DESIGN, INSPECTION AND CONSTRUCTION CHALLENGES OF INSTALLING MICROPILES IN KARST TERRAIN

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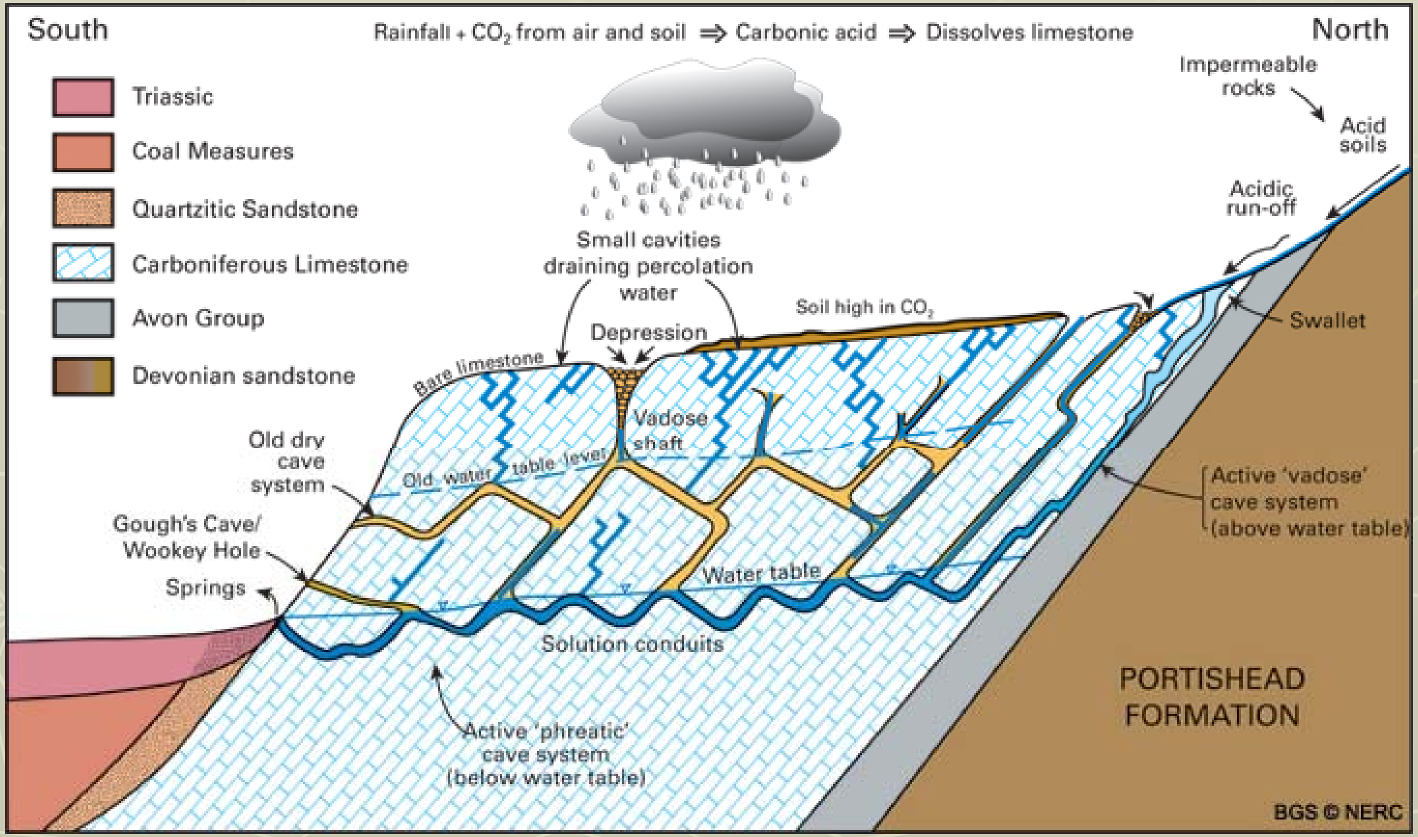
SUMMARY

- INTRODUCTION
- DRILLING
- GROUTING
- LOAD TESTING
- DOCUMENTATION
- CASE HISTORY
- CONCLUSIONS
- FUTURE RESEARCH

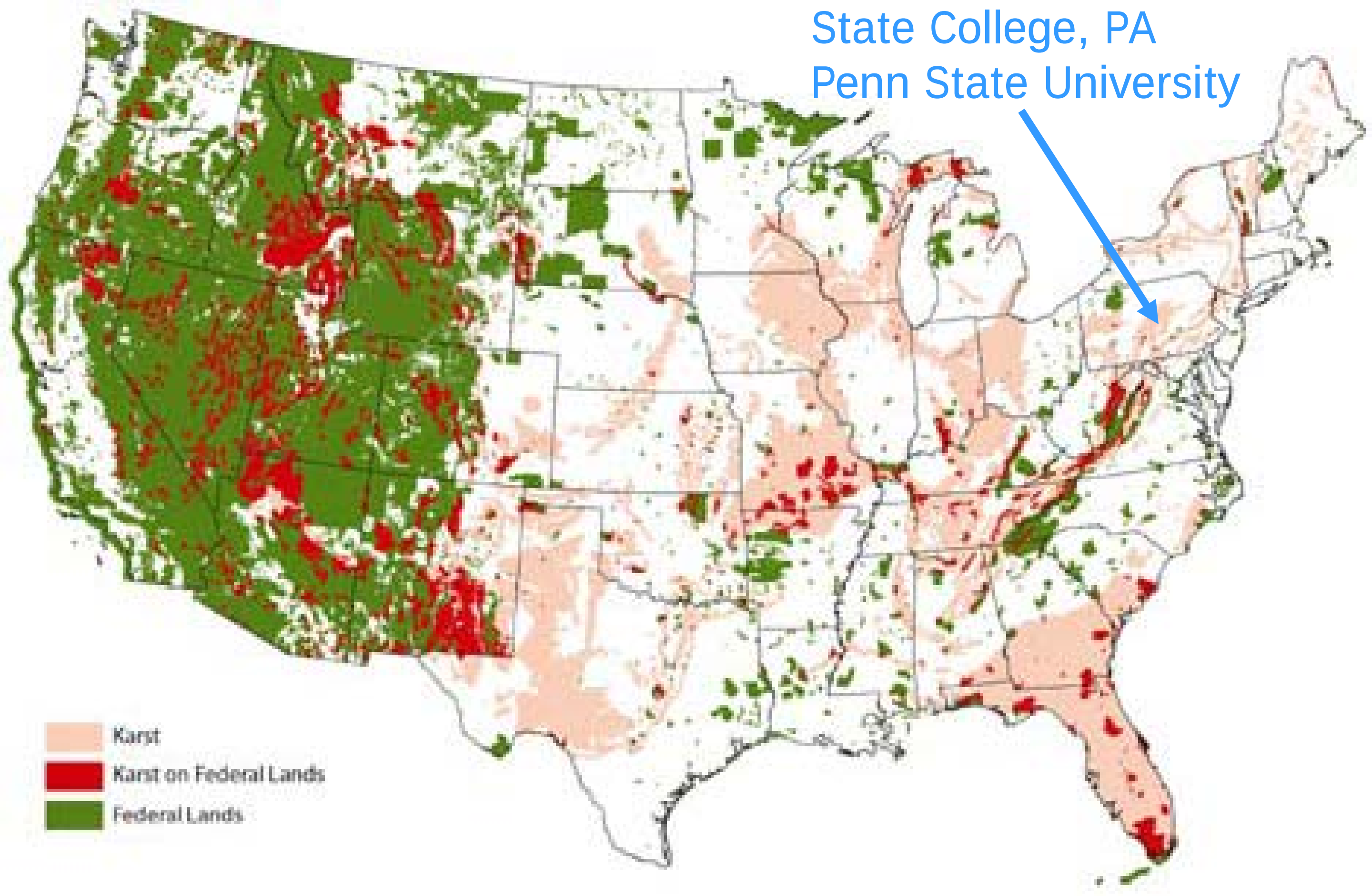
INTRODUCTION

- What is Karst?
  - Carbonate Bedrock
    - Limestone ($CaCO_3$) and/or Dolomite ($CaMg(CO_3)_2$)
    - Topography: Closed and Open Depressions (Sinkholes)



