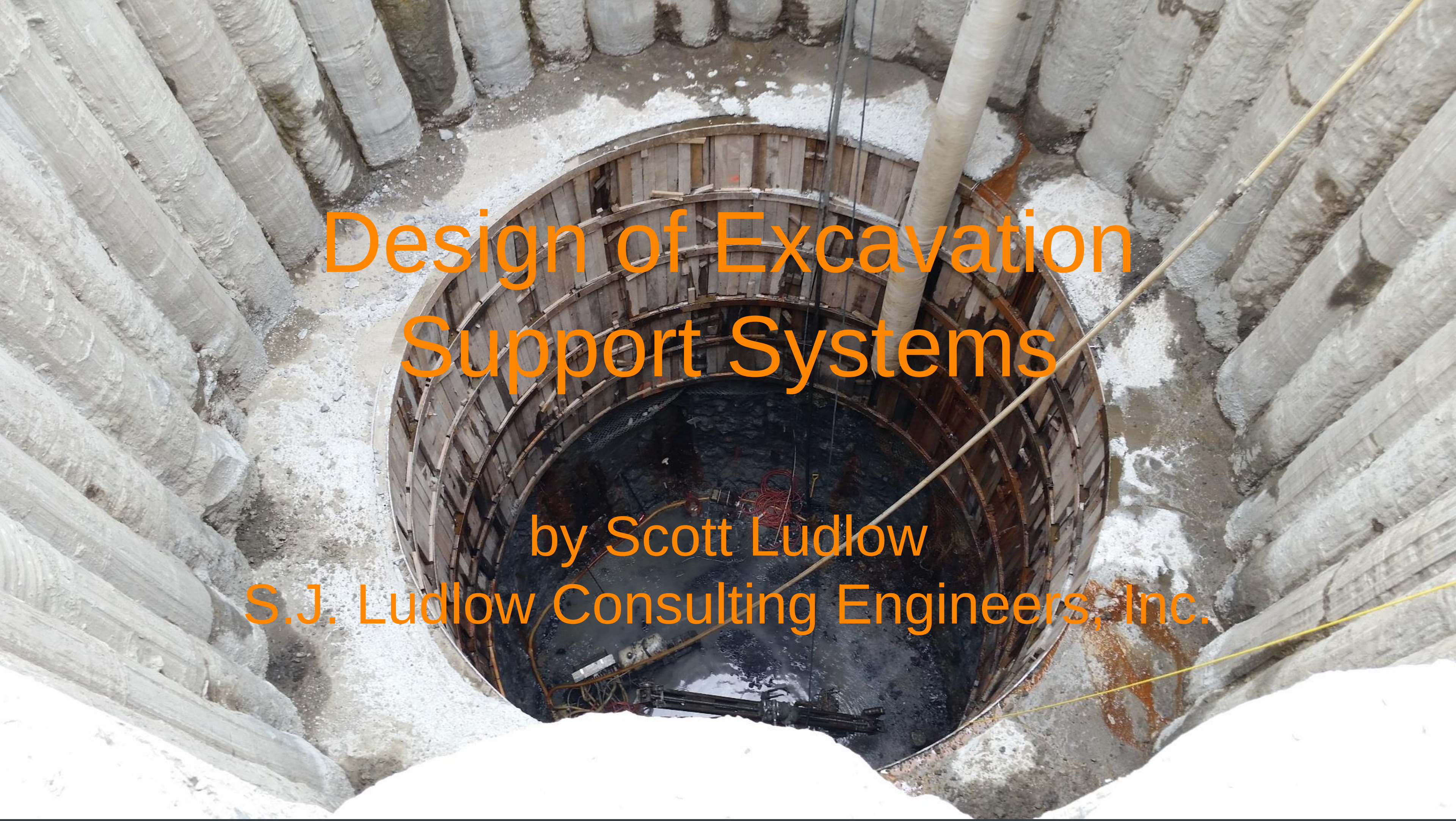

Design of Excavation Support Systems

by Scott Ludlow
S.J. Ludlow Consulting Engineers, Inc.

GEO-Omaha 2023, 40th Annual Geotechnical Conference, Omaha, Nebraska

February 10, 2023


"The key to the design of excavation support systems is to understand the deflection of the system at any given point during construction. This includes a thorough understanding of the geometry and stiffness characteristics of the support system in relation to the development of earth pressures as well as models for use in structural analysis."
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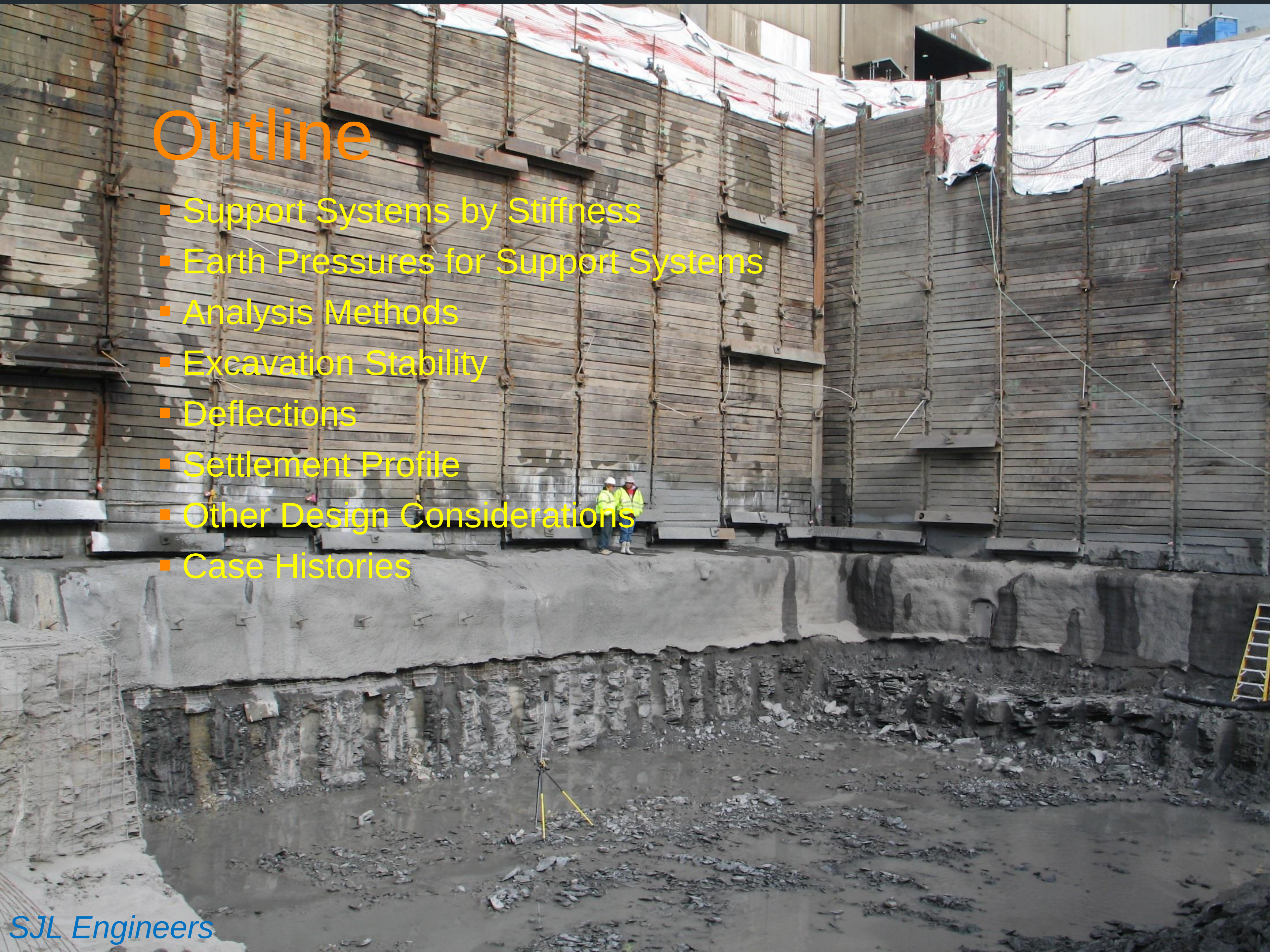
Outline

- Support Systems by Stiffness
- Earth Pressures for Support Systems
- Analysis Methods
- Excavation Stability
- Deflections
- Settlement Profile
- Other Design Considerations
- Case Histories



Support Systems by Stiffness

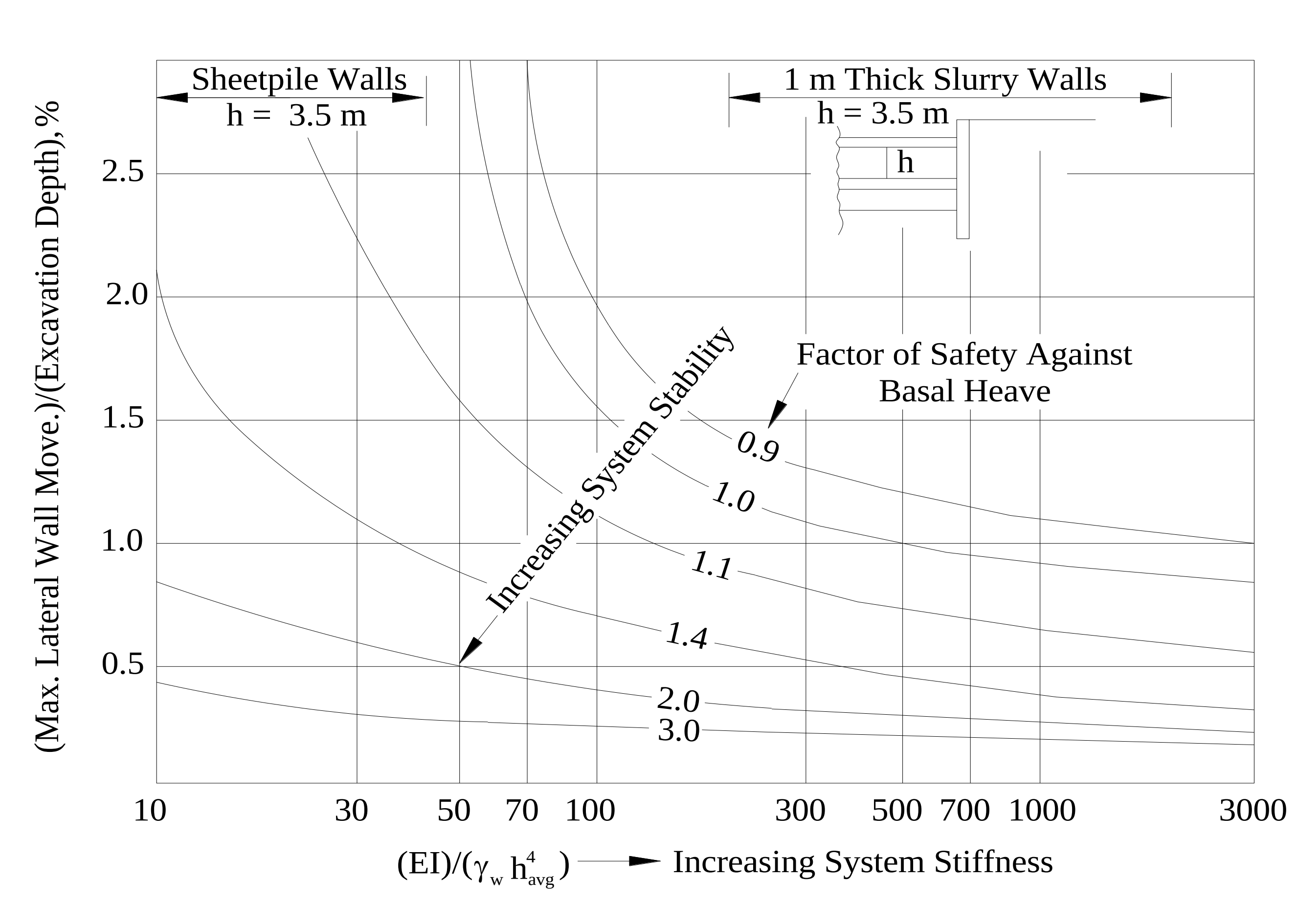
1. Flexible ($EI/\gamma_w * h_{avg}$^4) ≈ 10 – 40*
   - Cantilever
   - Sheet Piling (≥ one level of bracing)**
   - Soldier Pile and Lagging (≥ one level of bracing)**
2. Stiff (> one level of bracing)** ($EI/\gamma_w * h_{avg}$^4) ≈ 200 – 2000*
   - Tangent Pile
   - Secant Pile
   - Diaphragm
3. Other (deep shafts – geometry circular/ellipse/horseshoe]/sequence/type)

* After Clough & O'Rourke, 1990

** Externally Stabilized or Internally Braced

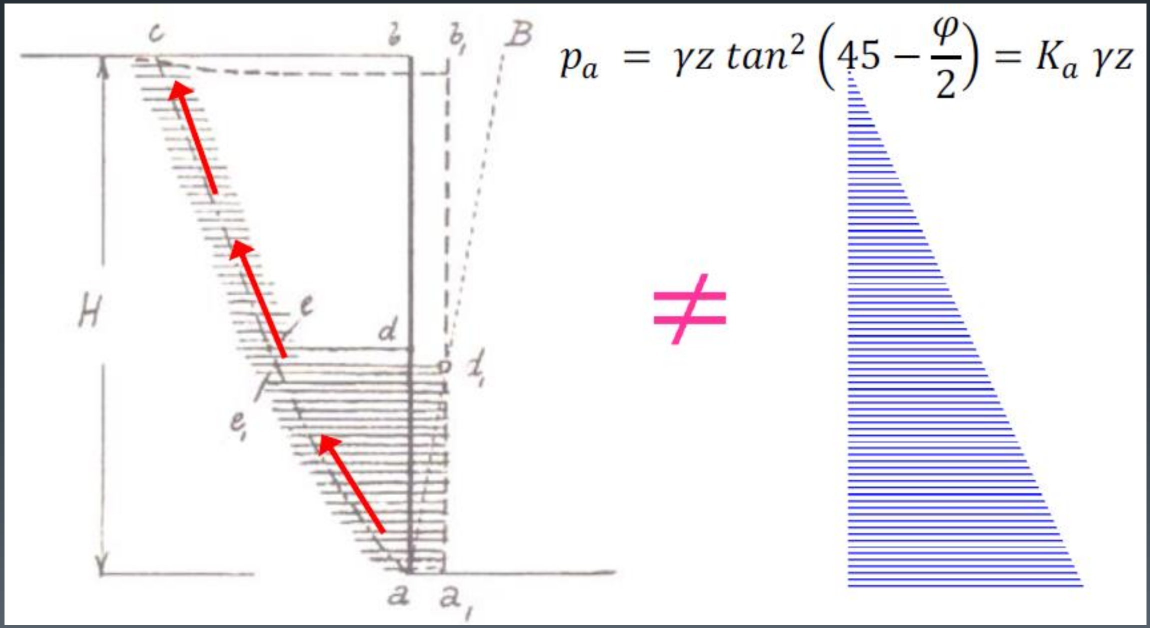
Support Systems by Stiffness

(after Clough & O'Rourke, 1990)

