Ground Improvement: Options and Guidance for Ohio

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Ground Improvement for Transportation Projects

- Ground Improvement options
- Selecting the best Ground Improvement option for your project
- Subsurface exploration
- Ground Improvement Specifications
  - method-based
  - performance-based
- Acceptance testing
- Performance Monitoring during and after construction
SAFETY
Right here…
US 40 crosses 5 soil units between N Wheatland and I-70
Different structures
Different locations

• The answers to these questions should help define your exploration and testing programs:
  ▪ How many borings/soundings?
  ▪ What type?
  ▪ How deep?
  ▪ Sampling type and interval?
  ▪ Install monitoring instruments?
Project Overview and Objectives

- What types of construction or structures are planned
- New construction or rebuilding / renovating
- How will the planned construction change the loading on the soil
- What is known about the soil properties
- What soil properties can be determined
- How and when will additional information become available
Specific Geotechnical Information

- Depth to rock or other dense and strong layer
- Depth of groundwater table
- Identification of soil stratigraphy
- Properties of each layer
  - Unit weight
  - Relative density
  - Plasticity limits
  - Natural water content
  - Strength
  - Compressibility
  - Permeability
Geotechnical Considerations

- Loading conditions
  - Applied bearing pressure
  - Size of the area being loaded
- Stress increase versus depth
- Bearing capacity
- Slope stability
- Global stability
- Total settlement
- Differential settlement
- Subsurface voids (sinkholes, karst, abandoned mines, abandoned utilities, etc.)
Performance Expectations

- Strength related – are factors of safety adequate
  - bearing capacity, sliding, overturning, global stability, slope stability, short term conditions, long term conditions, etc.
- Serviceability – are settlements and/or lateral deformations acceptable
  - Total settlement
  - Differential settlement
  - Rate of settlement
- Is groundwater a concern (level, contamination, flow rates, etc.)
What’s Next

• Can the problem be solved with more or better geotechnical data?
  – Additional exploration and testing

• Can ground improvement methods be used to overcome the problem?
  – Is additional geotechnical information needed
  – Preliminary selection of ground improvement method(s)
  – Evaluation of ground improvement options
  – Recommended ground improvement method(s)
Geotechnical Evaluation – do we have enough information?

- Can How do you expect the soil to behave with your project on it?

- How do you need your project to perform?
  - What has to change to meet project expectations?
Planning Geotechnical Explorations

- What are the risks associated with not obtaining additional geotechnical data?
- What information is needed?
- What questions will be answered with the information?
- What is the potential cost savings?
- How many borings/soundings?
- What type?
- How deep?
- Sampling type and interval?
- Install monitoring instruments?
NHI Course No. 132031
Geotechnical Engineering Circular No.5

Geotechnical Site Characterization
Objectives of Ground Improvement

- Reduce total & differential static settlement
- Increase allowable bearing pressure
- Change seismic site classification
- Reduce risk of liquefaction
- Improve slope stability or global stability
- Reduce sinkhole or subsidence risk
What will Ground Improvement do?

- Increase the strength
- Decrease the compressibility
- Reduce the hydraulic conductivity
Ground Improvement Methods

- Apply surcharge load and wait
- Insert elements (wick drains) to accelerate drainage
- Applying energy to densify the soil
- Reinforcing the soil with granular or cemented elements
- Combine the soil with a cementitious binder
- Filling void space with injected materials
Options and Selection: Suggested References

- FHWA-NHI-16-027 / FHWA GEC 013 / NHI Course No. 132034

- FHWA-NHI-16-028 / FHWA GEC 013 / NHI Course No. 132034

- [https://geotechtools.org](https://geotechtools.org)
  Developed for the second Strategic Highway Research Program Project Number R02
  (SHRP 2 R02) Geotechnical Solutions for Soil Improvement, Rapid Embankment
  Construction, and Stabilization of the Pavement Working Platform +
  [http://www.trb.org/SHRP2](http://www.trb.org/SHRP2)
Selection of Ground Improvement Techniques – The Engineers Challenge