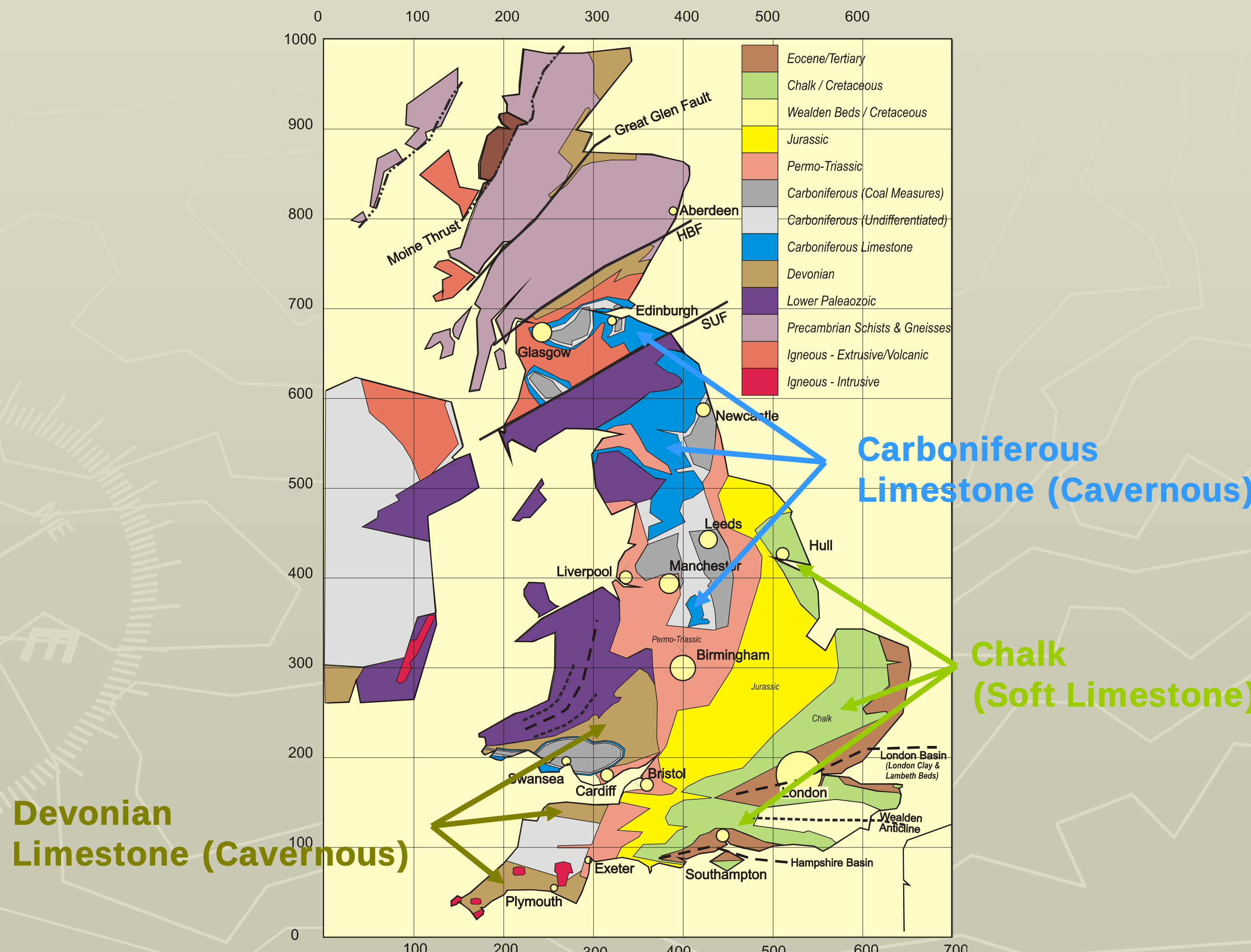
INTRODUCTION

- Distribution of Karst in the U.S. (USGS)



INTRODUCTION

- Distribution of Karst in the United Kingdom (Thanks to Michael Turner)

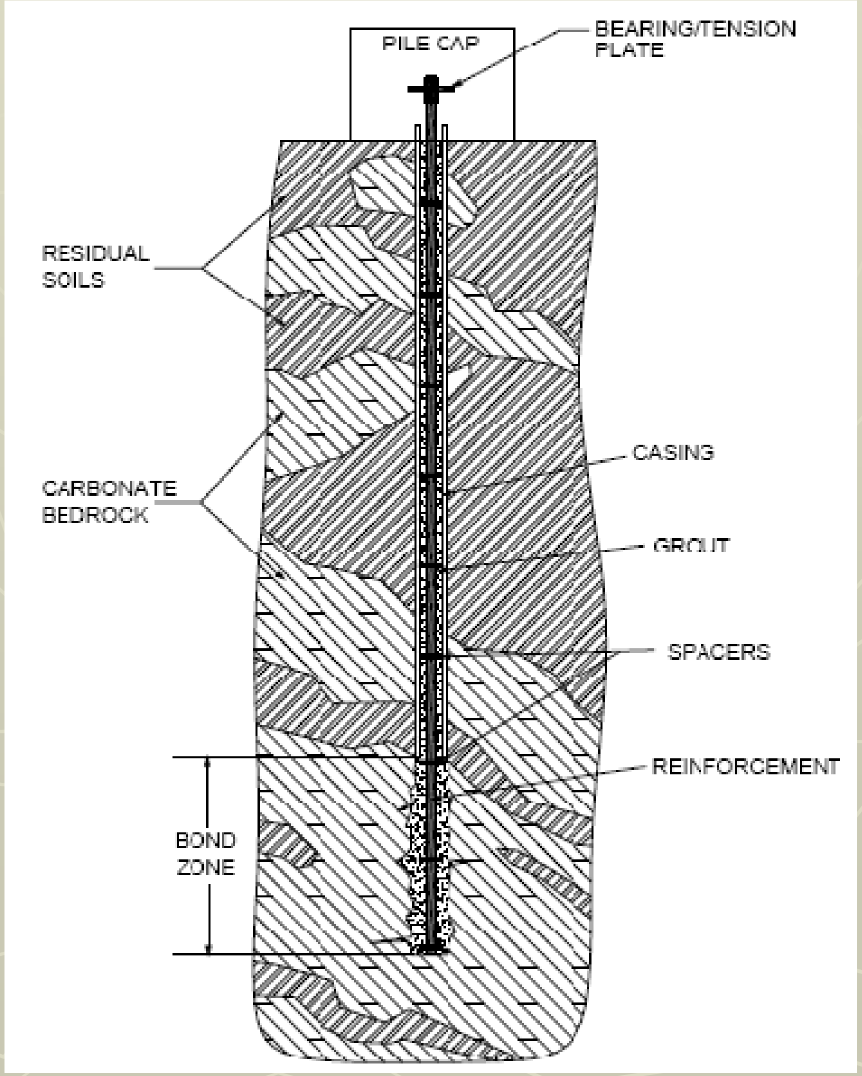


INTRODUCTION

- Why are micropiles a well-suited technology for karst terrain?
  - Advanced drilling equipment “easily” penetrates boulders and broken/fractured overburden
  - Friction design precludes issues with voids or soft soils below bond zone
    - Driven Piles or Drilled Piers
  - Inspection is fairly straight forward and does not require pilot holes
    - Drilled Piers/Caissons
  - High capacities and production rates make them a cost effective alternative to conventional deep foundations