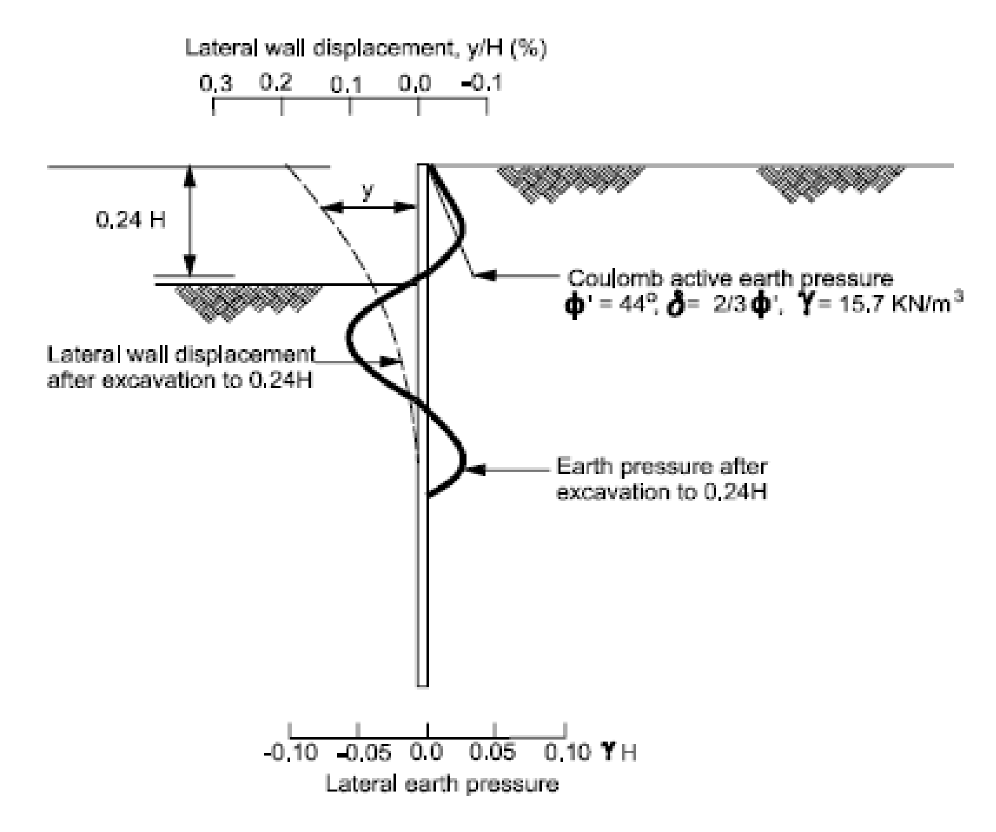


Earth Pressures

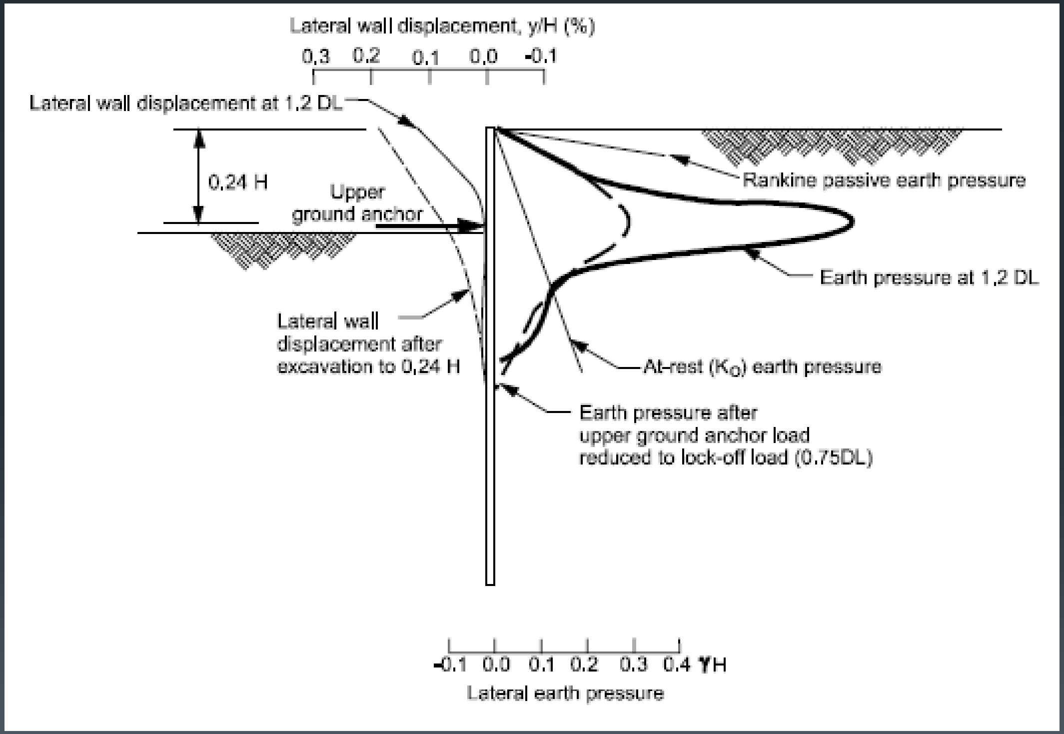
- Fallacy in earth pressure calculations
- Experience did not match classical earth pressure distributions
- Higher apparent stresses at top and lower at bottom of excavations



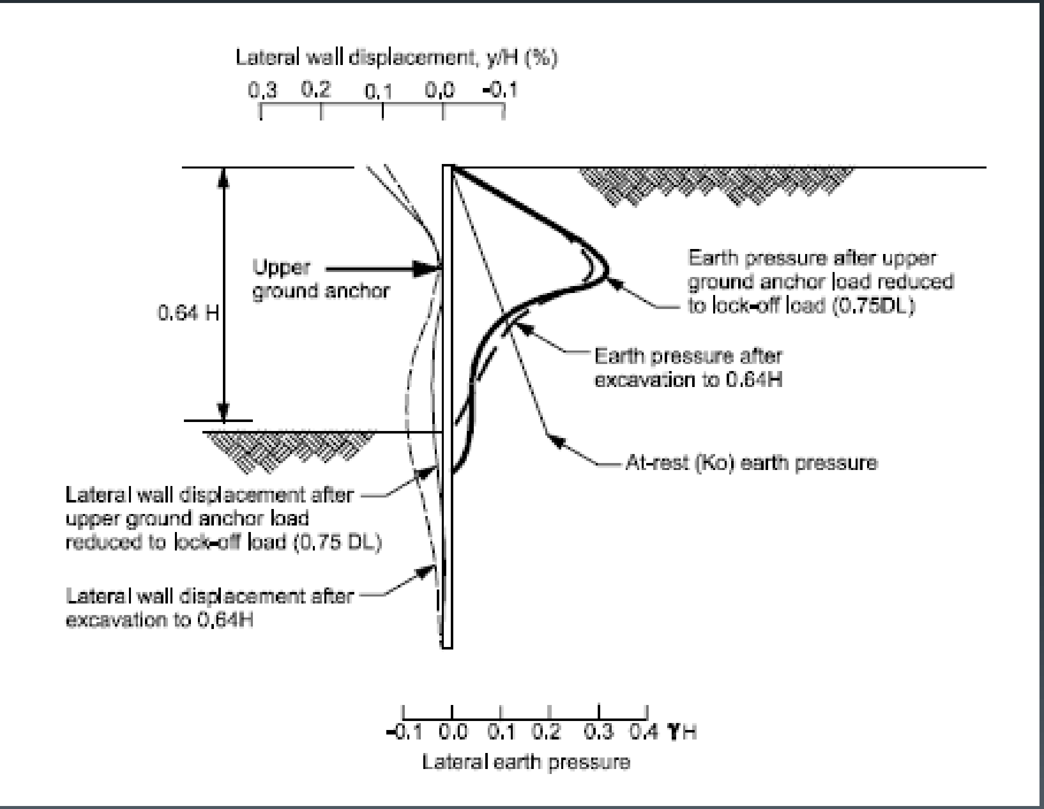
Earth Pressures (cantilever stage)



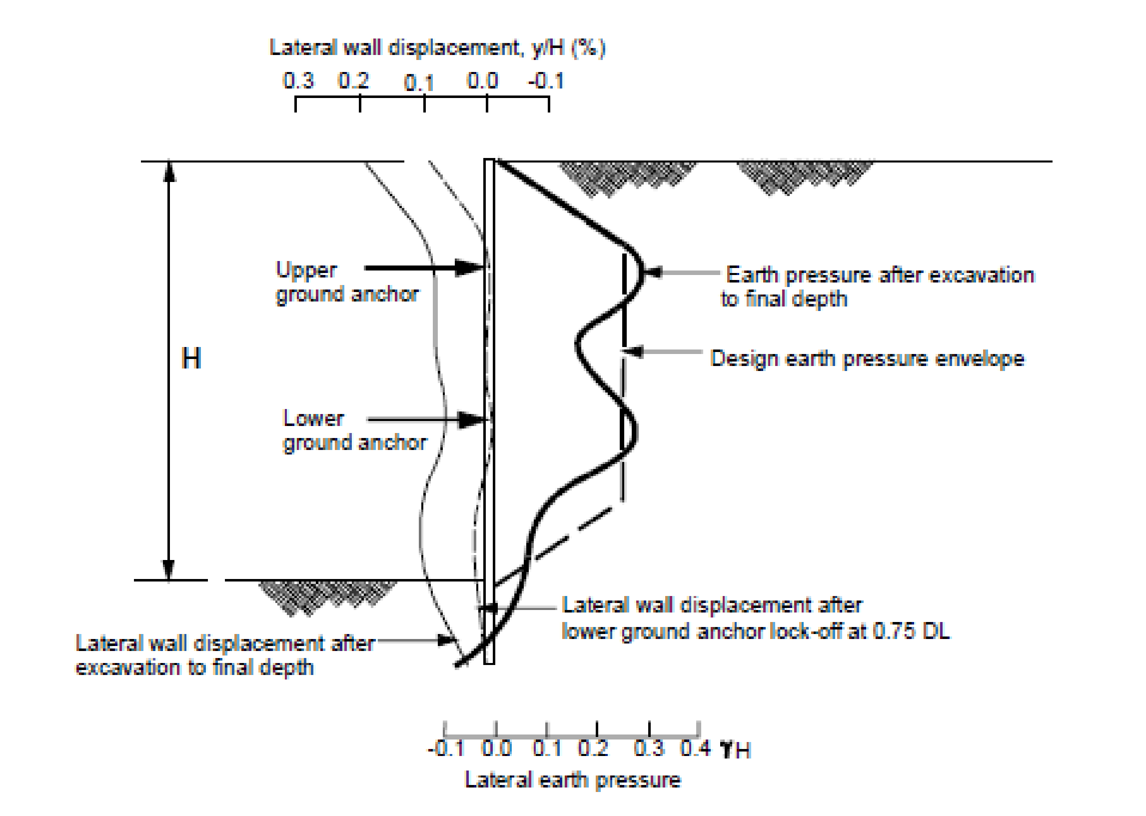
Earth Pressures (stressing of upper anchor)

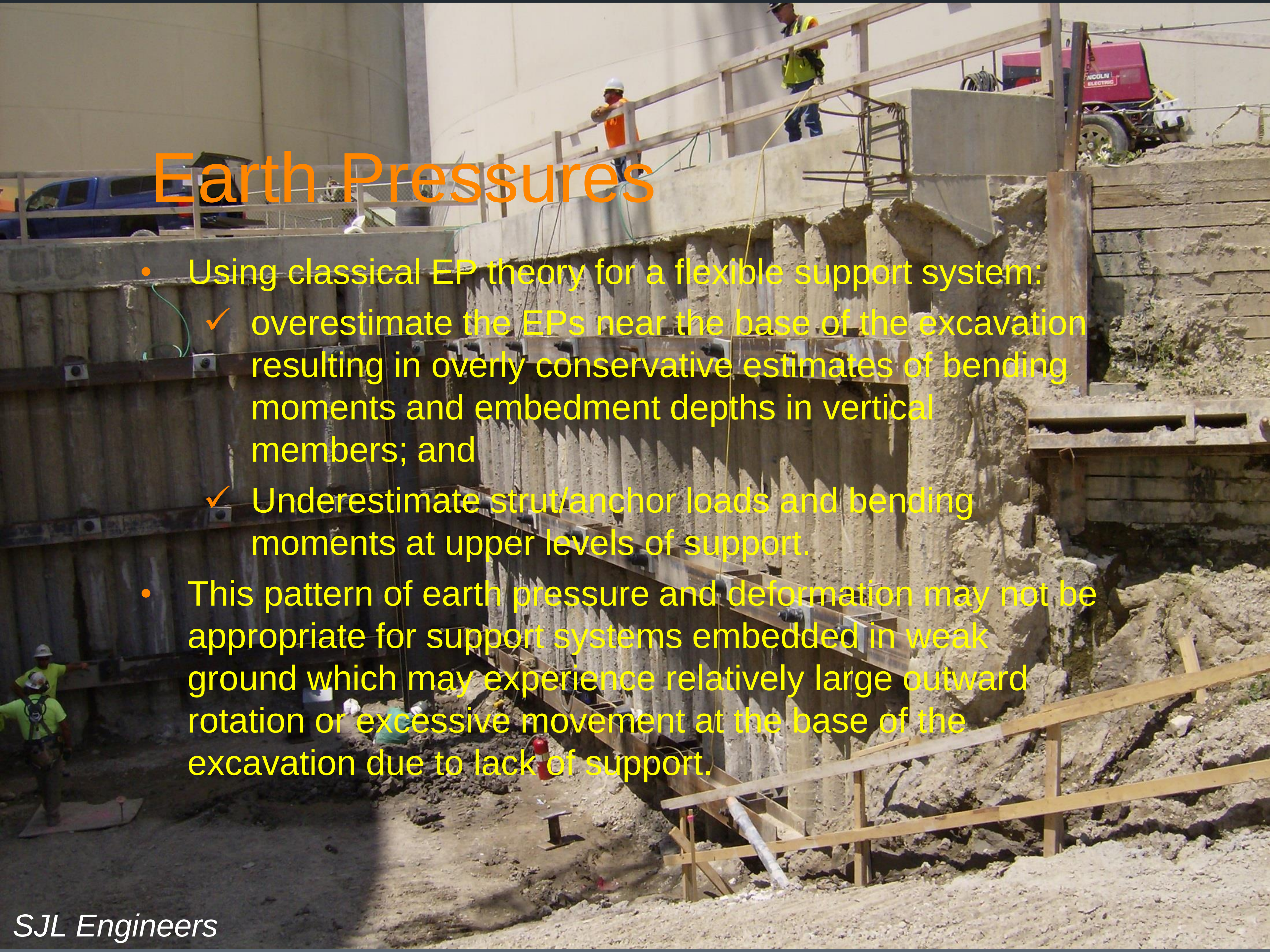


Earth Pressures (excavation at lower anchor)



Earth Pressures (end of construction)



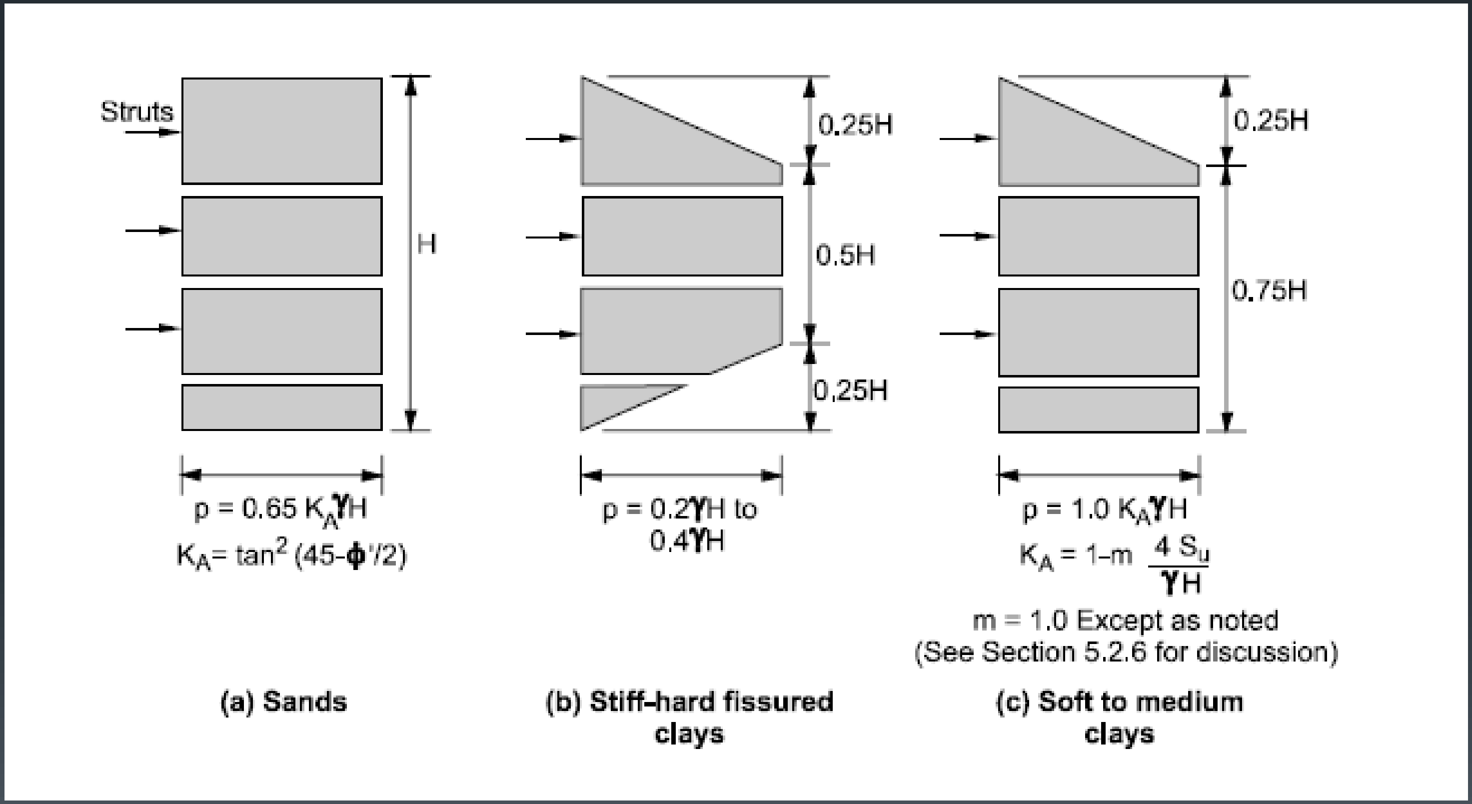


Earth Pressures

- Using classical EP theory for a flexible support system:
  - ✓ overestimate the EPs near the base of the excavation resulting in overly conservative estimates of bending moments and embedment depths in vertical members; and
  - ✓ Underestimate strut/anchor loads and bending moments at upper levels of support.
- This pattern of earth pressure and deformation may not be appropriate for support systems embedded in weak ground which may experience relatively large outward rotation or excessive movement at the base of the excavation due to lack of support.