Soil Type Governs the Ground Improvement Technique

- Mine Spoils
- Undocumented Fill
- Loose Sand
- Low Strength Cohesive Soils
Wick Drains

- Prefabricated Vertical Drains (PV drains, PVD’s)
- Wick Drains
- Synthetic drains
- Band Drains
- Strip Drains
Wick Drains – The General Idea

Without Drains

With Drains

Clay

Bedrock

Bedrock
Consolidation – key parameters

- Length of the drainage path, $H$
- Time, $t$
- Required average degree of consolidation, $U_{avg}$
- Fill availability/cost
- Coefficient of consolidation, $c_v$ and $c_h$
  - Neither are easy to determine
  - $c_h$ tends to be greater than $c_v$ due to clay deposition and layered stratigraphy
- Are there sand layers that can speed up consolidation?
- Factor in disturbance/smear if factoring up.
Dissipation Curves

ASSUMPTIONS:
1. Radial drainage only
2. Uniform soil deposit
3. No back pressure from horizontal drainage
4. Soil parameters constant in time and position
5. No drain resistance considered
6. No disturbance considered

![Dissipation Curves Diagram](image)

- **$U_0$**: Input
- **$U_{max}$**: Maximum
- **%**: Consolidation
- **Time (days)**:
  - Spacing 1: 6.00 ft, 388 days
  - Spacing 2: 5.00 ft, 251 days
  - Spacing 3: 4.00 ft, 146 days
  - Spacing 4: 3.00 ft, 72 days

**Vick Drain Pattern**: Triangular
**Equivalent Drain Diameter**: 0.22 ft

![Dissipation Curves Graph](image)
Selection of Ground Improvement Techniques – The Engineers Challenge

Soil Type Governs the Ground Improvement Technique

Densification Reinforcement

Mine Spoils
Undocumented Fill
Loose Sand
Low Strength Cohesive Soils

Vibro Stone Columns
Vibro-Compaction
Vibro-Replacement with Wick Drains
Densification techniques rearrange particles -- decreasing void space, increasing grain to grain contact

Note: This is only possible if there are no fines in the soil matrix
Densification: Dynamic Compaction
• INDOT: I-69, White River Segments
  - Vibro Stone Columns and Dynamic Compaction
Densification: Vibro Compaction

Gunderson Lutheran Hospital Parking Deck, La Cross, WI
What happens when we introduce fines into the soil matrix?

We now must move from Densification to Reinforcement.
Selection of Ground Improvement Techniques

Soil Type Governs the Ground Improvement Technique

Undocumented Fill
Low Strength Cohesive Soils
Aggregate Piers/Stone Columns

• Piers or columns of dense aggregate installed as foundation elements to support light to medium loads.

• Often referred to as an intermediate foundation system, i.e. not shallow but also not deep.

• Usually about 24 to 36 inches in diameter and about 10 to 40 feet deep.
Aggregate Piers – When to use them?

- Usually used to reduce expected settlements for Retaining Walls/Embankments (also have a wicking effect).
- May be used to increase bearing capacity.
- Used to increase FS against Global Stability Failure
- Installed in cohesive and cohesionless soils.
- Installed above and below the groundwater table.
Case Studies: Aggregate Pier/Stone Column Installations

INDOT I-69 CSX to White River Washington, IN

I90/94 - I290 "Circle" Interchange Chicago, IL
Case Studies: Aggregate Pier/Stone Column Installations

Ohio River Bridges
Louisville, KY
Aggregate Pier/Stone Column Nomenclature

**Trade Names**
- Geopiers
- Vibro Piers
- VSC (Vibro Stone Columns)
- Terra Piers

**Install Methods**
- “Rammed” Aggregate Piers
- Vibro Replacement
- Vibro Displacement
- Top Feed/Bottom Feed
- Impact Piers/Rampact Piers
Aggregate Pier/Stone Column Nomenclature

Neutral Terms are "Aggregate Columns", “Aggregate Piers”, “Stone Columns”, etc.