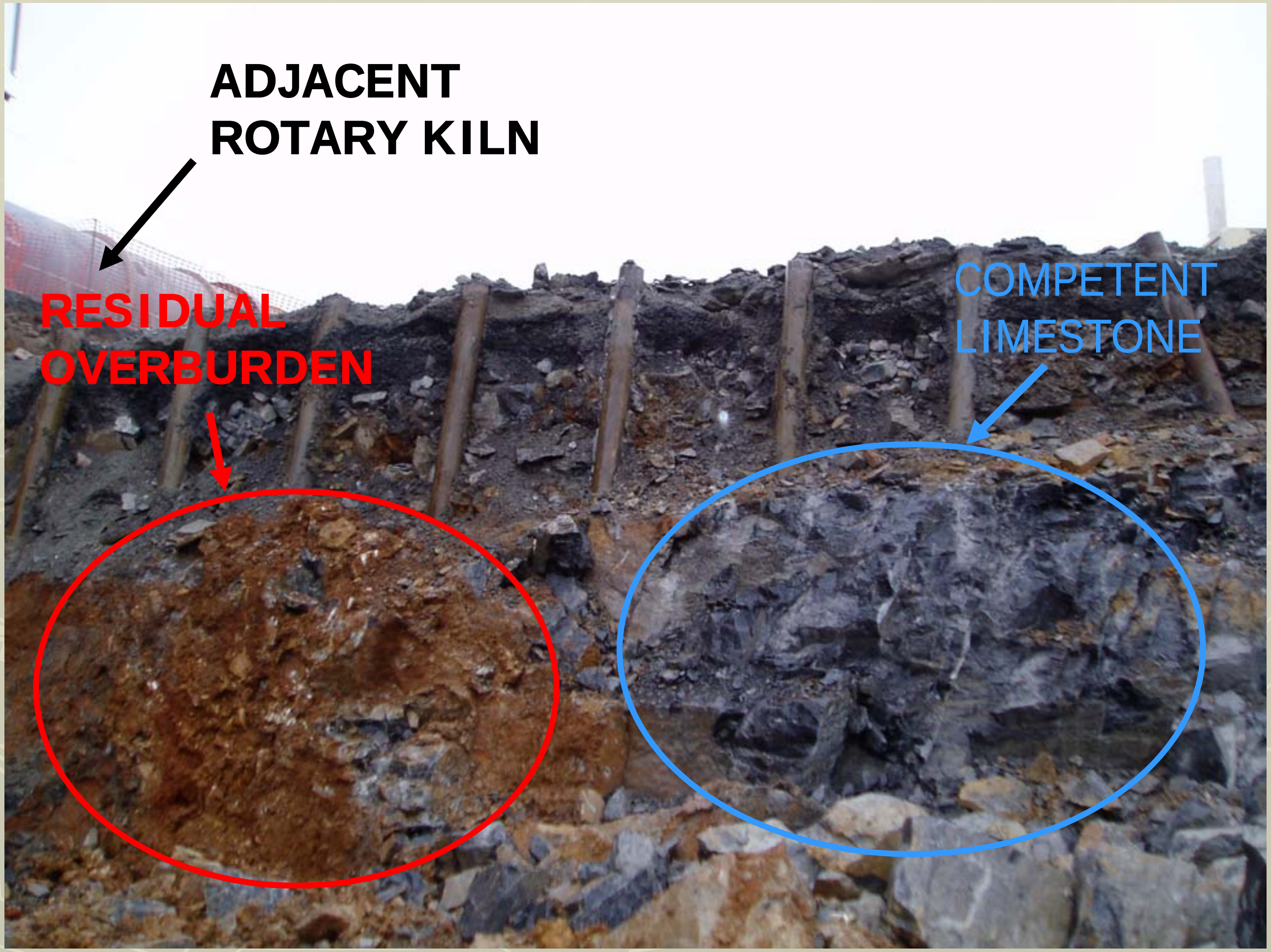
INTRODUCTION

- High Capacity Micropiles in Karst (typical)