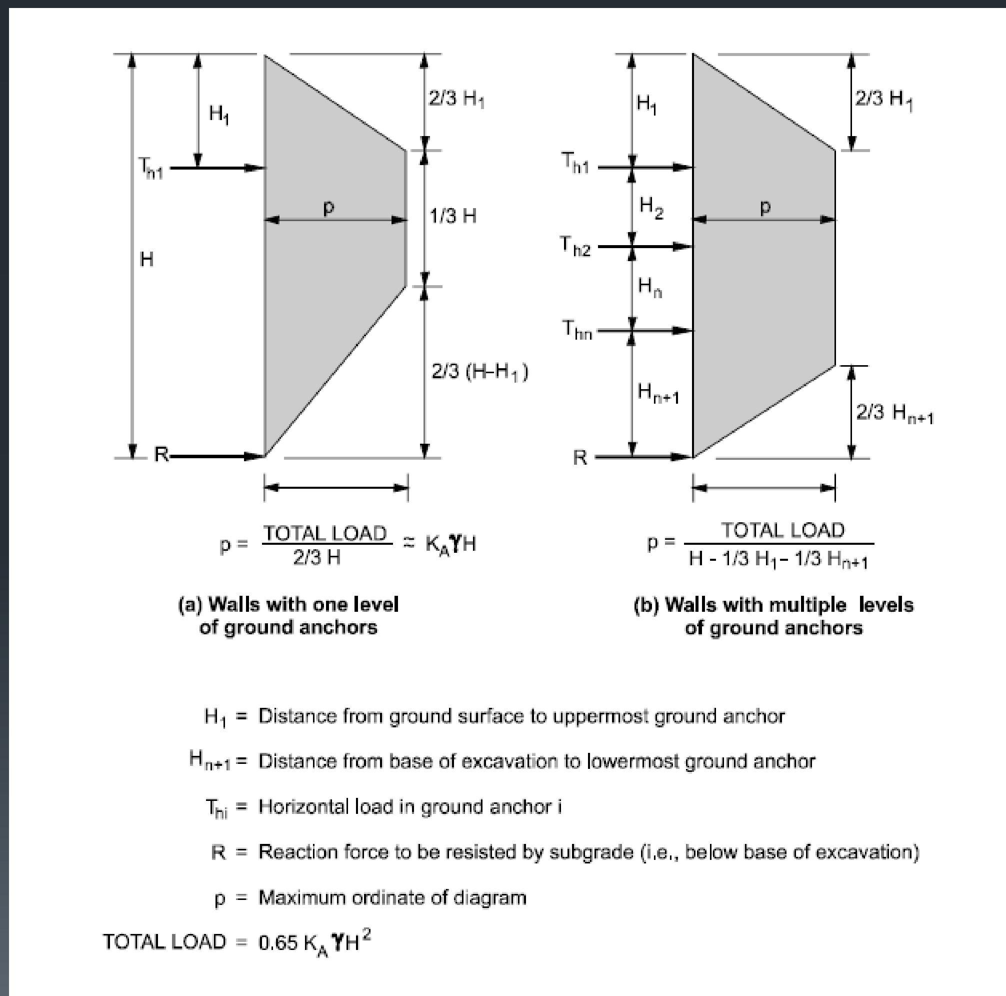
Earth Pressures (AEP)

After Terzaghi and Peck, 1967 (for flexible support systems)



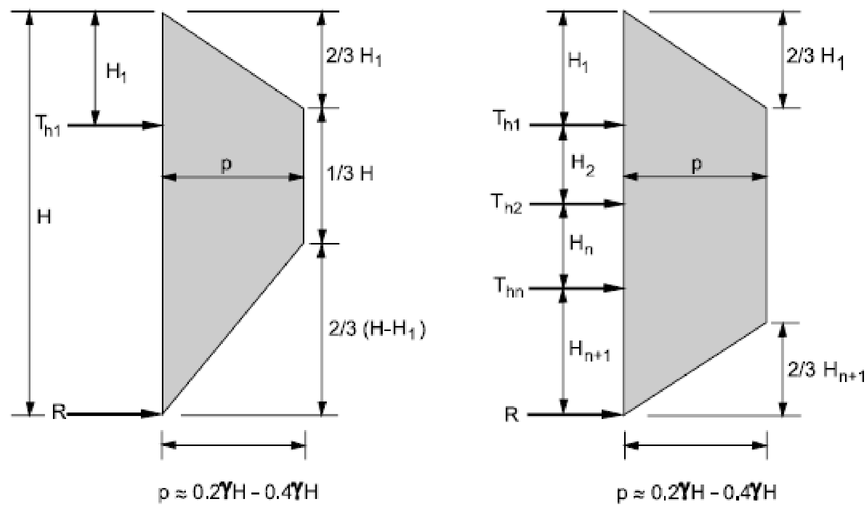
Earth Pressures (AEP - Sands)

After GEC 7 (for flexible support systems)



Earth Pressures (AEP – Clays)

For Stiff to Hard Clays (Ns ≤4); after GEC 7 (for flexible support systems)



(a) Walls with one level of ground anchors

(b) Walls with multiple levels of ground anchors

H_1 = Distance from ground surface to uppermost ground anchor

H_{n+1} = Distance from base of excavation to lowermost ground anchor

T_{hi} = Horizontal load in ground anchor i

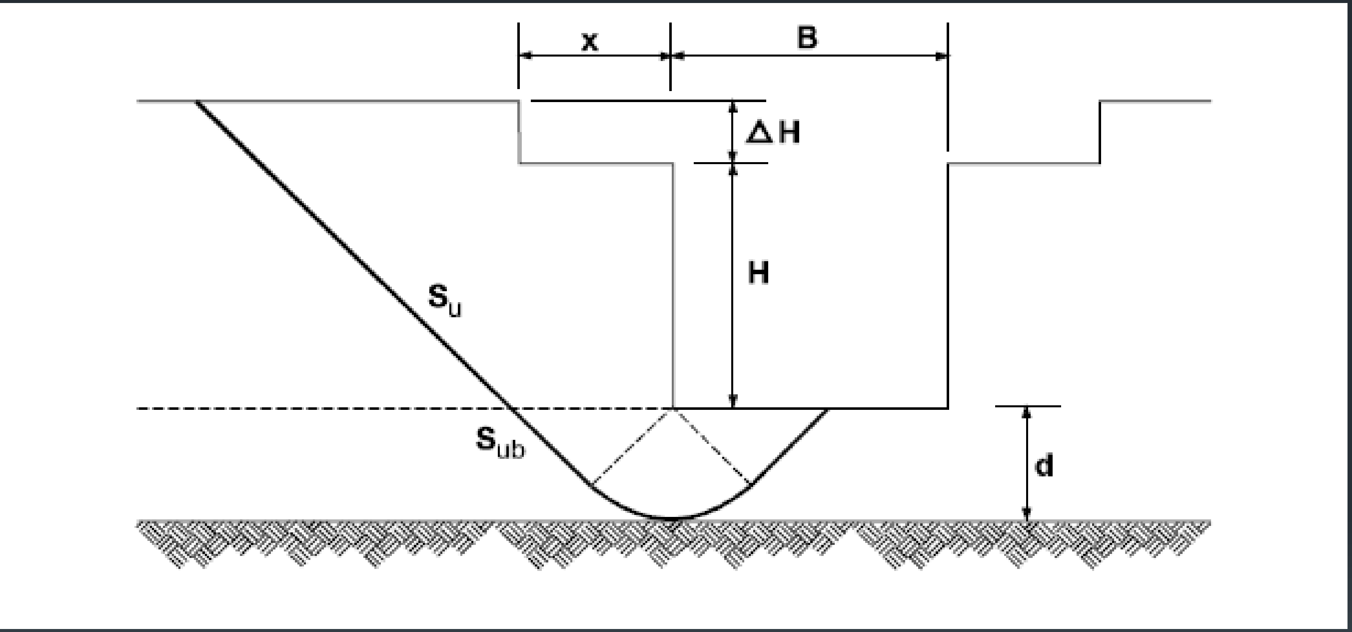
R = Reaction force to be resisted by subgrade (i.e., below base of excavation)

p = Maximum ordinate of diagram

TOTAL LOAD (kN/m/meter of wall) = $3H^2 - 6H^2$ (H in meters)

Earth Pressures (AEP – Clays)

For Soft to Medium Clays (Ns>4); after GEC 7 (for flexible support systems)



$$K_A = 1 - m\frac{4S_u}{\gamma H}$$

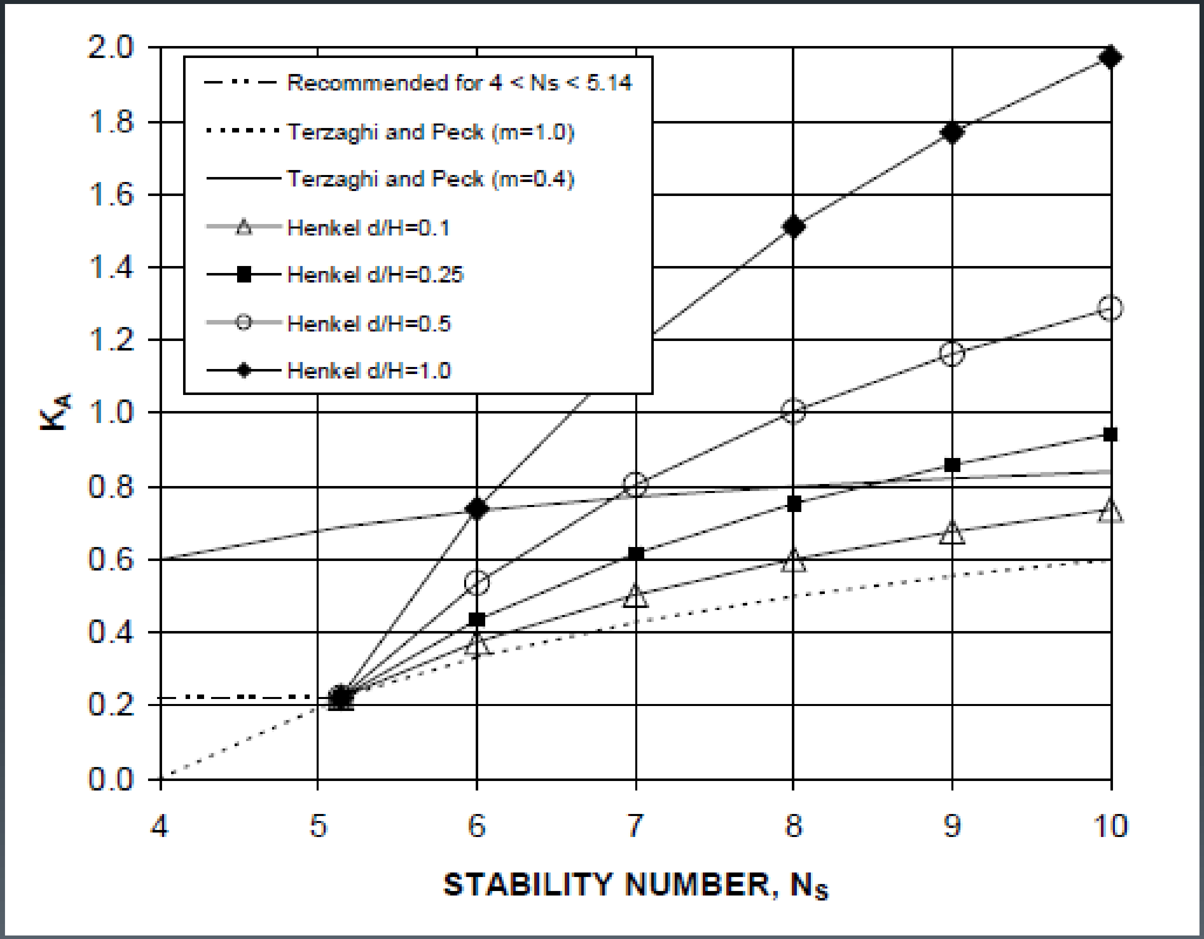
Peck

$$K_A = 1 - \frac{4S_u}{\gamma H} + 2\sqrt{2}\frac{d}{H}\left(1 - \frac{5.14S_{ub}}{\gamma H}\right)$$

Henkel

Earth Pressures (AEP – Clays)

For Soft to Medium Clays (Ns>4); after GEC 7 (for flexible support systems)



Earth Pressures

General notes for design of flexible support systems:

- Perform a staged analysis;
- For struts/anchors, use full pressure from AEP diagram and tributary area;
- Wales are generally considered continuous across struts/anchors, and use 2/3 of moment from AEP diagram for arching;
- For mixed soil profiles w/good base stability (i.e., Ns<4), use a classical distribution, increase the total load by 1.1 to 1.3, and distribute the factored total load into an AEP diagram.
- Earth pressures below cut (i.e., active and passive) based on limit equilibrium method; and
- Check factor of safety for support embedment below lowest level of support (force equilibrium or moment equilibrium about the lowest level of support [including bending resistance of vertical elements])

Earth Pressures

General notes for design of stiff support systems

- Perform a staged analysis;
- Actual earth pressures tend more toward classical distributions and use of AEP diagrams is questionable;
- Soil arching between bracing/anchor levels is minimal or may not exist;
- Lateral loads on struts/anchors at lower levels are greater than that from AEP diagrams;
- Address base stability; and
- Check factor of safety for support embedment below lowest level of support as for flexible support systems

Analysis Methods

1. Continuous and discontinuous vertical elements with rigid supports;
   - Limit equilibrium calculations (software/hand)
2. Structural analysis models, e.g., soil springs (i.e., beam on elastic foundation/displacement method) with non-rigid supports;
3. Numerical analysis methods
   - Finite Element
   - Finite Difference

Excavation Stability

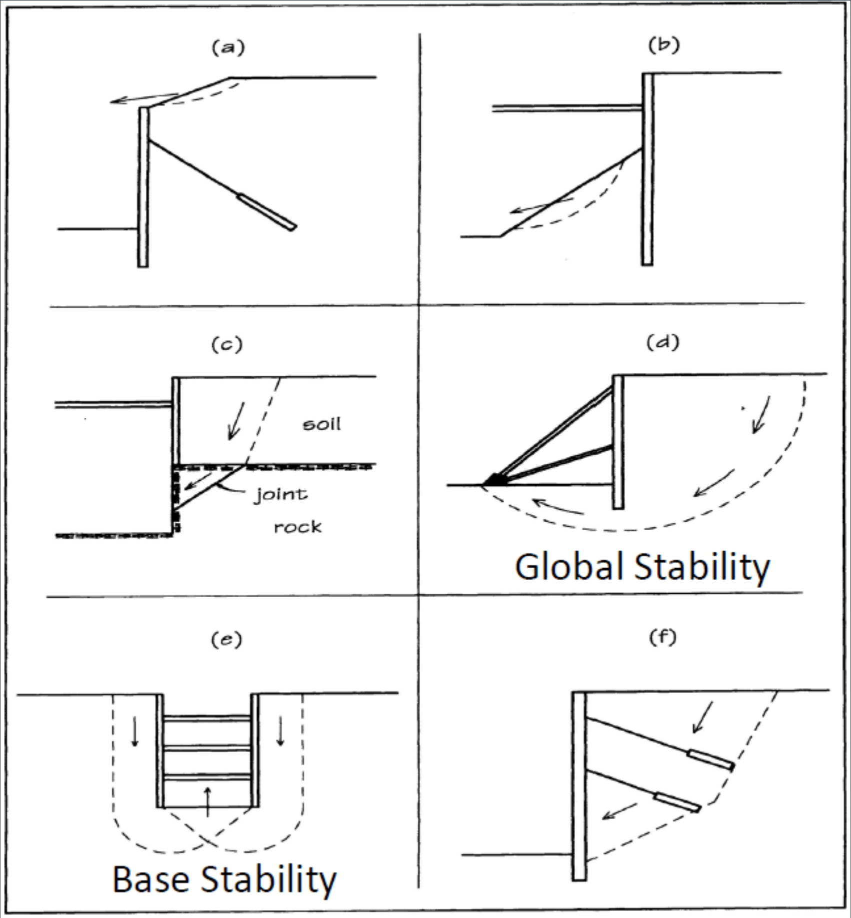
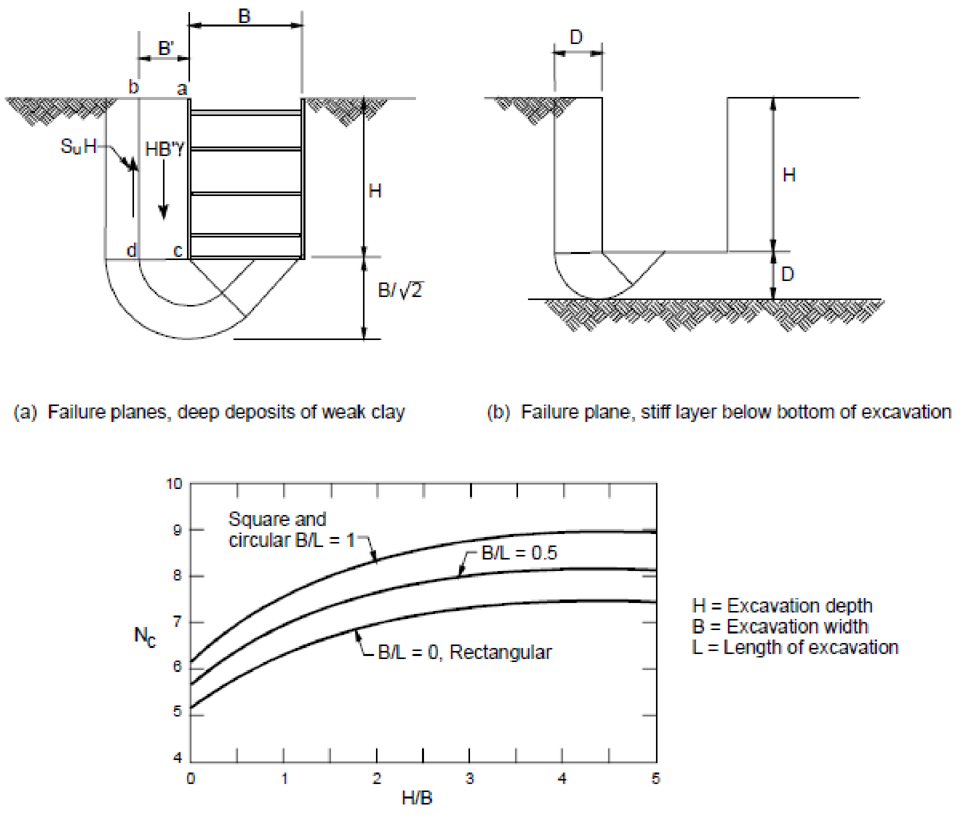