Any term that doesn't include an install method or trade name

Coke and Pepsi = Cola

Kleenex and Puffs = Tissues
Aggregate Pier Design Methodology

Design references:
Elastic Settlement Relationships:
• Ground Improvement Design and Construction of Stone Columns, Volume 1+2 1983 FHWA-RD-83-026 PB84-190024

Cylindrical Cavity Expansion + Vertical Deformation:

Equivalent Spring Deformation Methods:
• Sehn and Blackburn, Lawton and Fox, others.

Full-scale load tests with published papers.

Thousands of successful installations.
Construction Process
Limitations

- Requires soil that can provide adequate lateral support (confinement) of the aggregate pier.
  - for cohesive soils, usually want average N > 4.

- Can be expected to reduce settlements by a factor of 2 to 4 (high treatment ratio).

- Soft clays, peats, organic soils thicker than about 2 to 3 feet (Enter Rigid Inclusions, Soil Mixing).

- Upper bound to the load carrying capacity of the Aggregate Pier/Soil Matrix system – very heavy loads may not be appropriate. ~100 kips per Pier…
What are Rigid Inclusions (RI)?

- High modulus grout columns

- Typical grout strength is 2,500 to 4,000 psi

- Typical diameters 12” to 18”

- Works in conjunction with a load transfer platform (LTP)
Why Rigid Inclusions?

- Geotechnical
  - Reduce Settlement
  - Increase Bearing Capacity

- Structural
  - Shallow Spread Footing
  - Slab-on-grade replaces structural slab

- Environmental
  - Little to no spoil (contamination)
  - Quiet compared to pile driving
Benefits

- **Cost:** Shallow spread foundations and slab-on-grade vs. pile caps and structural slab
- **Schedule:** Gain time compared to surcharge or surcharge with wick drains
- **Reduce settlement more than aggregate piers**
- **Minimizes spoil created at ground surface**
- **Quality verification through data acquisition and testing**
Rigid Inclusions for Transportation

- Iowa DOT -
- Ohio River Bridge – Louisville, KY
  - Embankment Support next to active roads
- I-64 High Rise Bridge – Norfolk, VA
  - Embankment Support next to Sheet Pile wall
- SD River Bridge Double Track – San Diego, CA
  - MSE wall support for new commercial railroad tracks
- Hopkinton Department of Public Works – Boston, MA
  - Foundation and slab-on-grade support
  - Moncrief-Dinsmore Rd Bridge – Jacksonville, FL
  - Box culvert support
- SR 713 Kings Highway – Fort Pierce, FL
  - Utility Support
Load Transfer Platform

- A load transfer platform (LTP) is used to transfer load from the structure to the Rigid Inclusions
- Structural Fill – Granular soil (DGAB)
- LTPs may include 1 to 4 layers of embedded geogrid or steel mesh (or none at all…)

![Graph showing sieve opening size vs. percent passing with an acceptable gradation range highlighted.](image-url)
Load Transfer Platform
Rigid Inclusions - Applications

Ohio River Bridge
Louisville, KY

Harrisburg, PA

Norfolk, VA

Albany, NY

SD River Bridge
Double Track
San Diego, CA

Ithaca, NY
Applications: MSE Walls / Retaining Walls
Typical Soil Profile for Rigid Inclusions

Uniform Load with raise-in-grade

1. 44 ft

2.

3.
RI Design – Settlement Reduction

Estimated settlement without ground improvement – 6 inches
Estimated settlement with aggregate piers – 1.5 to 3 inches
Estimated settlement with rigid inclusions – less than 1 inch
RI Design - Finite Element Analysis

- Axisymmetric and Plain Strain (2D models)
- 3D models for difficult geometry and refined analysis
- What Level of Analysis is Appropriate?
  - Constitutive Models (governs soil behavior)
  - Soil-Structure Interaction (governs interaction with dissimilar materials)
RI Design - Finite Element – 3D Analysis