INTRODUCTION

- Graymont (PA) Lime Plant Rotary Kiln Foundations – Pleasant Gap, PA

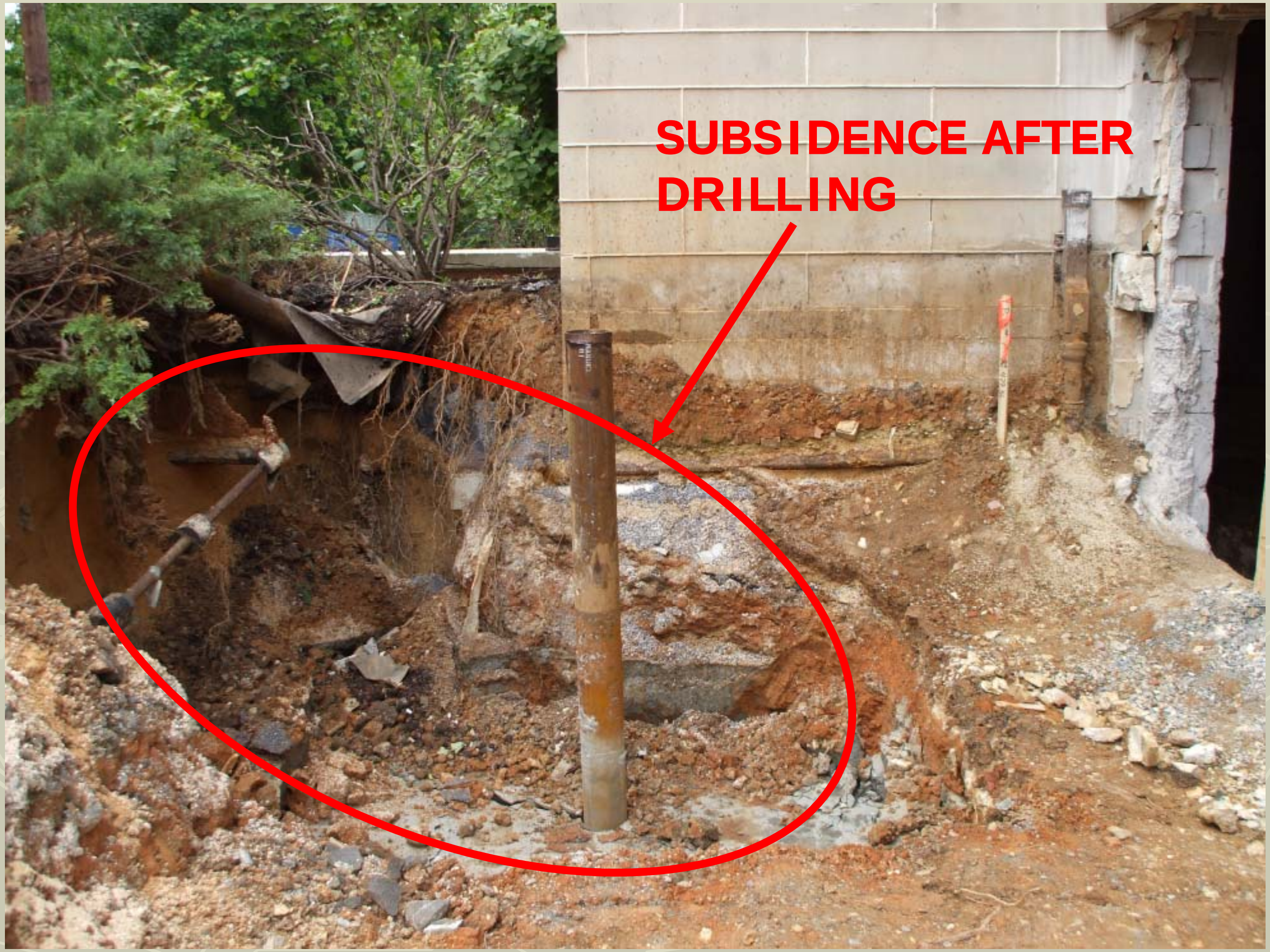


INTRODUCTION

- What are the engineering, construction and inspection challenges?
  - Engineering
    - Highly variable depths and potential elastic deflections that could lead to differential settlement issues
    - Communication between geotechnical, structural and geostructural team members
  - Construction
    - Drillers with little experience in karst
    - Verification of bond zone, especially in deep (>30m) micropiles
    - Creating sinkholes by eroding overburden with flush around casing
    - Excessive grout loss into fractures and voids
    - Maintaining verticality in pinnacled formations
    - Successful placement of reinforcement in compressive piles
  - Inspection
    - Inexperience with percussive drilling
    - Verification of bond zone competency (rate and noise)
    - Verification of reinforcement depth (rope/tape/grout tube?)
    - Maintaining "field independence"

INTRODUCTION

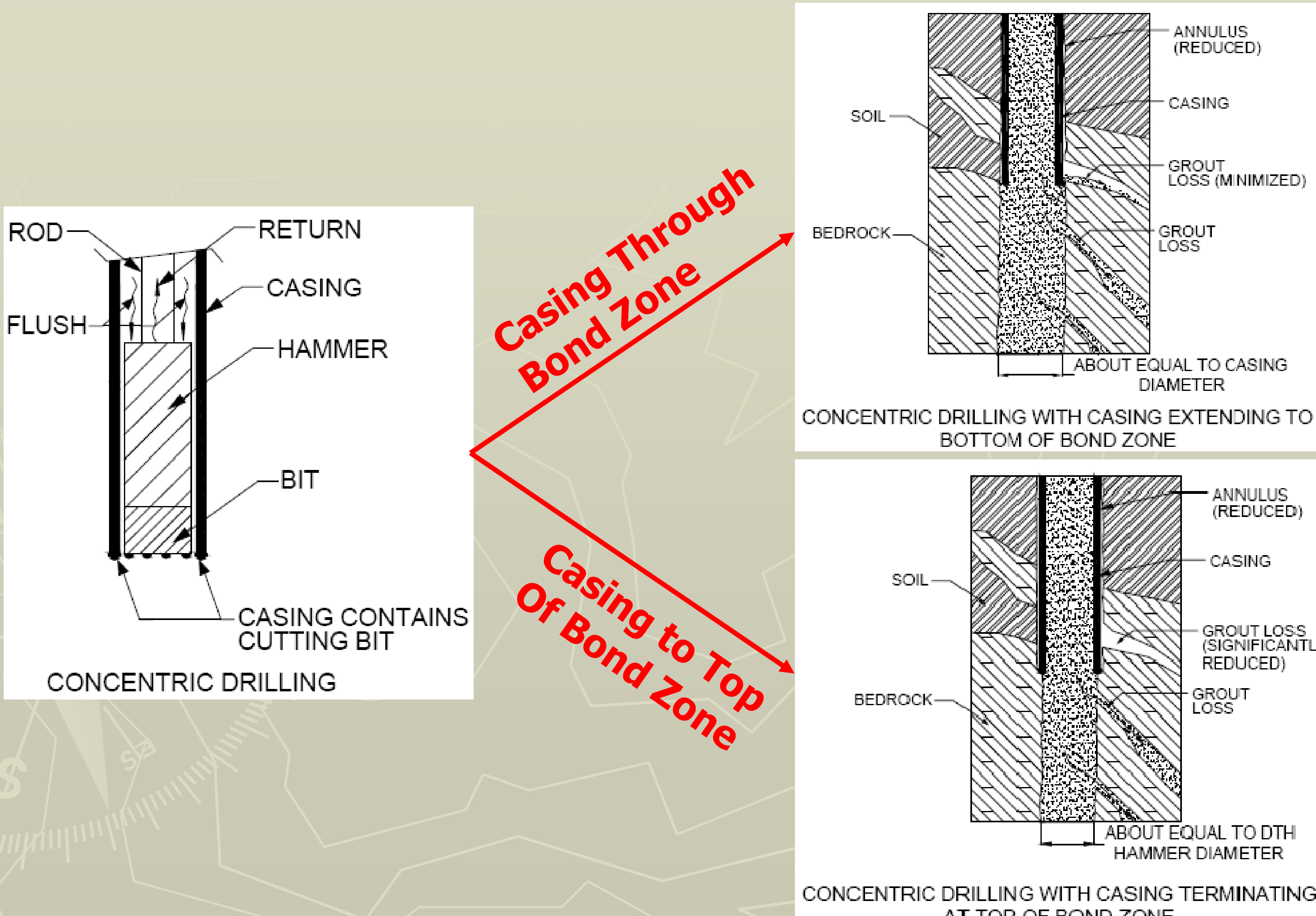
- Dickenson School of Law – Carlisle, PA



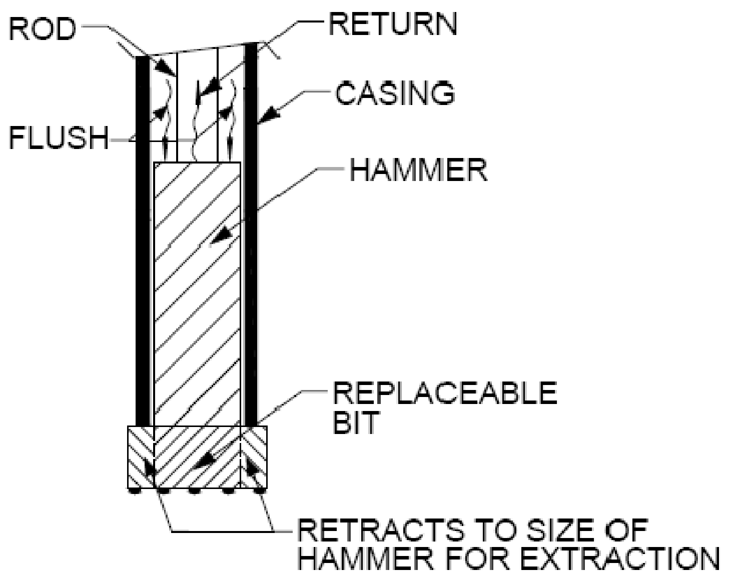
DRILLING MICROPILES IN KARST

- Open-hole drilling is discouraged and cased hole methods are typical and often necessary
- Concentric Drilling (Rotary Percussive Duplex) and Eccentric Drilling techniques are typical
- Considerations
  - Friction on casing during drilling
  - Sealing potential to limit grout loss above bond zone
  - Bond zone diameter
  - Casing “hang-ups” in broken or highly weathered rock
- Direct or reverse circulation limits potential for erosion of overburden typical of end of casing flushing techniques