Figure 4-1
Modes of Stability Failures

Excavation Stability

After GEC 4

$$FS = \frac{N_c\, S_u}{H\left(\gamma - \frac{S_u \sqrt{2}}{B}\right)}$$



(c) Bearing Capacity Factor, N_C

$$FS = \frac{N_c\, S_u}{H\left(\gamma - \frac{S_u}{D}\right)}$$

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FS for: permanent =2.5; and temporary = 1.5

Deflections

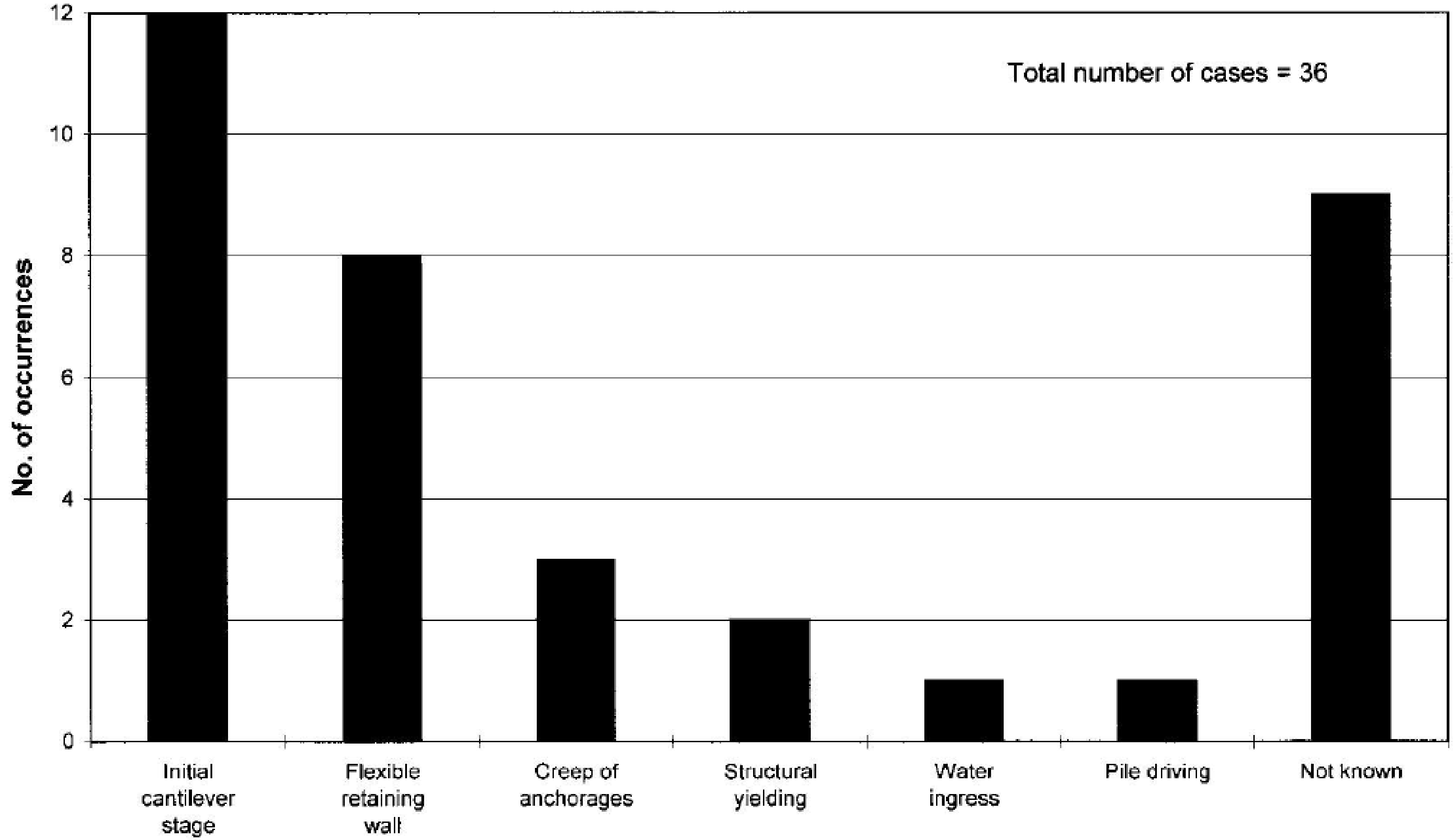
Primary Sources:

- Excavation and support type process
- Low factor of safety for basal stability

Secondary Sources:

- Open panel excavations (i.e., secant piles and diaphragm walls)
- Vibrations from steel piling installation
- Removal of existing structures in front of the wall
- Over-excavation below to install next level of support
- Groundwater lowering outside the excavation

Deflections



Long (2001) **FIG. 18. Reasons for Excessive Deflections ($\delta h_{max}/H > 0.3\%$)**

Deflections

Primary Sources:

- Empirical correlations
- Structural analysis methods
- Numerical analysis methods

Deflections

Sands and Stiff Clays (after Clough & O'Rourke, 1990)

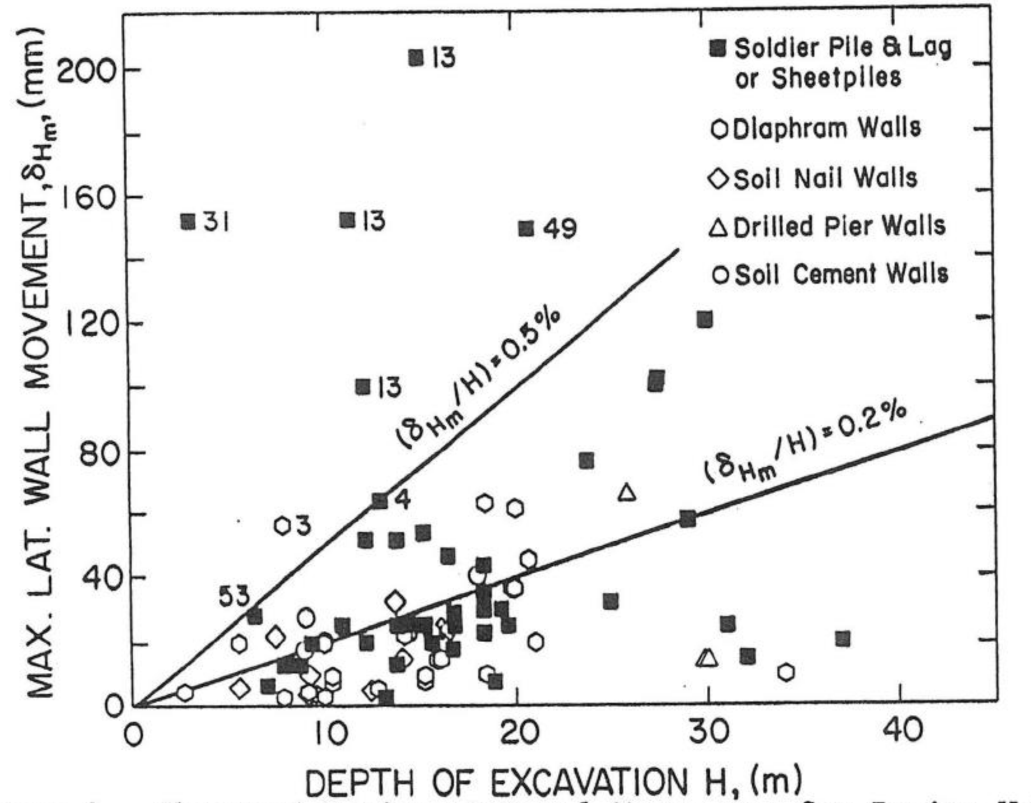
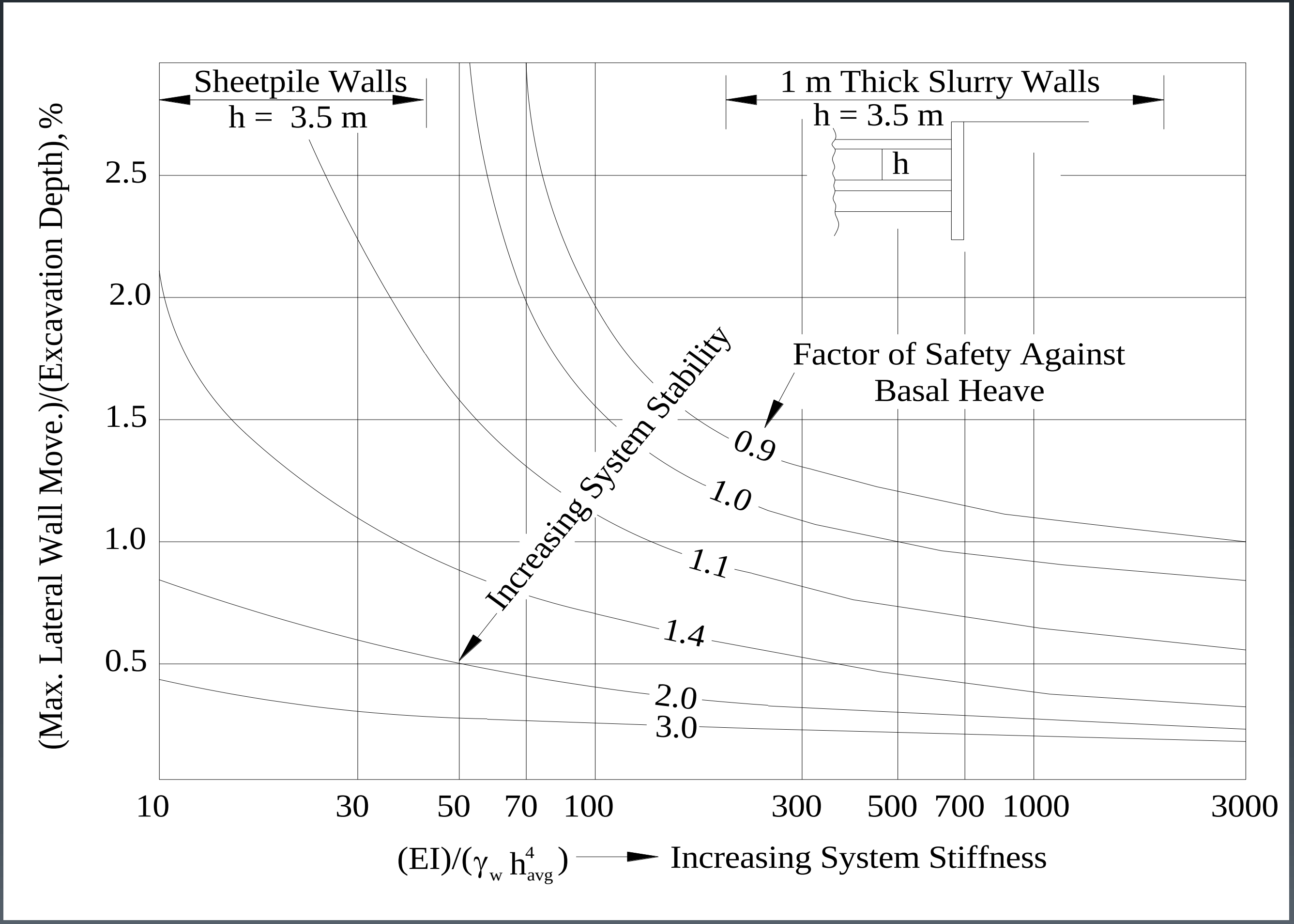


Figure 2. Observed Maximum Lateral Movements for Insitu Walls in Stiff Clays, Residual Soils and Sands.

Deflections

Soft to Medium Clays (after Clough & O'Rourke, 1990)



Deflections vs. Settlement

Maximum ground settlement (i.e., behind the support system) ranges from 0.5 to 1.0 of the maximum wall deflection

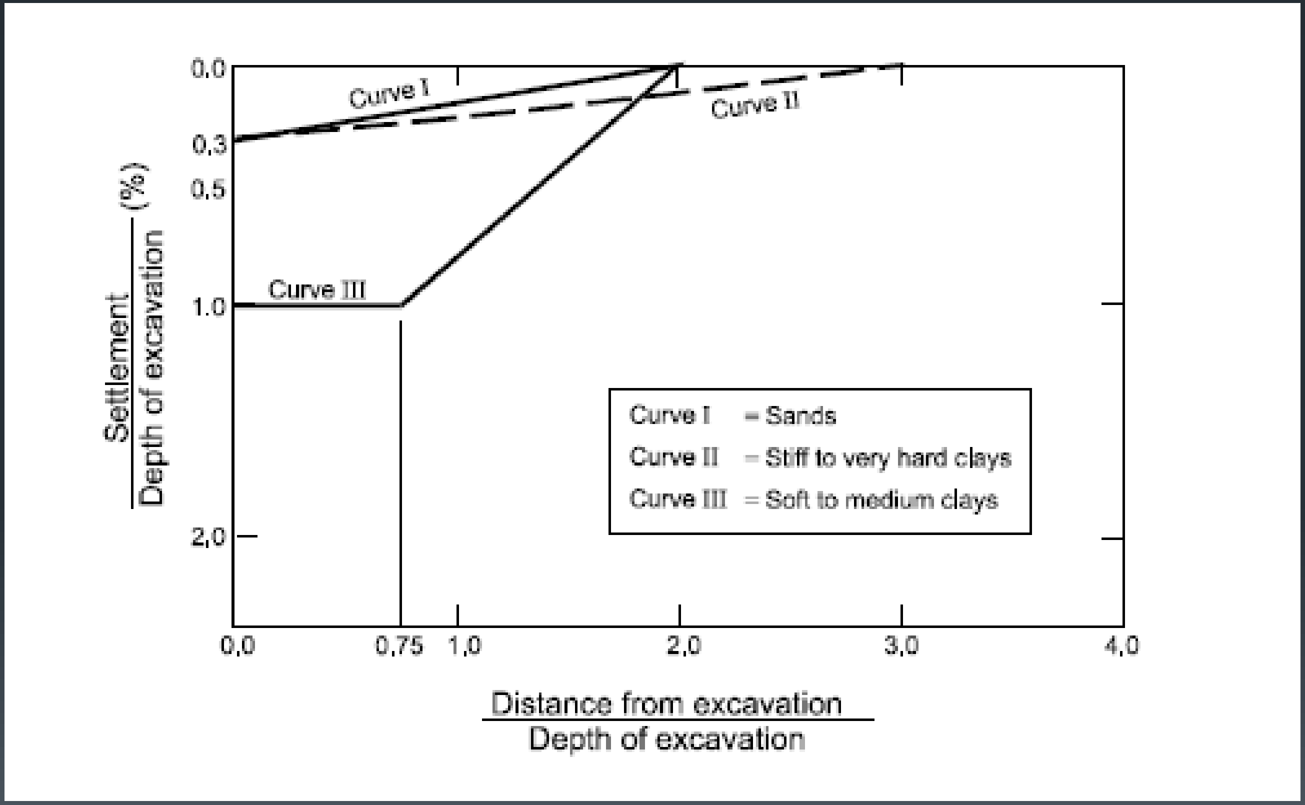
Typical to use ratio of maximum settlement to maximum wall deflection of 1.