<table>
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<th>Layer</th>
<th>Material</th>
<th>Borehole 1</th>
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<td>Structural Fill</td>
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<td>Structural Fill</td>
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<tr>
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<td>Med. Dense Sand</td>
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<td>5</td>
<td>Loose Sand</td>
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<td>6</td>
<td>Sandy Clay</td>
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<tr>
<td>7</td>
<td>Yorktown - Dense Sand</td>
<td>-53.00</td>
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Head: 9.000
Preconsolidation

Soil layers:
- Water
- Initial conditions

Diagram showing Slab RI and Footing RI.
Quality Control: Grout Mix Design

Pumpable Strength

Compressive
RI Quality Control - DAQ

Rigid Inclusion Installation Report
77 Court Street

RI Name: 299  
Job No.: 200384  
Location: Newton, MA

Installation Date: 5/2/2016  
Diameter: 12.00 in  
Installed Length: 30.08 ft

Neat Volume: 23.66 cf  
Actual Volume: 27.43 cf  
Grout Factor: 1.159

Stroke Count: 45  
Stroke Factor: 0.61 cf  
Target Grout Factor: 1.1

Penetration / Withdrawal (feet)

Torque / Crowd Pressure (psf)

Grout Pressure (psi)

Time (min)

Volume (cf)

- Drilling Rate
- Withdrawal Rate
- Torque Pressure
- Crowd Pressure

Grout Volume:
- Target Volume
- Neat Volume
RI Quality Control - DAQ
RI Quality Control - Load Testing

- Static Load Testing
- 150% to 200% Design Load
- Design Load from FE Analysis
CASE STUDY: Ohio River Bridges, Louisville, KY/Jeffersonville, IN

- East End Connector
- Downtown Crossing
Downtown Crossing
The Downtown Pursuit Interchange Reconstruction – 41 Embankments, Ramps, MSE Walls
HBI PRE-BID EFFORT

- HBI reduced available geotechnical data into average subsurface profiles for every 500 feet of roadway.
TEST EMBANKMENT - LOCATION
TEST EMBANKMENT CPTU PLAN
TEST EMBANKMENT AND SELECTION OF INSTRUMENTS (GETEC)
TEST EMBANKMENT – LAYOUT
TEST EMBANKMENT – IMPLEMENTATION
TEST EMBANKMENT – IMPLEMENTATION
TEST EMBANKMENT – IMPLEMENTATION
DATA COLLECTION BOX
BUILDING THE EMBANKMENT
TEST EMBANKMENT COMPETE!!
KEY FINDINGS

Pore pressure dissipates rapidly

Significant Rain Events (5+ inches)
KEY FINDINGS

RI's effective at limiting total settlement

Significant Rain Events (5+ inches)
### KEY FINDINGS

<table>
<thead>
<tr>
<th>Cell</th>
<th>Element Spacing</th>
<th>Predicted Pre-Treatment Settlement</th>
<th>Predicted Post-Treatment Settlement</th>
<th>Observed Settlement from Instruments</th>
<th>% Diff Predicted/Observed</th>
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<td>12' Square</td>
<td>9.32&quot;</td>
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<td>2.40&quot;</td>
<td>+6%</td>
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Soil Mixing methods can use a Wet process when dryer stiffer soils need to be mixed.

- **Wet mixing process**: Combines the binders with water and the binder is injected as a slurry during the mixing.

- **Top down soil mixing process**

- **The use of higher strength material in the design is possible with the wet installation process**
Dry Soil mixing methods are utilized in wetter softer soils or where spoil is a problem.

Dry binder materials are pneumatically injected into the soil during the dry mixing process.

Bottom up method of soil mixing.