DRILLING-GROUTING MICROPILES IN KARST

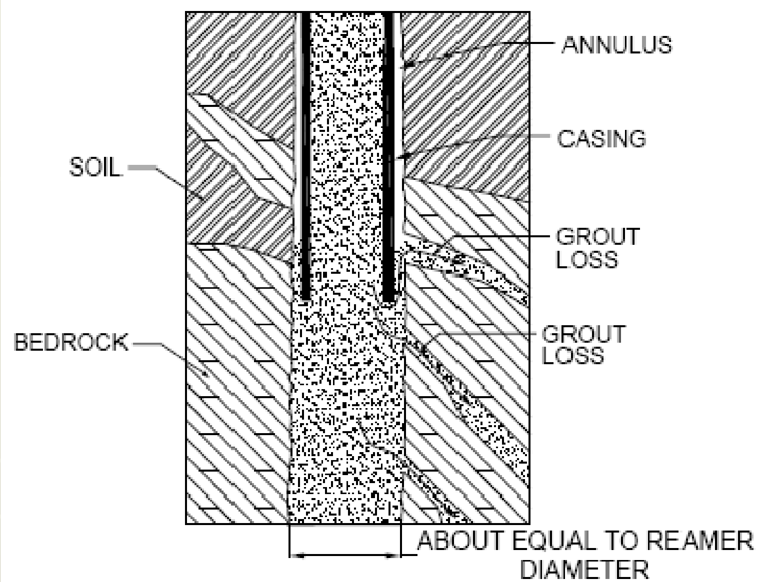


DRILLING-GROUTING MICROPILE IN KARST



ECCENTRIC DRILLING

END RESULT →



ECCENTRIC DRILLING AND GROUT LOSS ABOVE BOND ZONE

GROUTING MICROPILES IN KARST

- Grouting Methodology
  - Gravity fed through tremie tube at bottom of the hole after casing is withdrawn to top of bond zone
  - Pressure grouting is not recommended with water-cement mix (34.6 Mpa (5 ksi) typical)
- Challenges
  - Grout Loss
    - Thin fractures (secondary porosity) in bond zone
    - Up flow around casing as a function of drilling methodology
    - Low viscosity of water-cement mix
    - Head pressure as a function of hole depth
- Remedies
  - Thickening agent to increase viscosity
    - May affect ability to successfully place reinforcement
  - Primary-Secondary staged grouting
    - Place grout to sufficiently cover compression reinforcement in casing
    - Top-off pile after confirming primary grout has not subsided prior to initial set
  - Re-Drill grout from inside casing if grout subsides into bond zone (prior to placing reinforcement)

MICROPILE REINFORCEMENT

- REINFORCEMENT INSTALLATION METHODOLOGY
  - Drop through grout into bond zone
    - Efficient – Higher risk of “hang ups”
  - Lower into hole with rope
    - Inefficient – Lower risk of “hang ups”
    - How do you effectively remove rope?
- CHALLENGES
  - Compression reinforcement may not reach bottom of hole
    - Grout has high viscosity or has started to set
    - Centralizers catch on casing
    - Reinforcement lodges into rock socket
  - Verification that compression reinforcement has reached planned depth
    - Pre-measured string
    - Use tremie tube (pre-marked)

LOAD TESTING MICROPILES IN KARST

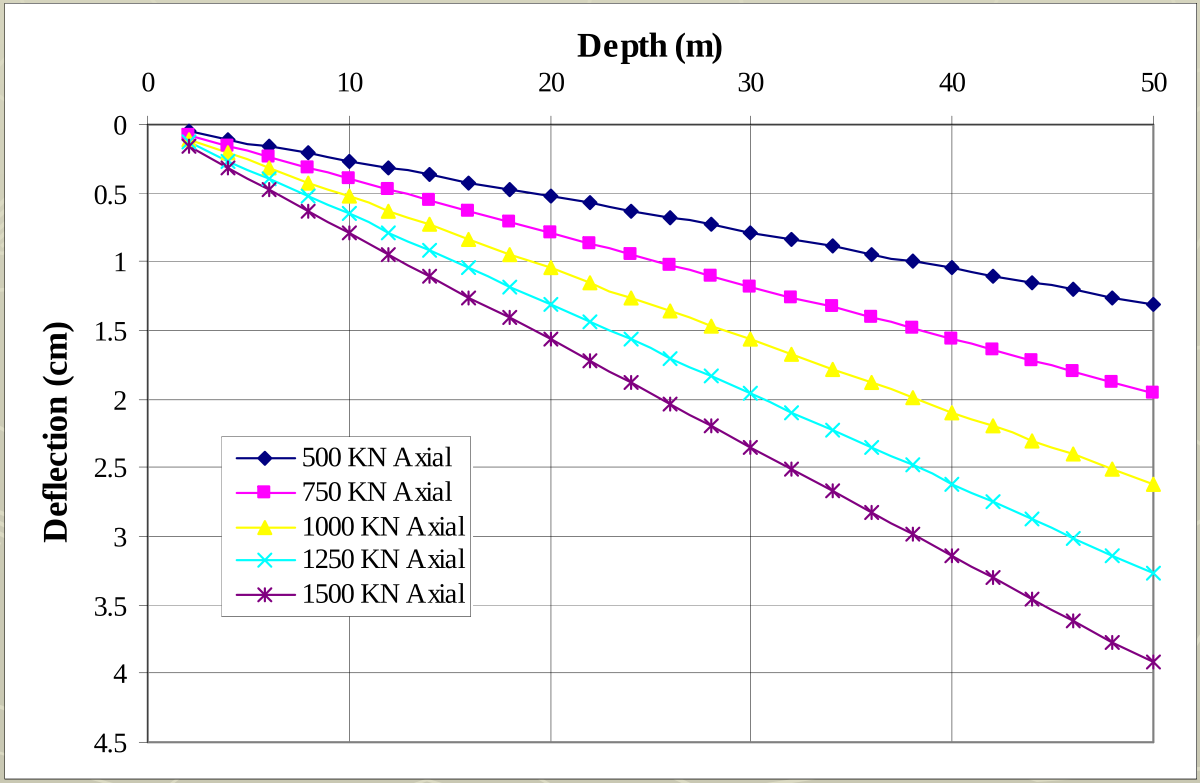
- “Quick Method” is typical for friction micropiles in karst
- Verify allowable bond capacity specified in geotechnical investigation, which is typically between 414 and 827 Mpa (60 and 120 psi)
- Measure deflection of piles and compare to elastic (PL/AE) curve to determine if additional reinforcement will be necessary during production
- Specify “control piles” be drilled at representative locations to allow for engineering team to make conservative judgments on the locations of the test piles

DOCUMENTATION

- The inspector is expected to aid in verifying bond zone competency and document the following:
  - Contractor information (organizing name, rig type, drilling method, driller, etc.)
  - Material characterization (overburden, broken rock, voids, competent rock, etc.)
  - Micropile description (casing/reinforcement size and strength)
  - Grout volume, design strength and methodology
  - Bottom of pile depth/elevation, cut-off elevation

DOCUMENTATION

- The Inspector is expected to communicate drilling information to the project team
- Changes to the design should be expected due to the potential for variable depths and deflections
- Deflection vs. Depth of a 17.78 cm OD 15.71 cm ID 552 MPa micropile with full length 5.72 cm 517 MPa reinforcement:

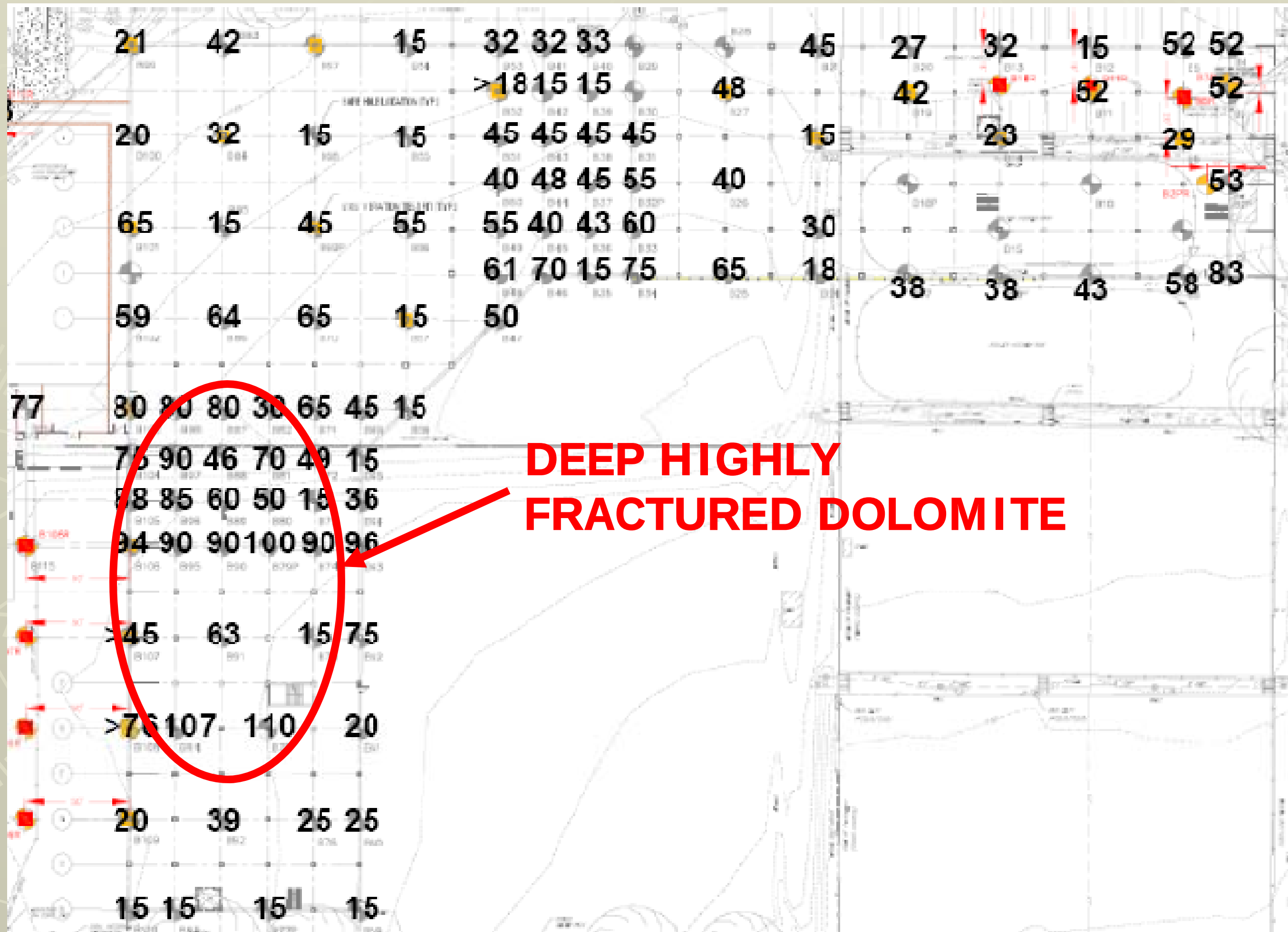


CASE HISTORY

- Project Description
  - Five (5)-story structure in Central Pennsylvania measures approximately 128 m x 161 m (420 ft x 530 ft) in maximum plan dimensions.
  - Unfactored interior column loads range between 2,100 and 2,700 kN (475 to 600 kips) and canopy truss column reactions vary from 4,450 kN (1,000 kips) uplift to 26,700 kN (6,000 kips) downward.
  - Significant lateral loading results from seismic and soil loading.
  - The site is underlain by the Nittany Formation (Ordovician Age), which consists of light to dark-gray finely to coarsely crystalline dolomite with alternating beds of sandy, cherty dolomite. Relative dip of bedding plane between 10 and 15 degrees with near vertical fractures and joints.

CASE HISTORY

- Depth (ft) to “competent” bedrock with minimum 90% recovery for 3 meters ranged between 4.5 and 30 meters below finished grade:



CASE HISTORY

- Why micropiles?
  - Deep and highly variable bedrock, soft/wet soils and high column loads made other deep foundations less attractive
  - Local experience with micropiles and difficulties associated with drilled piers and driven piles
- Typical micropile design
  - 17.78 cm OD 15.47 cm ID 552 MPa
  - Bond zone length of 3.43 m (11 ft) with a 19.68 cm (7.75 in) bond zone diameter
  - Eccentric drilling with direct flush (Numa Superjaws®)

CASE HISTORY

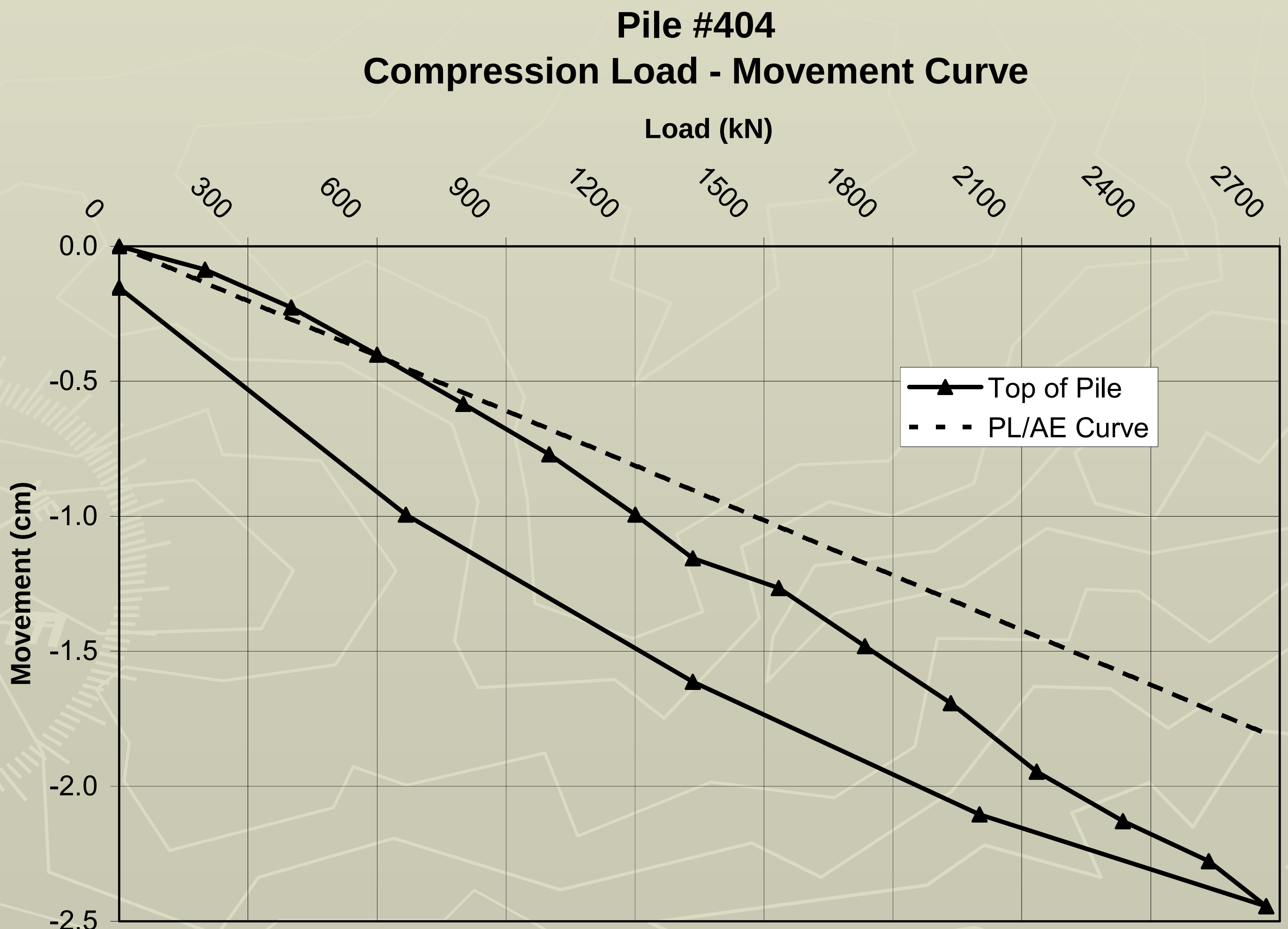
- Design Challenges
  - Typical Contractor Performance Specification
    - Pile design assumed typical axial and lateral loads with no moment, which was an unrealistic assessment given complex loading scenarios
  - Pile layout assumed by the Structural Engineer did not include a detailed analysis of individual piles within each cap
    - Required the contractor to design the a new pile layout based on the loading scenarios and combined stress analyses
  - Unacceptable predicted elastic deflections within individual pile caps required continual analysis of pile depths during construction
  - The contractors revised analyses revealed that upper casing reinforcement was periodically required to stay within combined stress limits