Settlement Profile

Empirical

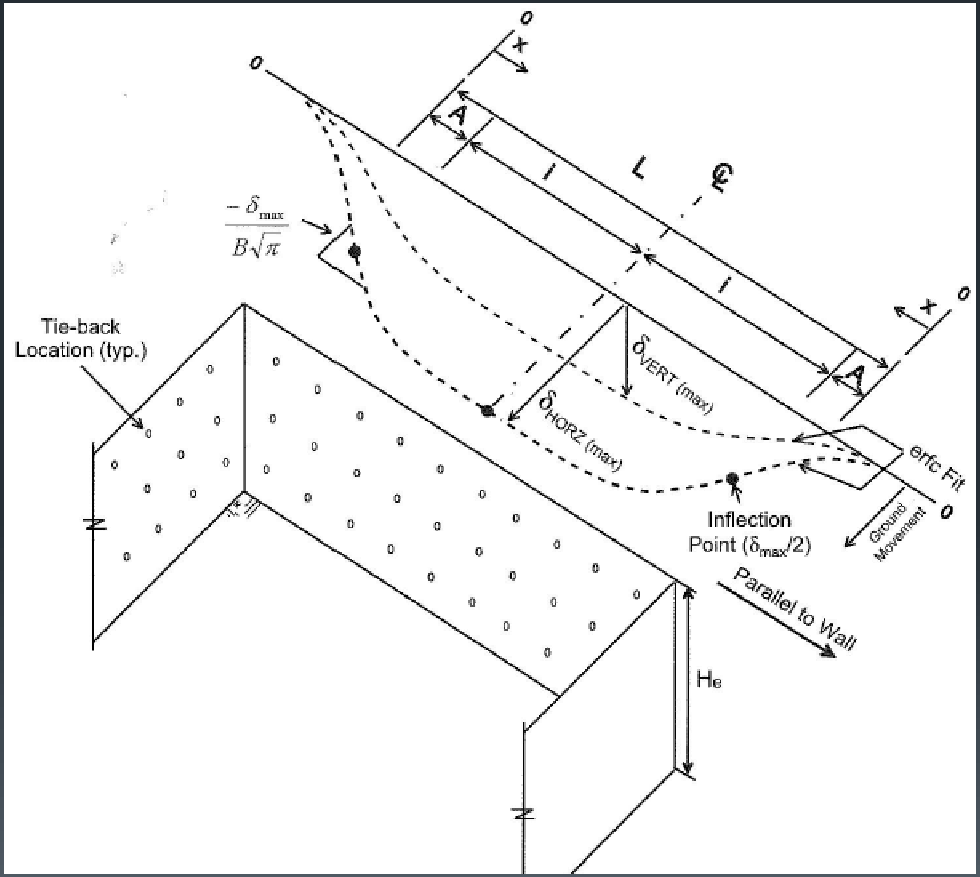
- Peck (1969)
- Goldberg et. al. (1975)
- Clough & O'Rourke (1990)
- Long (2001)
- Kung (2008)

Settlement Profile
(for flexible support systems; after GEC 4)

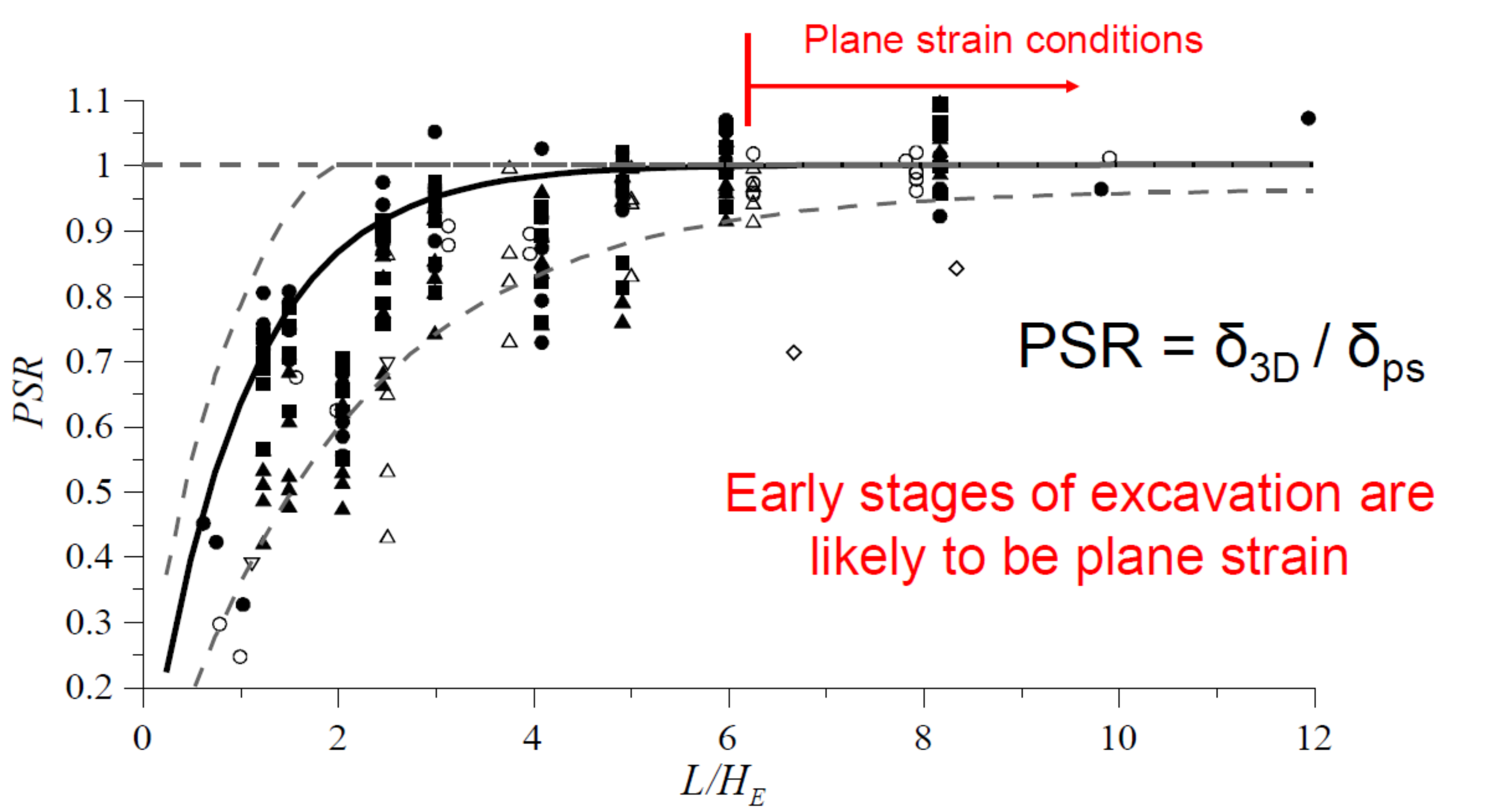


Three-Dimensional Effects

(for flexible support systems; after Roboski and Finno, 2006)



Three-Dimensional Effects
(after Finno, 2007)



Adjustments if conditions are not plane strain

Other Design Considerations

1. Check for (and design for the greatest):
   - Short- and/or long-term conditions;
   - Groundwater conditions; and
   - Surcharges
2. Penetrations
3. Loads (vertical/seismic)
4. Lagging and/or facing considerations
5. Thermal Effects
6. Corrosion Considerations
7. Watertightness and Drainage
8. Aesthetic Requirements
9. Constructability Issues
10. Contracting Approaches
11. Testing Requirements
12. Construction Inspection and Performance Monitoring Requirements

Case Histories

(abbreviated)

South Interceptor Force Main

Omaha, NE

Timken
Canton, OH

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Ashburton Reservoir

Baltimore, MD

SJL Engineers

Ashburton Reservoir

Baltimore, MD

SJL Engineers

Gerdau
Monroe, MI

SJL Engineers

ArcelorMittal Steel

Steelton, PA

SJL Engineers

Lower Pogue's Run Tunnel

Indianapolis, IN

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Pleasant Run Deep Tunnel

Indianapolis, IN

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Black River Tunnel

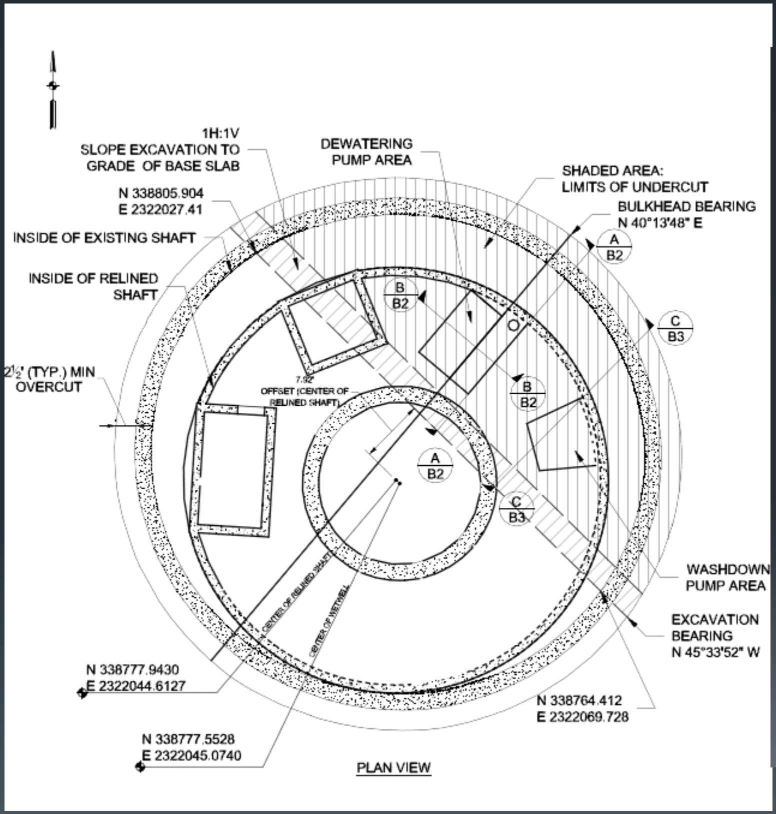
Lorain, OH

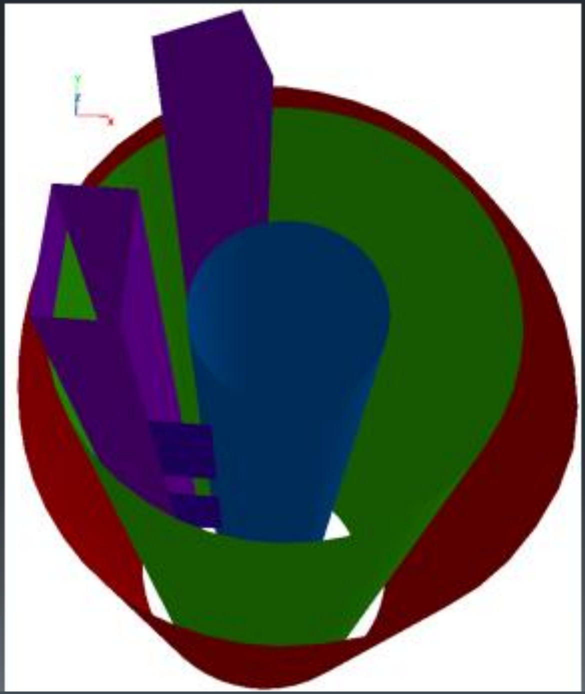
Boelus East

Howard Co., NE

West Ashley Sewer Tunnel

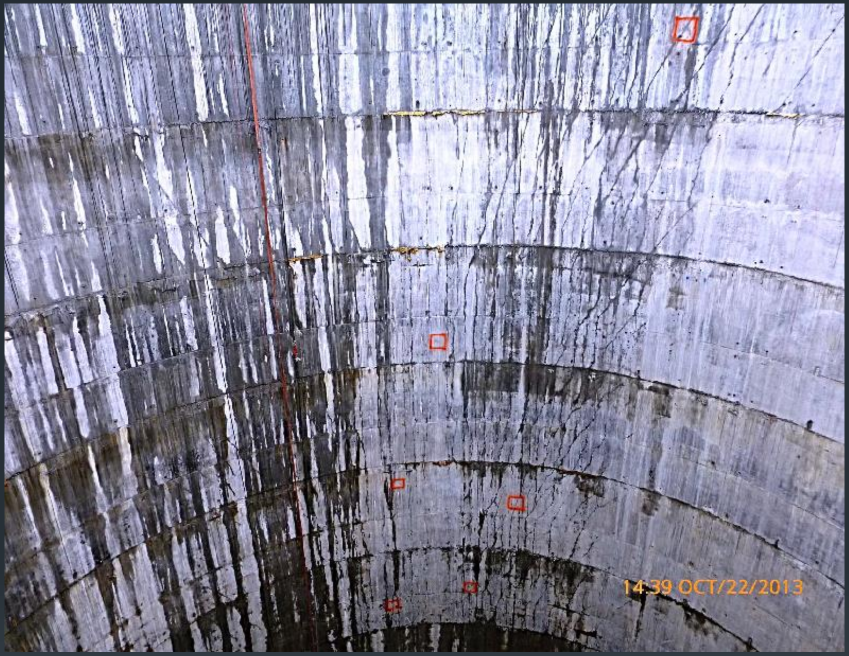
Charleston, SC





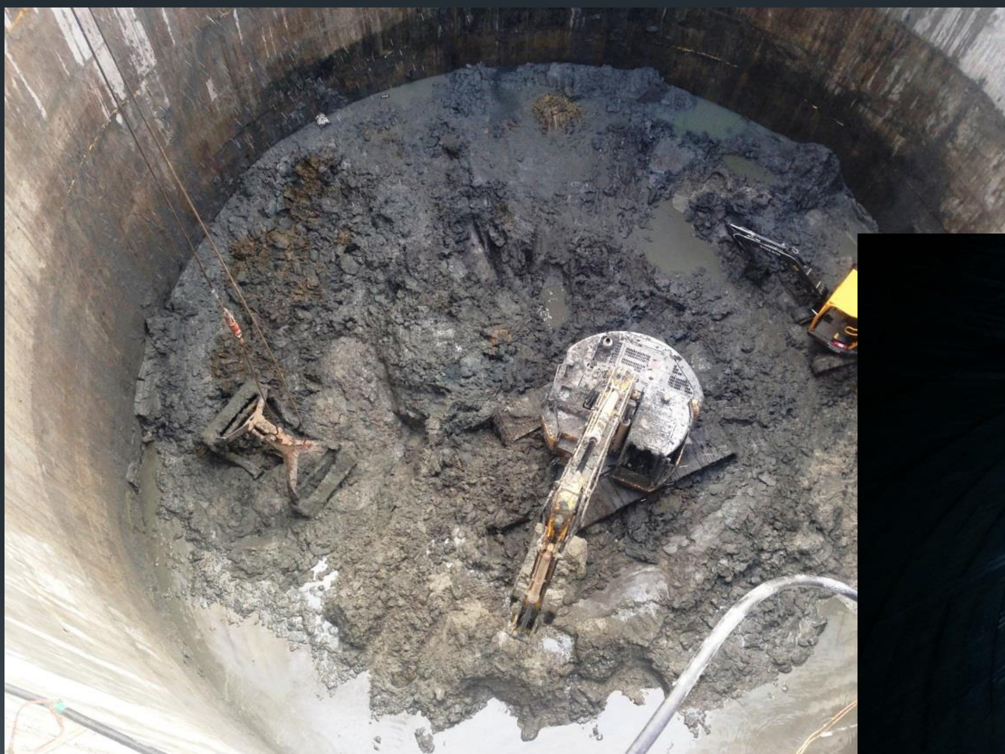
West Ashley Sewer Tunnel

Charleston, SC



West Ashley Sewer Tunnel

Charleston, SC



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West Ashley Sewer Tunnel

Charleston, SC

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West Ashley Sewer Tunnel

Charleston, SC

Analysis (FLAC3D)

- Static simulation (steps)
  - Setup properties, initialization of pore pressures and static stress (Ko)
  - Excavate in 18 steps and progressively reduce the stresses and pore pressure of the zones under excavation
  - Sink the shaft using the as-built geometry
  - Allow pore pressures to dissipate for only a brief period to keep and undrained response of the surrounding soil and develop equilibrium before excavating the next phase

West Ashley Sewer Tunnel

Charleston, SC

Analysis (FLAC3D)

- Dynamic simulation
  - Soil properties from static analysis
  - Damping (no data; based on available literature)
  - Explicit crack representation (i.e., residual v. intact)
  - Structural concrete (moment-curvature diagram for various levels of axial thrust)
  - Three different time histories (applied in two different directions and a vertical component of 2/3 horizontal)
  - Sensitivity analysis (zone size, mesh density)
  - Water levels in the wet well (no water, operational and maximum)

West Ashley Sewer Tunnel

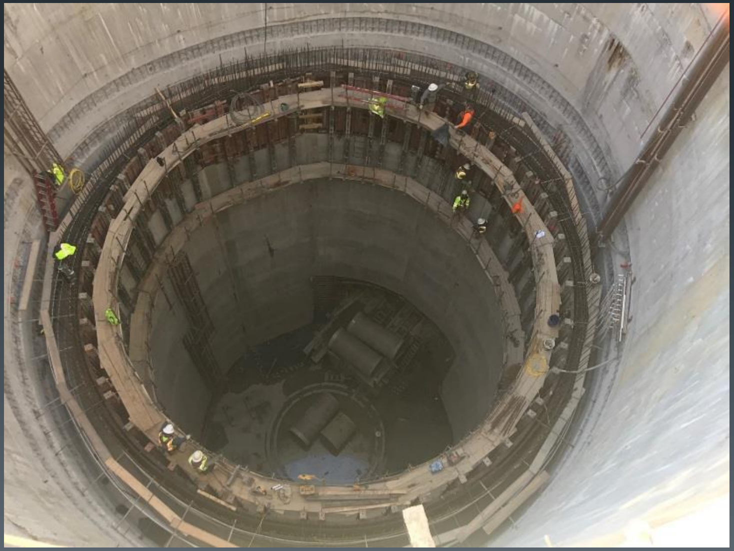
Charleston, SC

Repairs

- Stress resultants (review)
- 12-in. thick relined section
- Revisions to elevator, stairwell and wet well sections
- Develop a positive connection with the existing shaft wall