There must be adequate soil moisture for the binders to fully hydrate often limiting design strengths.
Batching/Delivery equipment setup at the project sites can be compact.
Dust Control
Binder Shuttle
24-Ton Tanker
“Air” Truck (unloading)
Shuttle Control Panel
Surcharge (2-ft)
Geofabric
Bench Scale Test Reporting
Preparing Specifications and Plans

• “Discussion of how to write specifications (method based, performance based, etc.) while avoiding proprietary aspects…”

Contracting Framework =

Design – Bid – Build
Preparing Specifications and Plans

• Avoid the use of “method” specifications
  ▪ Unlikely to accommodate available tools and approaches offered by the various specialist contractors
  ▪ May preclude certain methods that might otherwise provide desired performance more economically

• Performance is the ultimate goal
Do’s and Don’ts: Suggested References

• Guidance for Drafting Specifications for Ground Improvement
  
  Deep Foundations Magazine, April 2016
Performance Expectations and Requirements

• Regardless of **Design-Bid**-Build or **Design-Build**,
  
  ▪ Understand the performance requirements for the new construction
  
  ▪ Communicate them clearly, and completely, in the contract documents
  
  ▪ Anticipate natural variability and appropriate means of compensation
    • Unit price by “area” units is unlikely to fairly share risk
Performance Expectations and Requirements

• Specify, not only the required behavior, but also the *(acceptable)* design/analysis methods to be used by the specialist Ground Improvement engineer

• Define review and acceptance responsibilities among the parties
Information to be provided in contract documents

- Complete geotechnical report
  - Not just logs and test result tables
- Existing and planned grades
- Existing and planned utilities
- Groundwater regime and planned surface drainage features
- Information regarding site history, reported past activities
- Known contamination
- Planned construction sequence
Applied Bearing Pressures and Loading

• How is design bearing pressure to be computed?
  − FS against bearing capacity failure or serviceability/settlement?
  − At what location is the target bearing pressure to be computed?
    ▪ Average across structure or extreme edges?
• Are there different requirements for different structure elements?
Settlement

- Define acceptable magnitude of vertical displacement during construction and post-construction
  - Static, service dynamic, and seismic
  - Specify for which structure type each criterion applies, e.g., embankment fill, MSE wall facing, etc.
- Conditions under which settlement is to be computed
  - Provide and describe DL, Sustained LL, Transient LL and Extreme Service Loads
  - Define the necessary design loading combinations
Settlement

• Define acceptable displacements with regard to magnitude and time
  – Immediate/during construction
  – Primary consolidation settlement
  – Secondary compression/creep settlement
• Define where and how settlement is to be measured
  – Devices, precision, reference baseline
• Define when monitoring is to occur and by whom
• Define acceptable corrective actions
Slope Stabilization

- Acceptable analysis methods
- Appropriate soil strength parameters
- Required static and seismic FS against instability
- Any allowable temporary FS
- Monitoring method
- Monitoring frequency
- Acceptable corrective actions
Special Circumstances and Considerations

• Explicitly define operational constraints
  – Work hours
  – Staged construction
  – Noise, dust, vibration limits, etc.
  – Access
  – Water sources and disposal
  – Spoil management
Special Circumstances and Considerations

- Anticipate/report the presence of obstructions
- Anticipate/report flowing and/or artesian water condition
- Anticipate/report presence or potential presence of hazardous materials or gases
- Locale-specific considerations
  - Weight restrictions
  - Frost laws
  - Available or restricted local materials
  - Labor agreements/rules
The recurring expectation...

• Provide **clarity**
  - For the specialist engineer and construction team
  - For the reviewer(s)
  - For the Owner
Verification Methods

- Select the tools based on the means used to provide improvement:
  - **Drainage**
    - Observe and measure
      - Settlement monitors
      - Piezometers
  - **Densification**
    - Test program: verify adequacy of pattern(s) – adjust compensation
    - Volume change
      - Settlement monitors
    - Pre- and post-improvement penetration resistance or PMT/DMT modulus assessments
Verification Methods

- Reinforcement
  - System “analysis” and element behavior and quality
    - Single elements versus groups?
  - Observe and measure
    - Settlement monitors
    - Piezometers
    - Pressure cells
  - Consider Purpose
    - Quality Control
    - Quality Assurance
Verification Methods

- Be sensible with respect to scope and schedule of verification testing
  - Do X# “tests” manage risk better than Y# “tests”?
  - Remember “review period” costs money…
    - Specialty contractor resources don’t sit idle for free
When considering Ground Improvement …

- Evaluate project setting and risks
- Have the end in mind
- Don’t forget the fundamental soil mechanics