CASE HISTORY

- Construction/Inspection Challenges
  - Depths were greater, on average, than estimated from the test boring data
    - Broken dolomite rock with residual clay seams more prevalent than anticipated
  - Variable depths within individual pile caps required the use of additional inner steel casing and/or reinforcement to limit elastic deflection

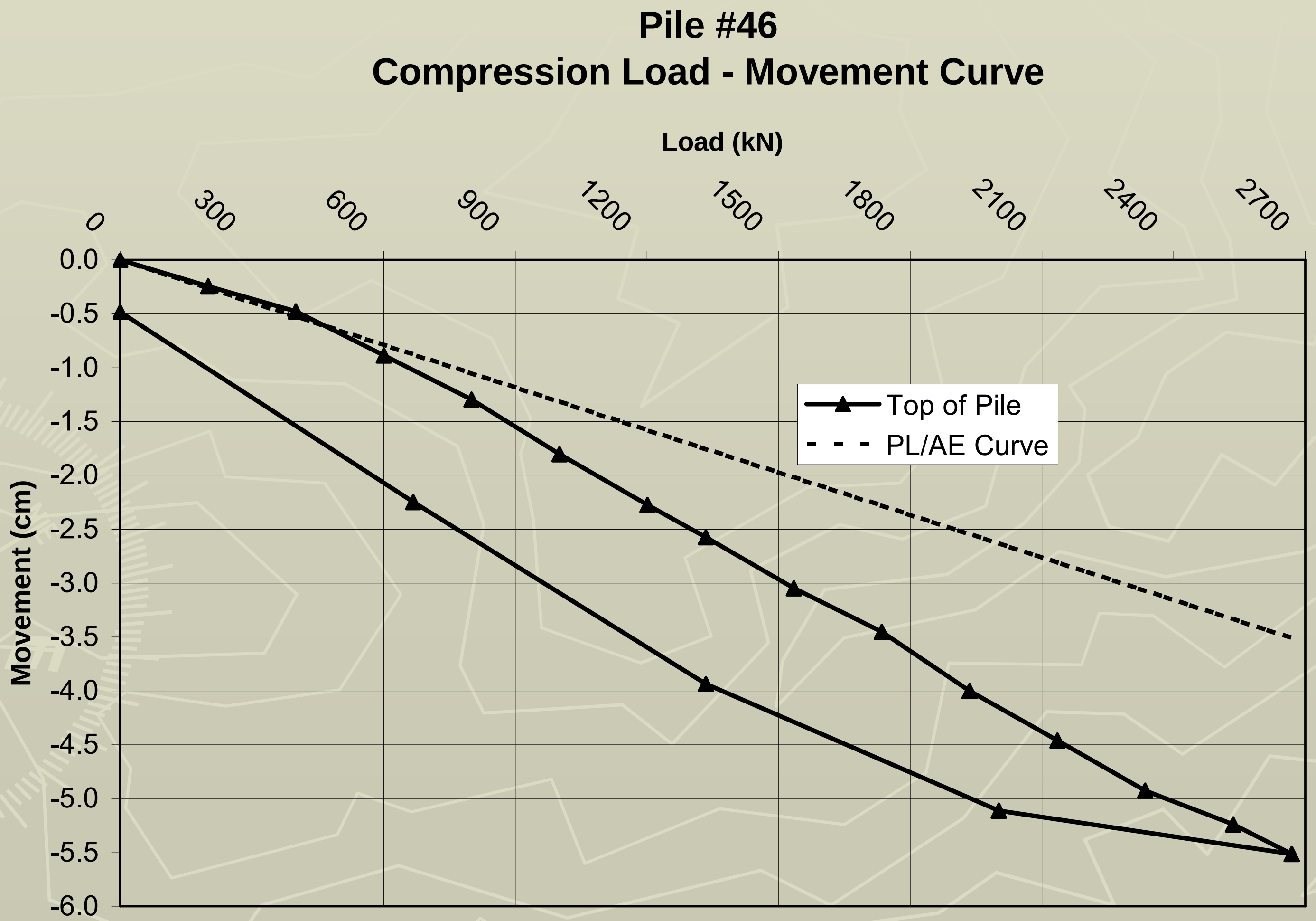
CASE HISTORY

- Load test on a 17.7m (58 ft) pile



CASE HISTORY

- Load test on a 33.2 m (109 ft) pile

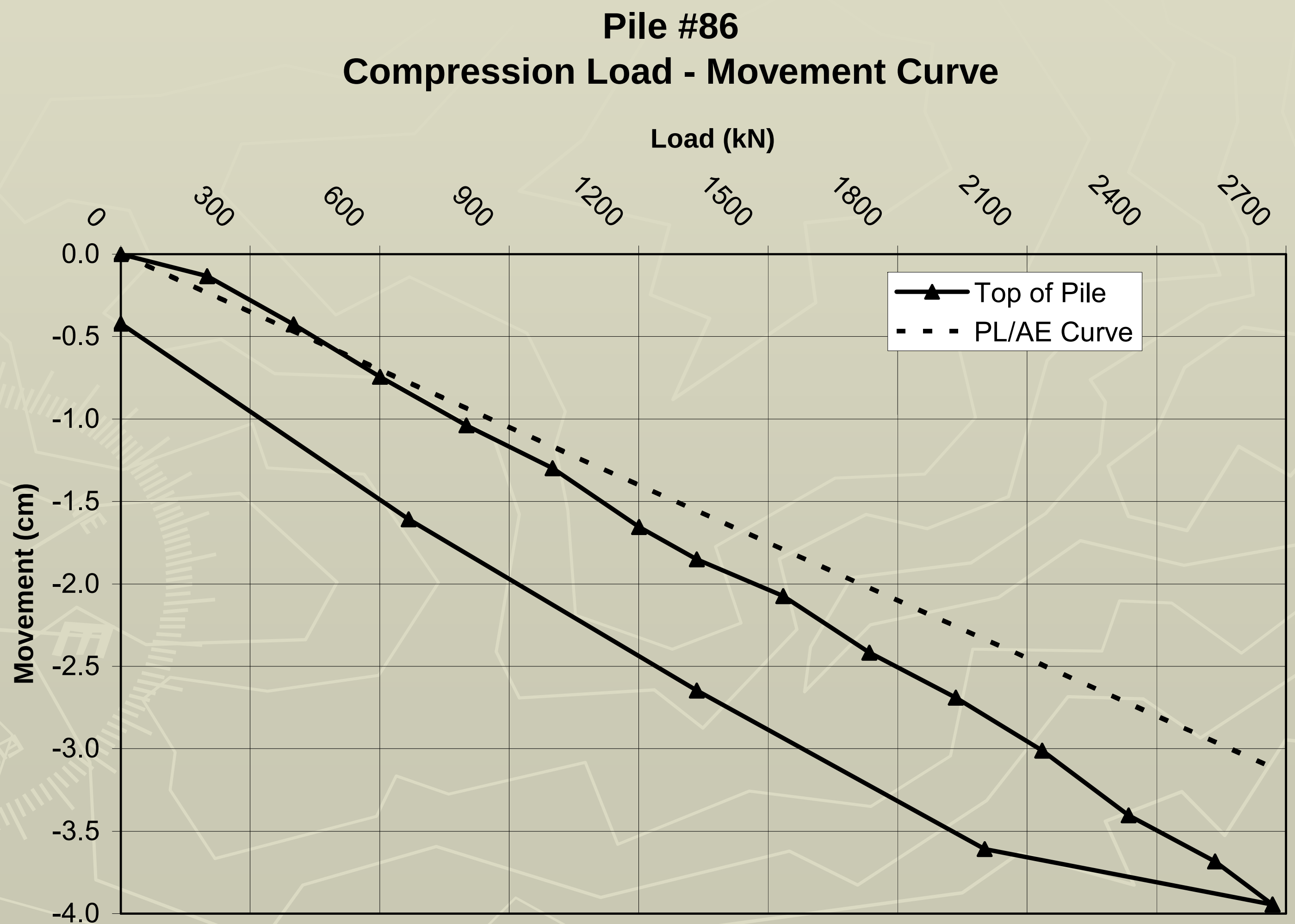


CASE HISTORY

- Construction/Inspection Challenges (cont'd)
  - Compression reinforcement placement
    - Re-drilling was required on several of the piles at the beginning of the project due to differential deflection considerations
    - It was discovered that the reinforcement (2-#18) did not extend sufficiently into the bond zone
      - Centralizers?
      - Casing?
      - Grout set-up?
      - Tip of reinforcement on ledge in bond zone?

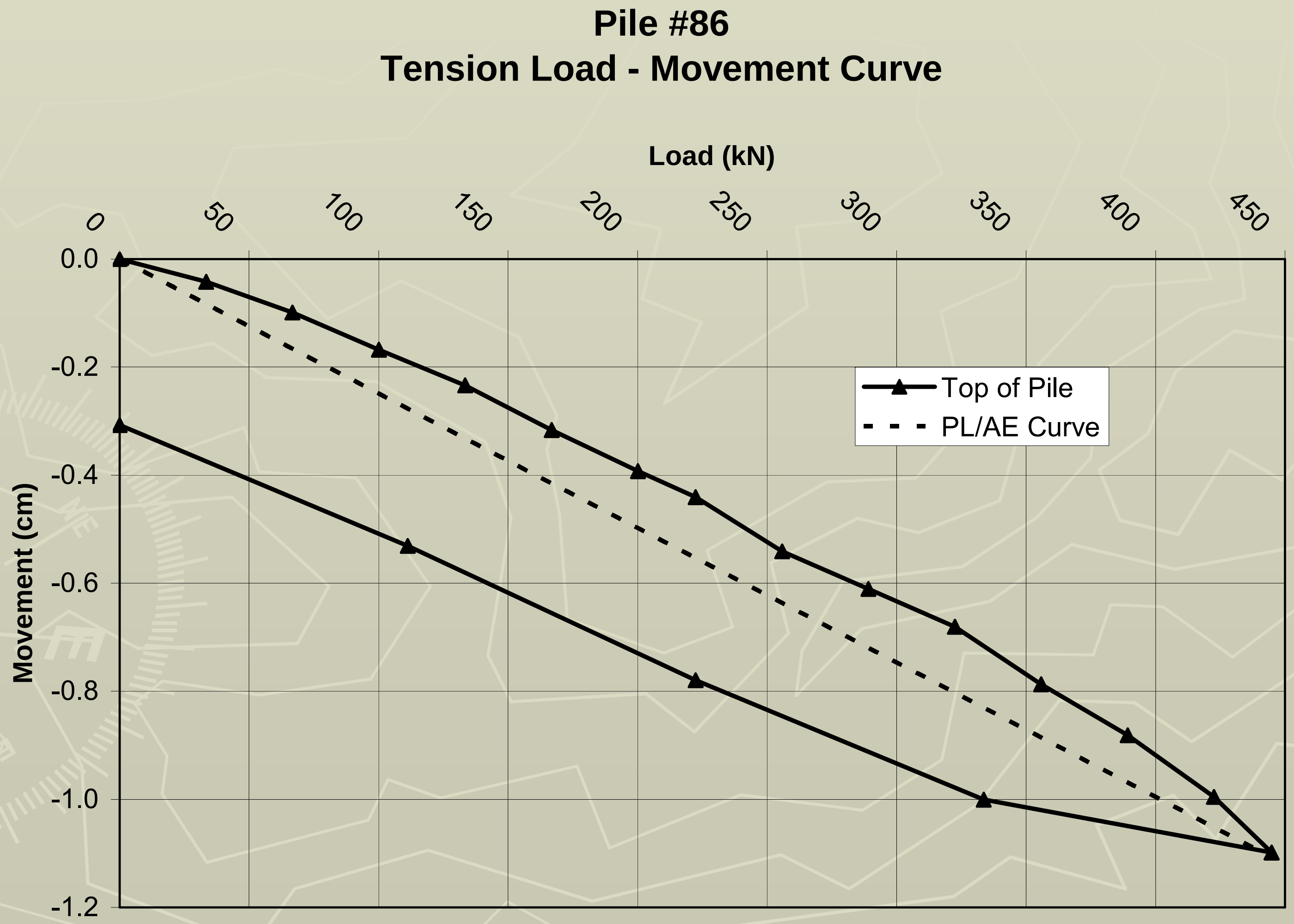
CASE HISTORY

- Compression **load test** on pile with 2-#18 bars 30.5 cm (12 in) in bond zone



CASE HISTORY

- Tension **load test** on pile with 2-#18 bars 30.5 cm (12 in) in bond zone



CASE HISTORY

CONCLUSIONS AND LESSONS LEARNED

- Engineering
  - Geotechnical Report → Structural Engineer Pile Layout → Contractor Design
  - Micropile Depth Variation
  - Karst Unknowns
- Construction
  - Drilling Experience: Pressures and Technique
  - Rock Quality: Cuttings, Rate and Sound
  - Grouting: Staging
  - Reinforcement: Centralizers, Bundled vs. Single, Lower vs. Drop
- Inspection
  - Experience: Design and Drilling Awareness
  - Verify Reinforcement Depth: String/Grout Tube
  - Communication with Design Team

FUTURE RESEARCH

- Bond Zone Verification
  - Down Hole Cameras
  - Photographic Mapping (Engineering Geology)
  - Sonic Drilling
- Why is reinforcement hanging up?
  - Bundled vs. Single
  - Tip Design
  - Centralizers
- Explore the significance of bond zone reinforcement. Can we end bear on a fully grouted bond zone?
- Fixed vs. Pinned Connections:
  - Fully Instrumented Lateral Load Test on Pile Array

QUESTIONS

- Thank you for your time and attention.