West Ashley Sewer Tunnel

Charleston, SC



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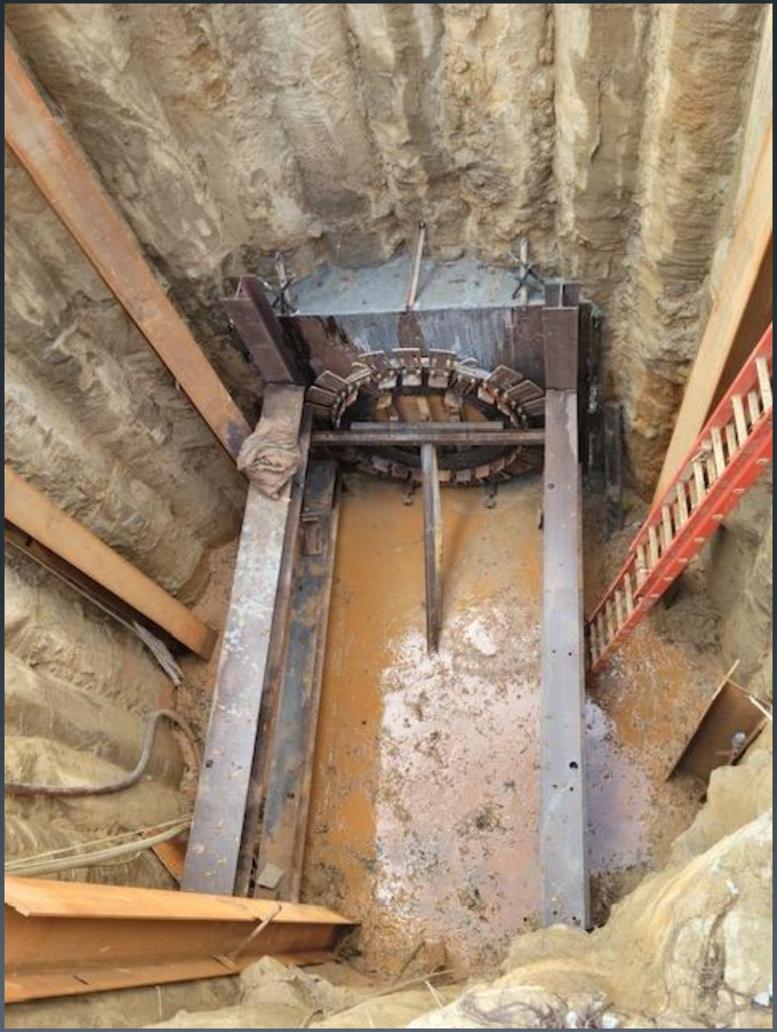
Dugway West Interceptor
Cleveland, OH

SJL Engineers

Collier’s Ferry Pump Station

Beaumont, TX



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George Bush Intercontinental Airport
Houston, TX

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Bellvue Transmission Pipeline

Greeley, CO

SJL Engineers

Gilboa Low Level Outlet Tunnel

Gilboa, NY

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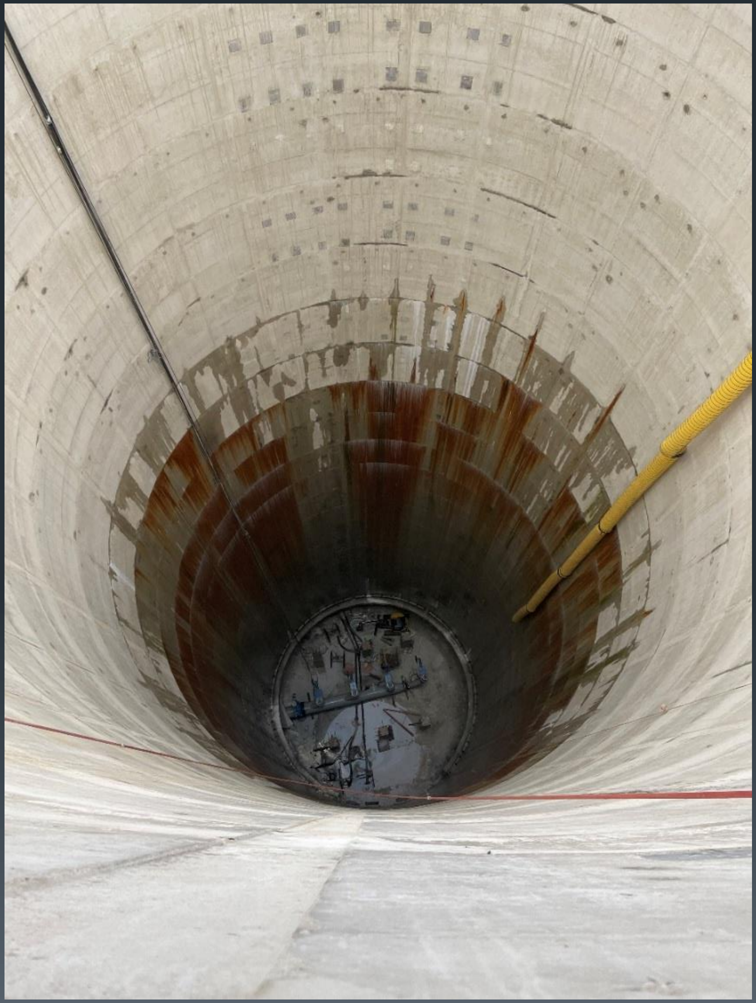
Three Rivers Tunnel
Fort Wayne, IN



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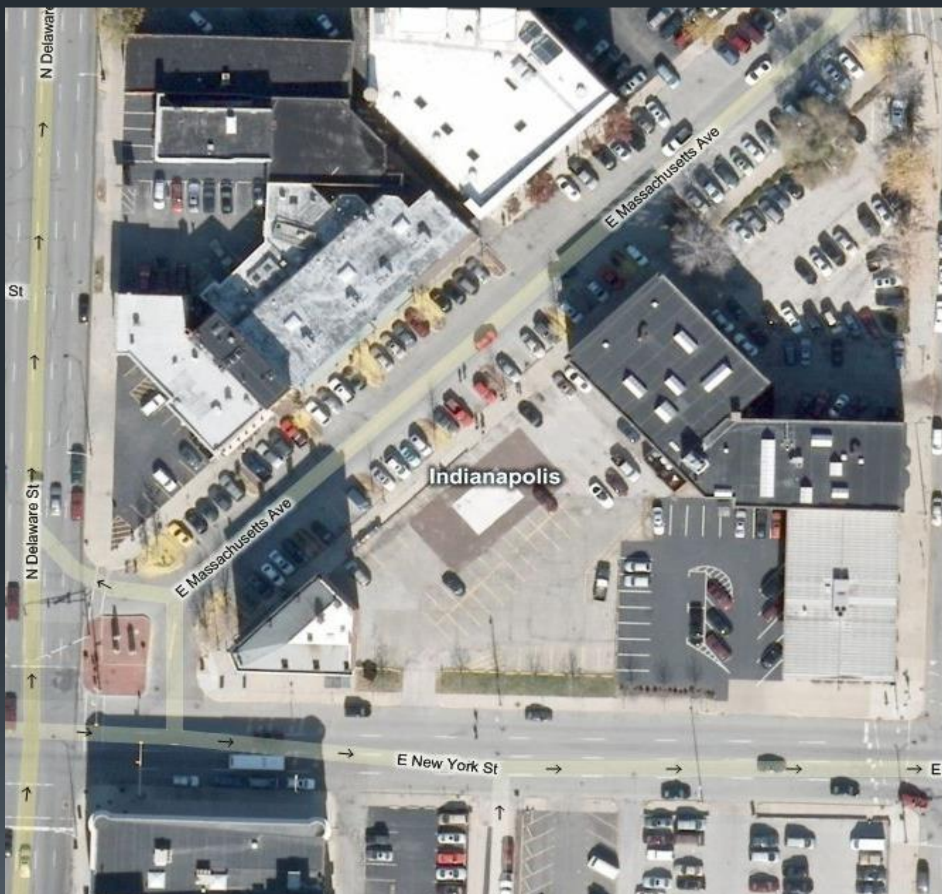
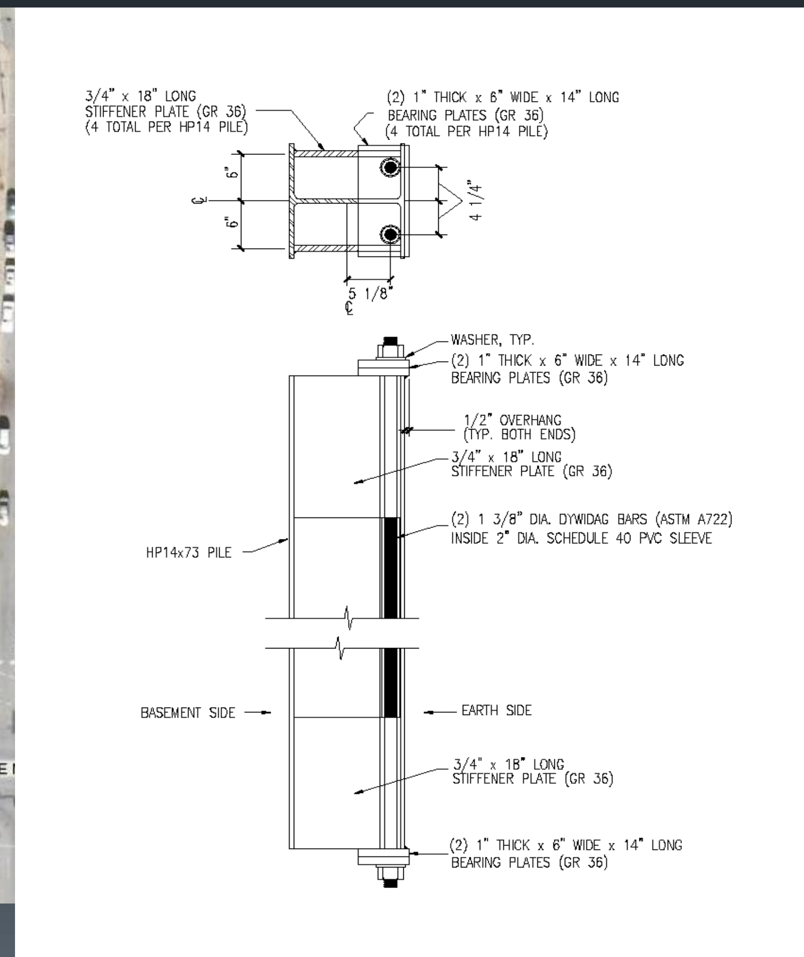
3 Mass

Indianapolis, IN





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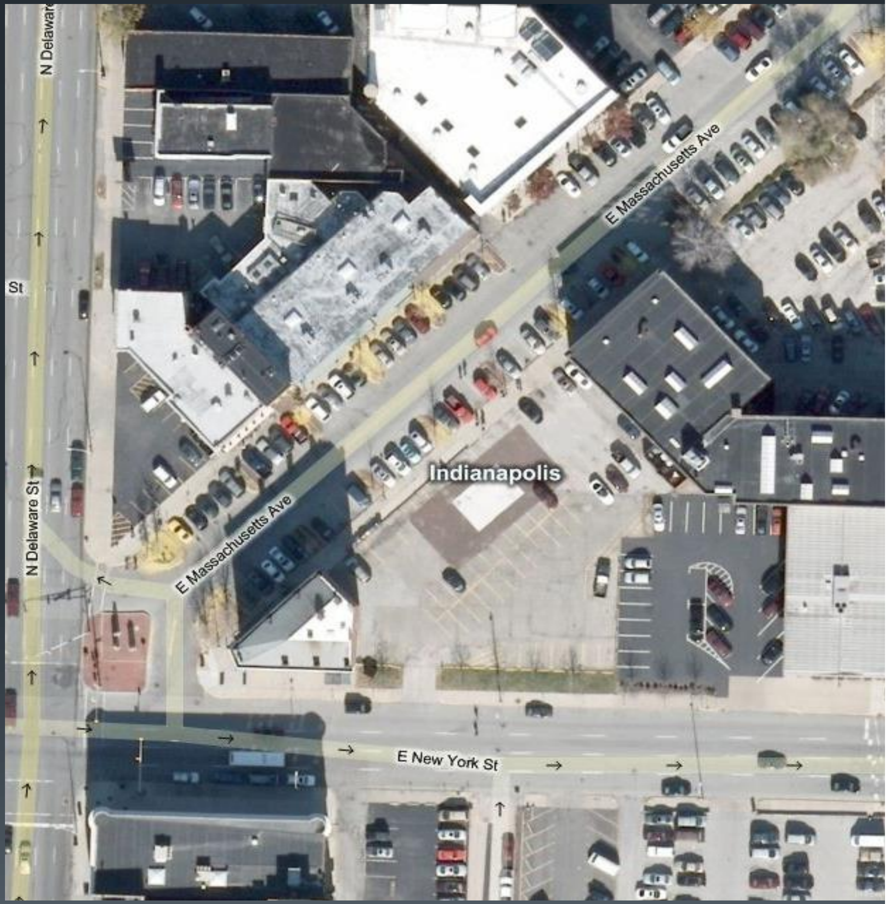
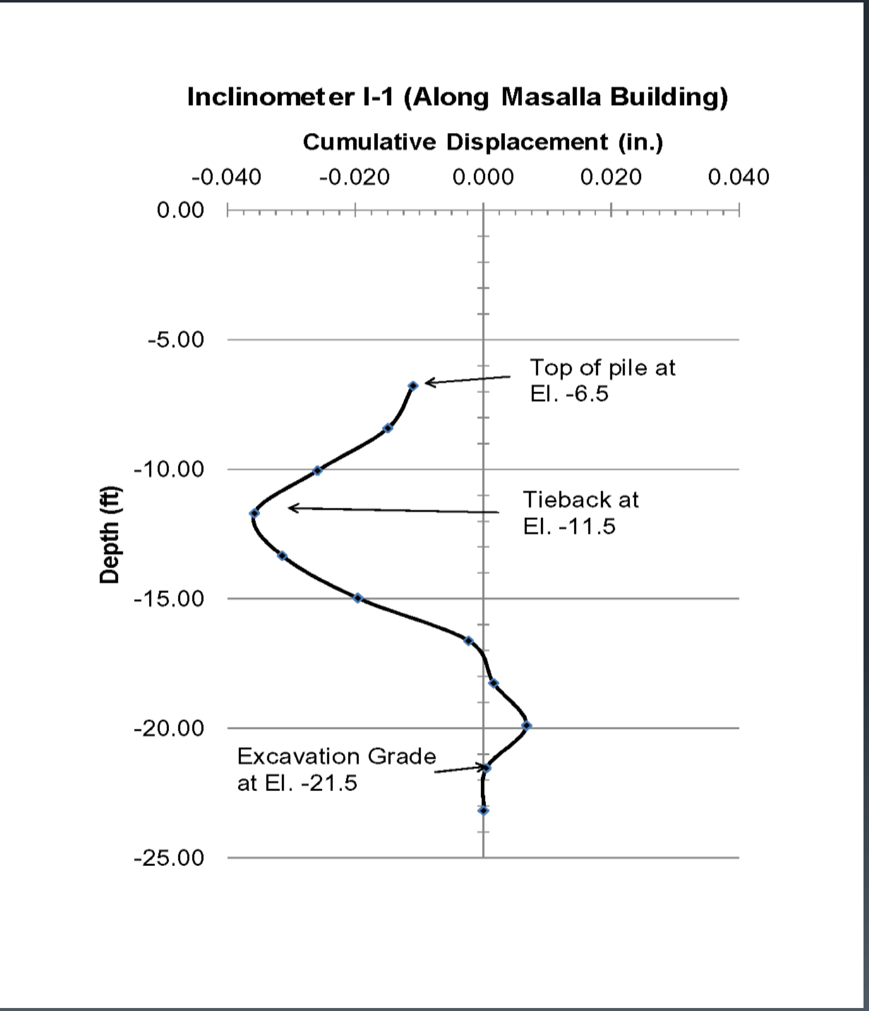
3 Mass
Indianapolis, IN





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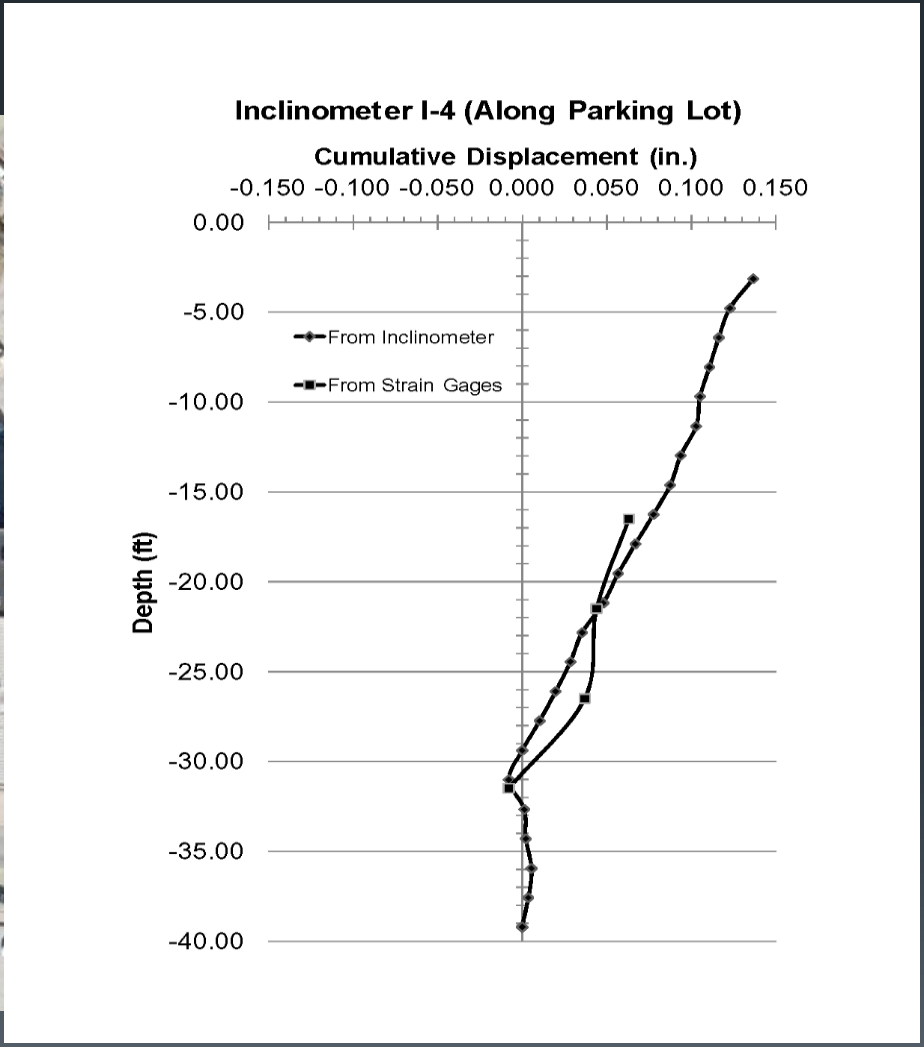
Indianapolis, IN



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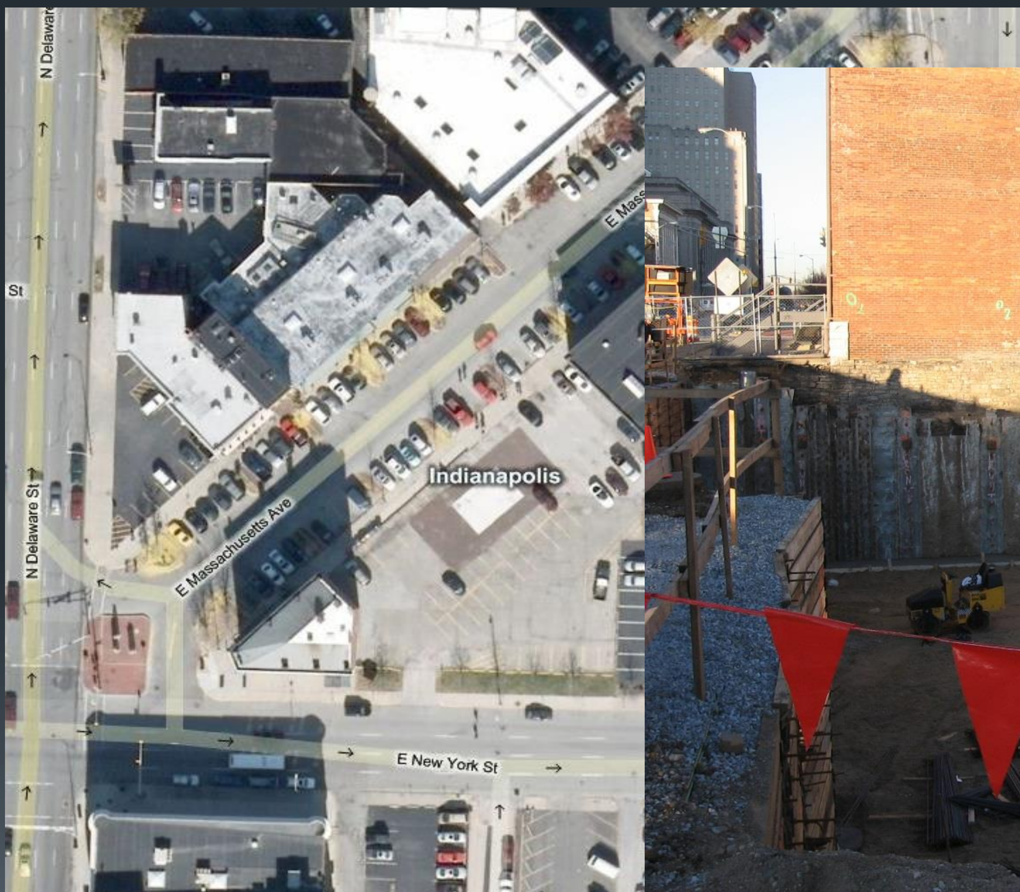
Indianapolis, IN



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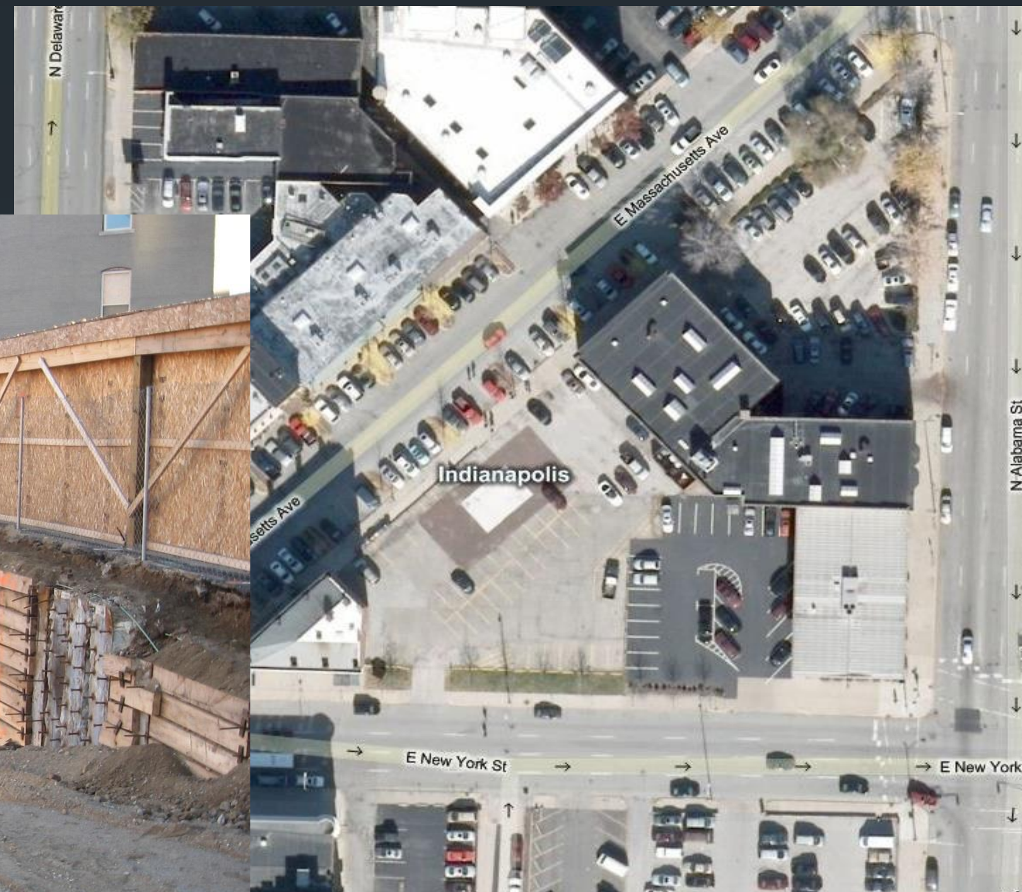
3 Mass
Indianapolis, IN



3 Mass
Indianapolis, IN

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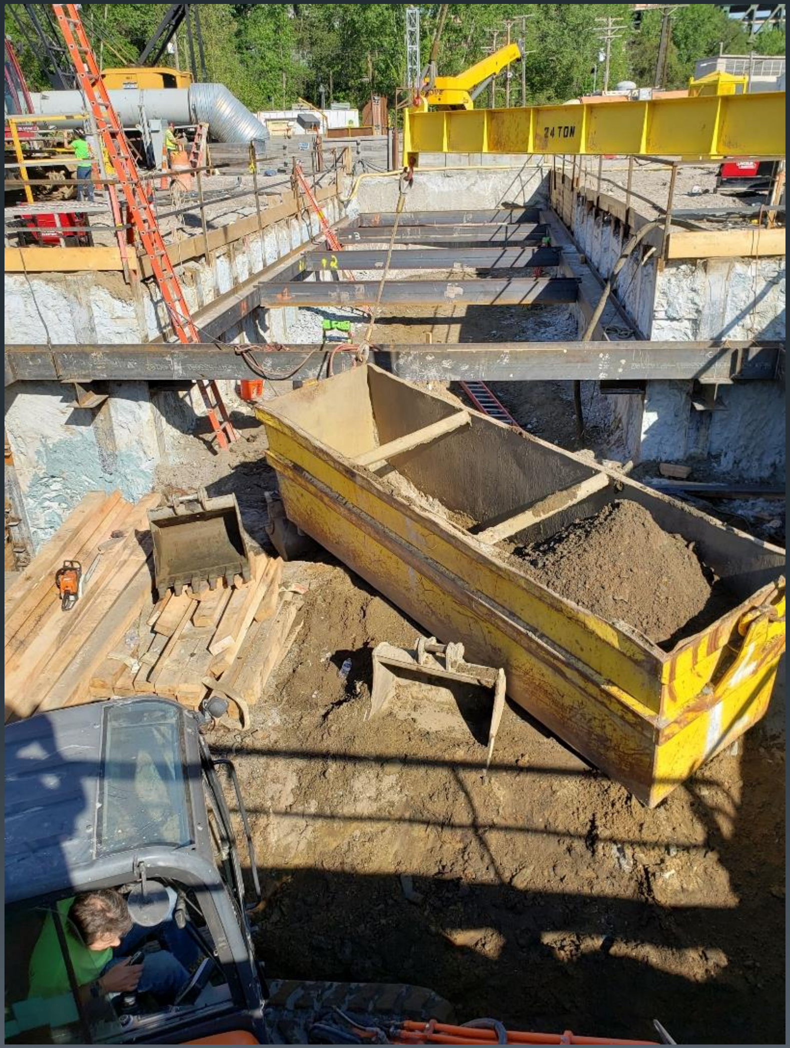
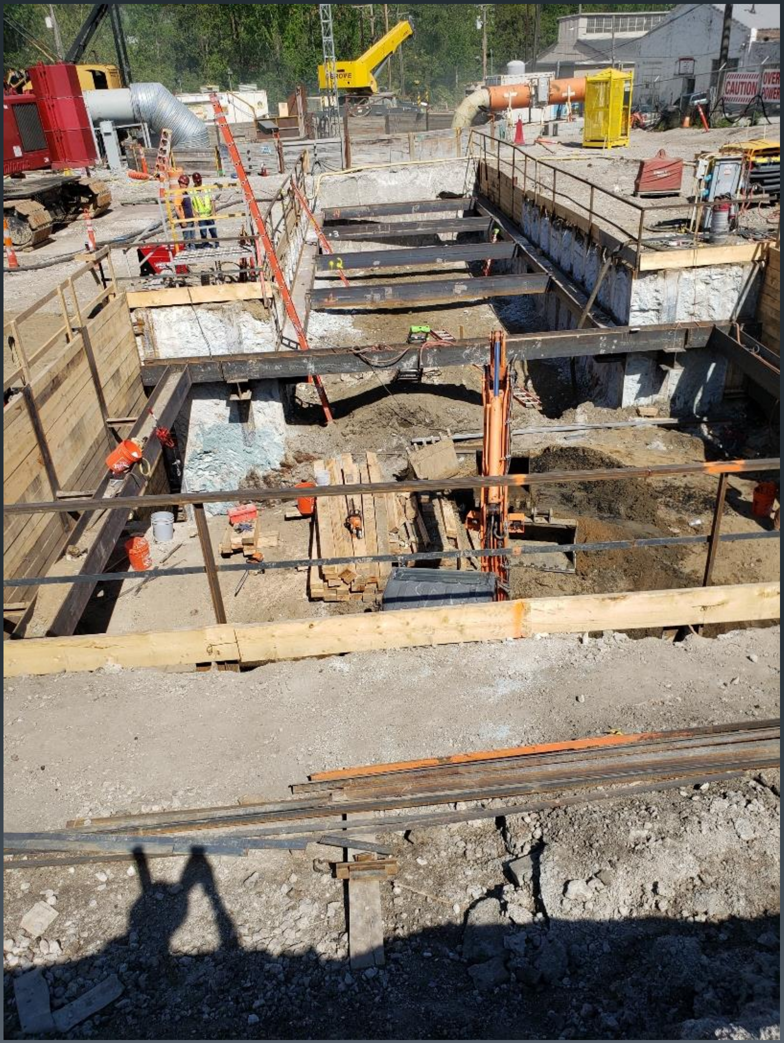
Westerly Storage Tunnel
Cleveland, OH





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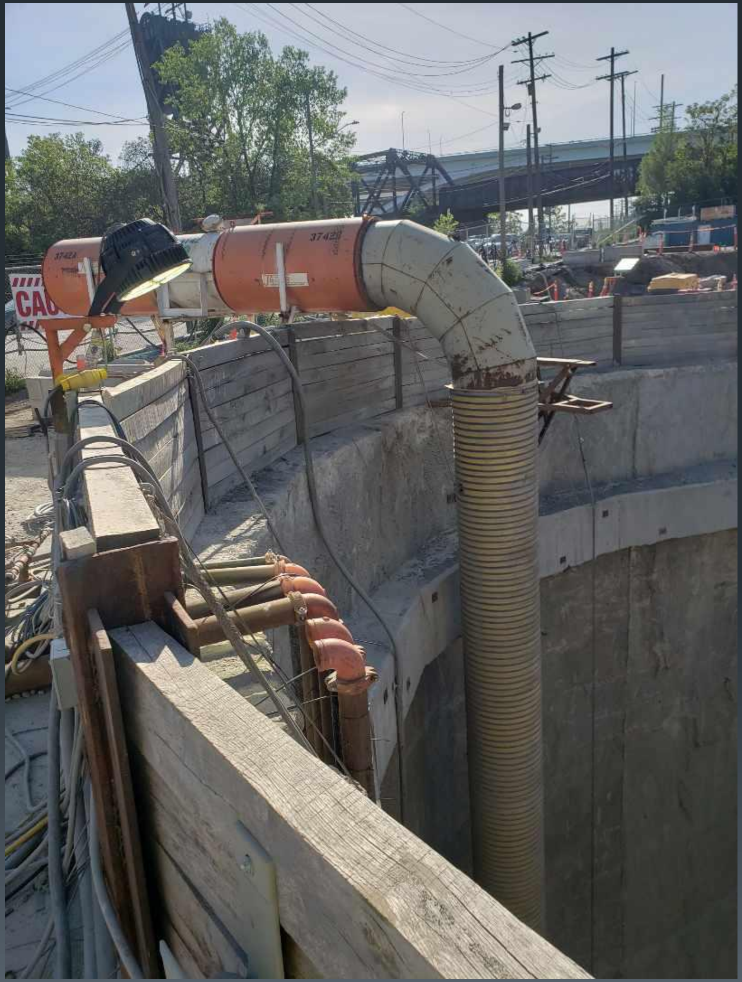
Westerly Storage Tunnel
Cleveland, OH



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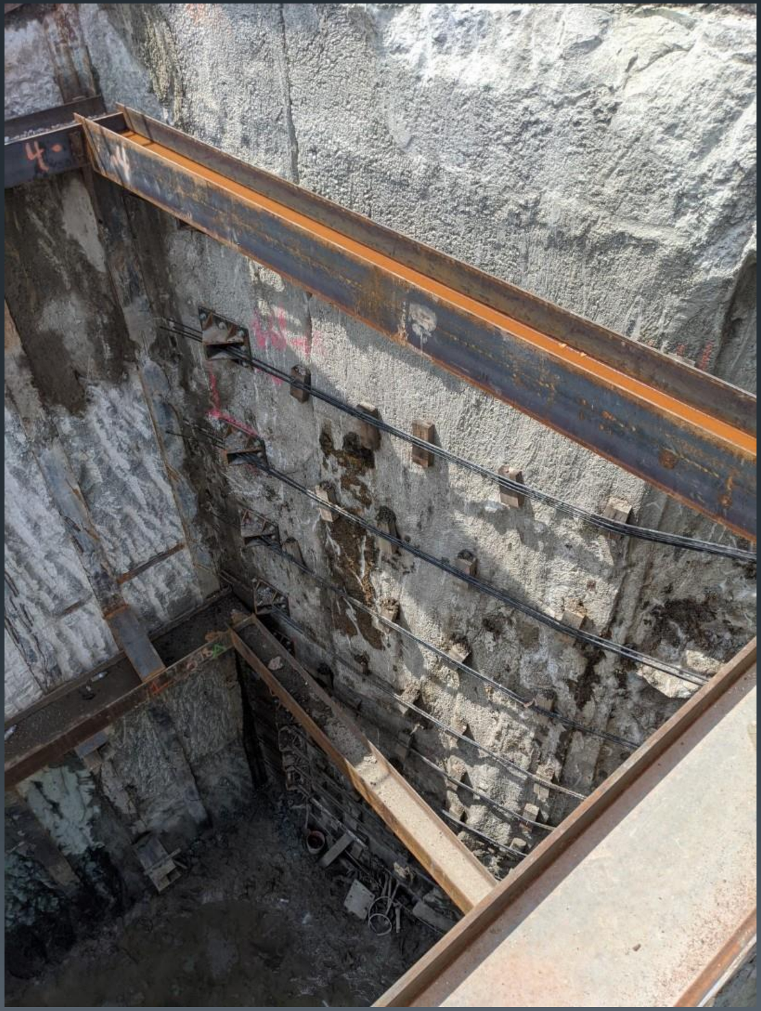
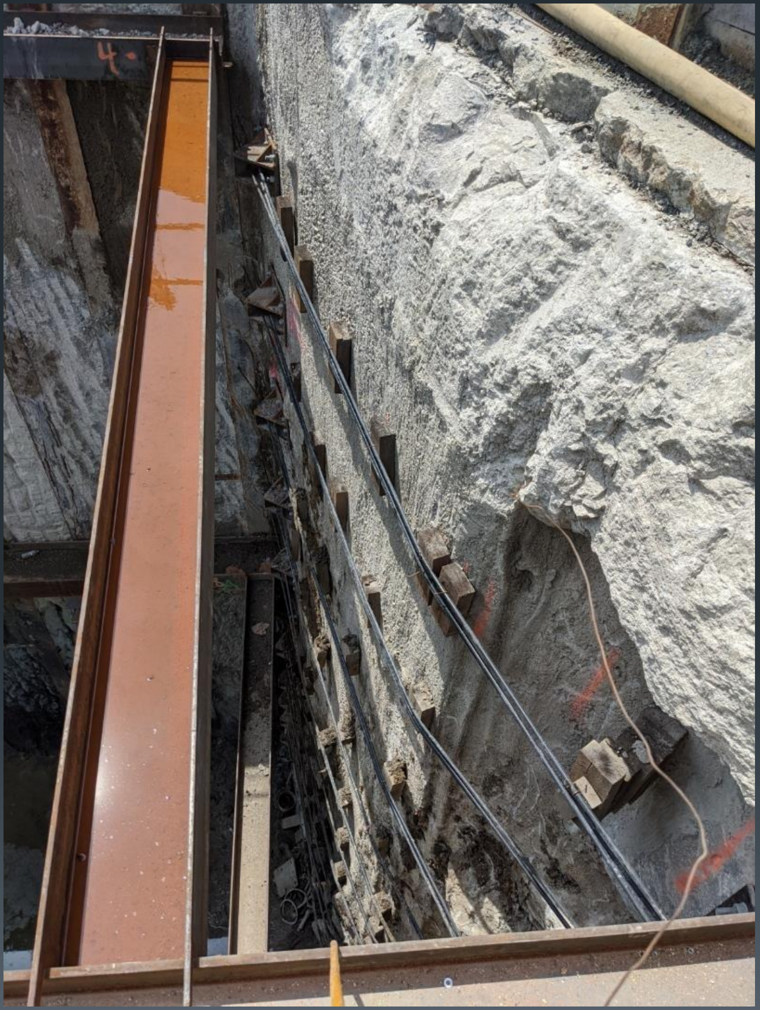
Westerly Storage Tunnel
Cleveland, OH





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I-64 and Grinstead CSO Basin
Louisville, KY

I-64 and Grinstead CSO Basin

Louisville, KY

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Cleveland Clinic
Cleveland, OH

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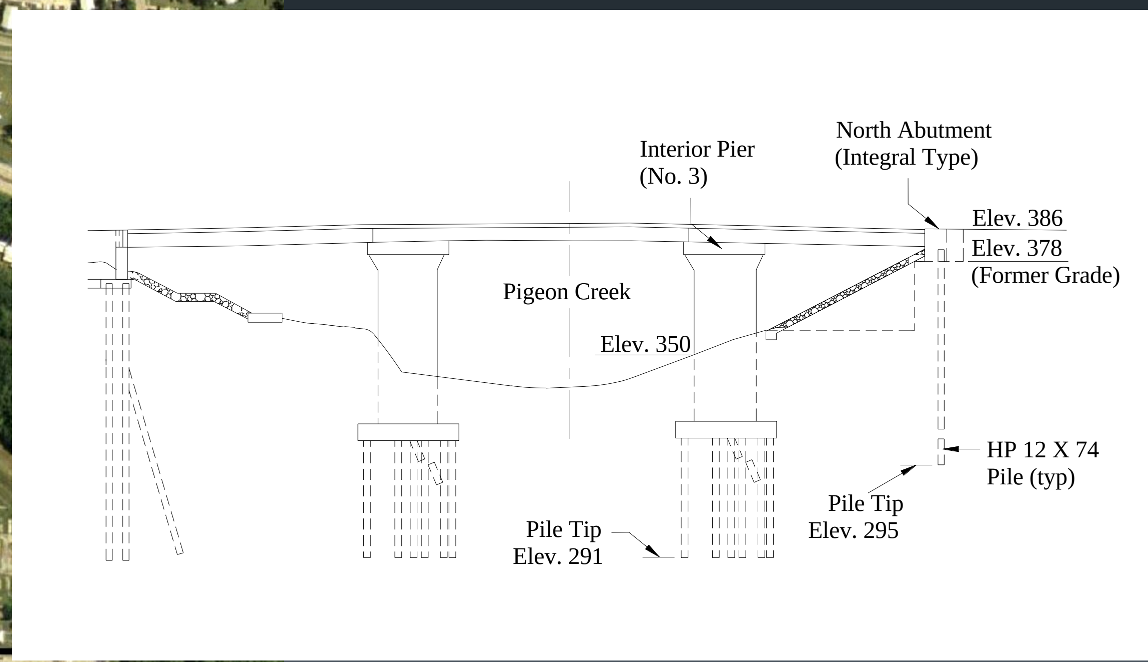
Fulton Avenue Bridge Replacement

Evansville, IN



Fulton Avenue Bridge Replacement
Evansville, IN

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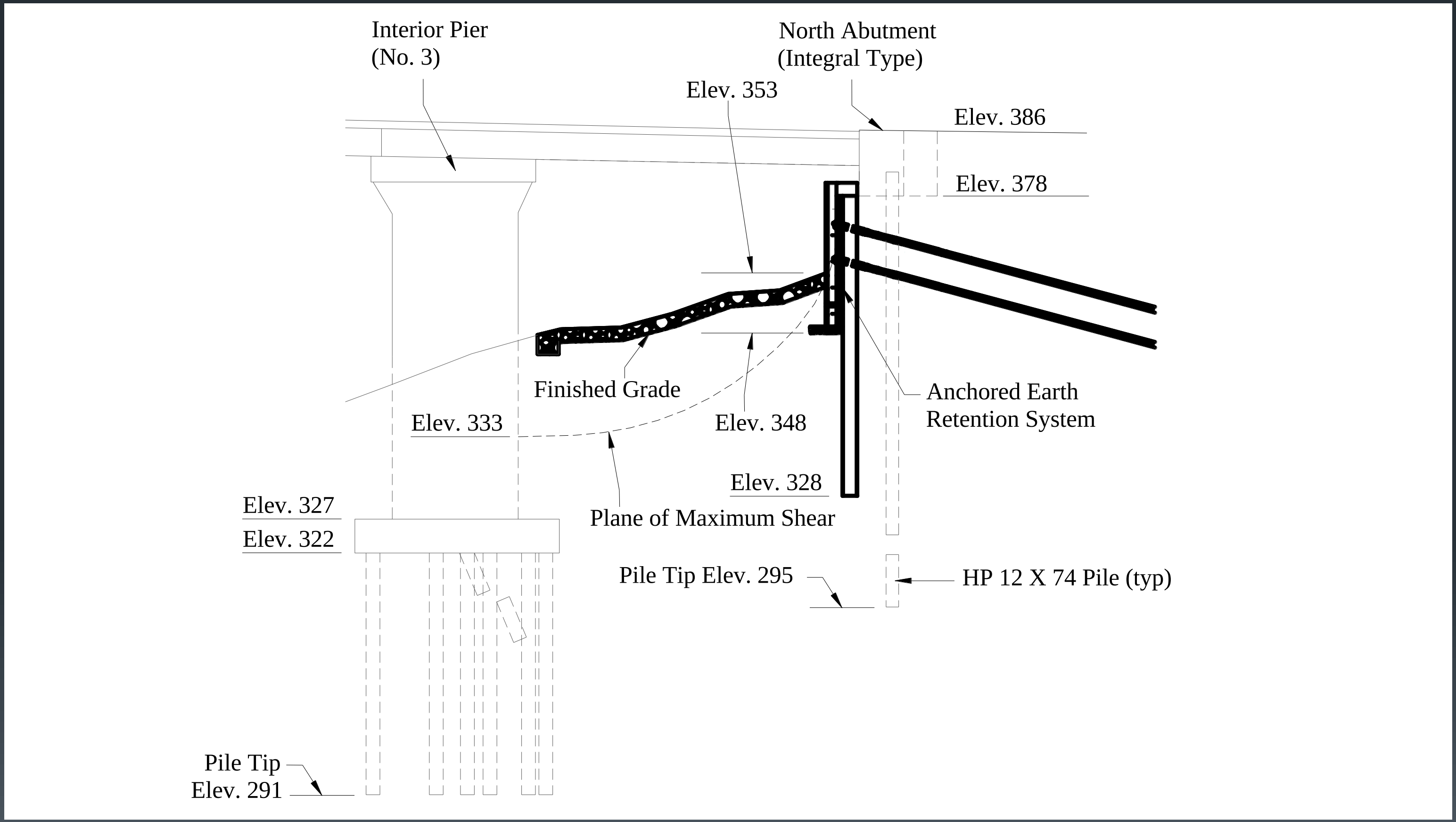
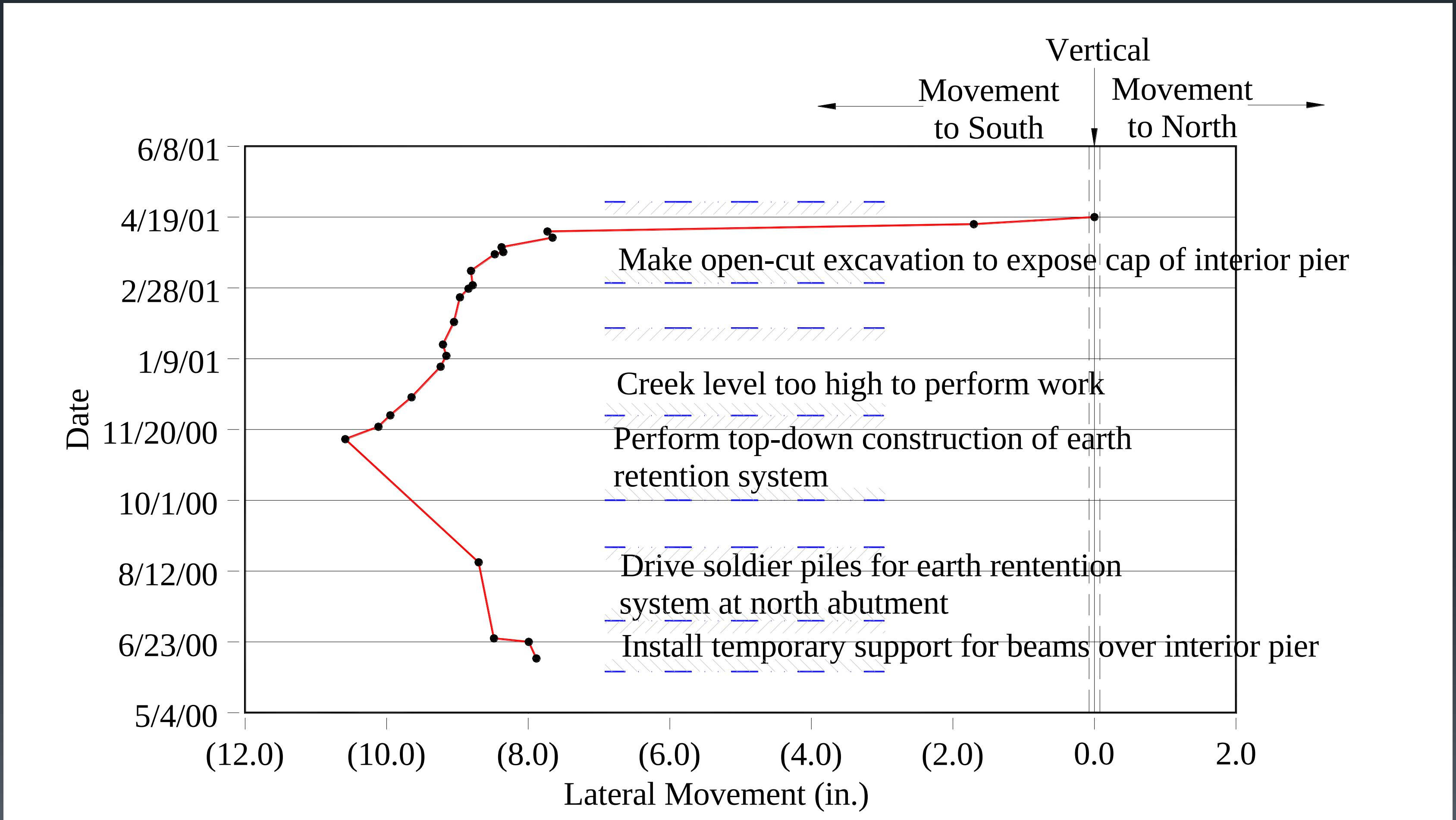
Fulton Avenue Bridge Replacement
Evansville, IN



Fulton Avenue Bridge Replacement
Evansville, IN



Lateral Movement Measured from Vertical at Top of Pier

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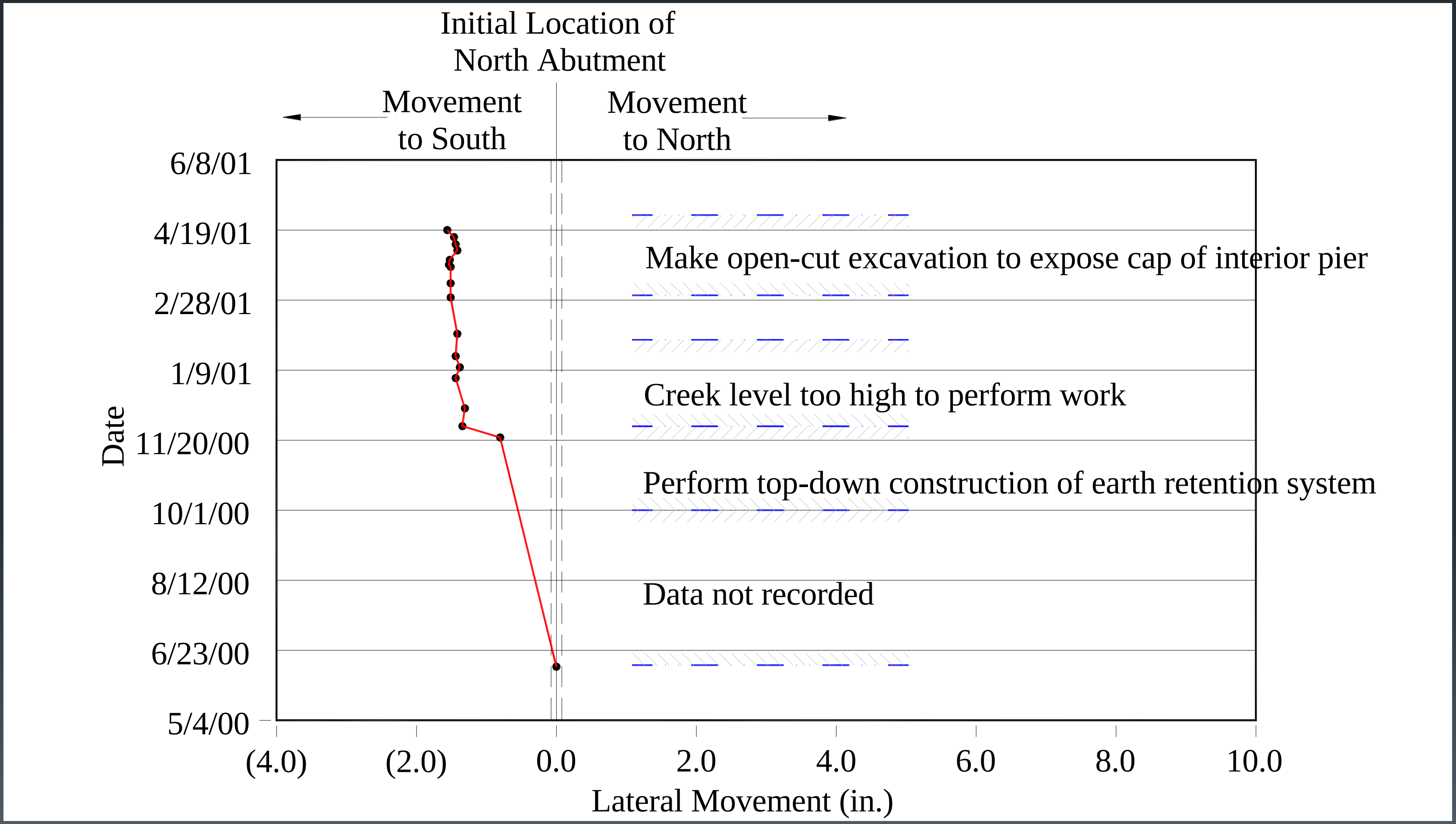
Fulton Avenue Bridge Replacement

Evansville, IN



Lateral Movement Measured from Vertical at Top of Abutment

SJL Engineers

Fulton Avenue Bridge Replacement
Evansville, IN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Fulton Avenue Bridge Replacement

Evansville, IN

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Fulton Avenue Bridge Replacement
Evansville, IN

SJL Engineers

Honda Manufacturing Facility

Marysville, OH

SJL Engineers

"The key to the design of excavation support systems is to understand the deflection of the system at any given point during construction. This includes a thorough understanding of the geometry and stiffness characteristics of the support system in relation to the development of earth pressures as well as models for use in structural analysis."

Thank you!

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