Design and Construction of Rigid Inclusion Ground Improvement Projects

Tanner Blackburn, Ph.D., P.E.
Chief Engineer
Hayward Baker

Ray Franz, P.E.
Vice President
Hayward Baker

45th Annual Midwest Geotechnical Conference
East Lansing, MI
What are Rigid Inclusions (RI)?

- Grout or cemented aggregate element used to reinforce soft soils:
  - Reduce settlement
  - Increase bearing capacity

- Trade names:
  - Controlled Modulus Column (CMC)
  - Grouted Impact Piers (GI)
  - GeoConcrete Columns (GCC)
  - Cast-in-place Ground Improvement Elements (CGE)
  - Controlled Stiffness Column (CSC)
  - Augered Pressure Grout Column (APGC)
Advantages and Applications

- Transfer loads through weak strata to a firm layer below
  - Bulging hazard for aggregate piers
- Load can be partly carried by soil
- Shallow spread footing design
  - No structural connections to elements
- Minimize spoils
Design of Rigid Inclusion ground improvement systems require the following components:

- structural capacity of the rigid inclusion element
- geotechnical capacity
- load transfer platform mechanics
- overall system settlement
Soil-structure Interaction

RI displacement is a function of the stress in the RI and the properties of the soil and the RI.

Deflection of the top of the soil layer is equal to the deflection of the top of the RI.

Stress in the RI depends on the stress in the upper soil and properties of the soil and the RI.

Stress in the upper soil layer corresponds to the deflection of the upper soil.

RI displacement is a function of the stress in the RI and the properties of the soil and the RI.
Geotechnical and Structural Capacity

Rigid inclusion – Load transfer interaction

Structural capacity of rigid inclusion

Side and tip resistance
Geotechnical and Structural Capacity

- Load-deflection interaction between the soil and the RI:
  - Negative and positive skin friction are functions of RI, soil type, spacing, LTP properties
  - Traditional deep foundation capacity methods are inadequate

- For preliminary and conservative estimates:
  - Displacement Pile Chapter - FHWA Augercast Pile Circular, GEC No. 8 (2007)
  - Deep foundation design methods based on SPT, CPT, $\phi$, $Su$, depth

- Structural capacity:
  \[ q_{allow} = 0.3 f'_c \]
Soil Structure Interaction

Rigid inclusion – Load transfer interaction

Negative Skin Friction

Positive Skin Friction

Deflection

Stress in the RI

Neutral Plane

Rigid Inclusion

Soil
A load transfer platform (LTP) is used to transfer load from the structure to the Rigid Inclusions and to minimize ‘dimpling’ or excessive bending stresses in a slab or footing.

LTPs often consist of 1 to 5 feet of well compacted granular soil and may include 1 to 3 layers of embedded geogrid or steel mesh (under embankments / tanks).
LTP Design Overview

Collin’s Beam Method

**Bridging Layer Design**

RL column soil stabilization requires a load transfer platform (bridging layer) to evenly distribute structural and overburden stresses to all columns. The design methodology used herein is the Beam Method (Collin, 2007). A reference paper exploring the method, obtained from the proceedings of GeoDenver 2007 (ASCE), is attached.

As shown in Figure 1, the Beam Method uses multiple layers of geosynthetic to support the soil within the arch. A minimum of 3 layers are used. Each layer is designed to support the average volume of the soil pyramid below the arch that is contained within that layer.

HBI shall use a high-strength woven geotextile for layer "Geogrid 1", while layers "Geogrid 2" and "Geogrid 3" shall be either woven or extruded geogrid.

![Diagram](image)

**Figure 1.** Vertical spacing and geosynthetic lengths at each level within the soil arching zone, for Beam Method

For the Beam Method, all of the following checks must be OK:

- \( h_{max} = \frac{3(n+1)}{2}\) in layers at least 3 layers of geogrid
- \( h_{min} \geq \frac{3(n+1)}{2}\) at least 3 layers of geogrid
- \( h_{max} \leq \frac{3(n+1)}{2}\) min geogrid spacing is 6 inches
- \( h_{min} \leq \frac{3(n+1)}{2}\) max geogrid spacing is 8 inches
- \( h_{avg} = \frac{3(n+1)}{2}\) bridging layer thickness not less than half of clear spacing between RL's
- \( h_{avg} \leq \frac{3(n+1)}{2}\) arch should fully develop within the bridging layer

**Check Strength**

\[
T_{u} = \begin{cases} 1512 & \text{lb} \\ \frac{722}{F} & \text{lb/ft} \end{cases}
\]

- \( g_{1} = \text{Minifl Geotext H5400} \)
- \( g_{2} = \text{Minifl H50031} \)

- \( T_{u1} \)
- \( T_{u2} \)

- \( T_{u} \)

- \( T_{u} \) allowable geogrid tensile force, per linear foot

- \( \text{Check}_1 = \frac{T_{u} \leq T_{u1}}{\text{bottom layer - geotextile}} \)
- \( \text{Check}_2 = \frac{T_{u} \leq T_{u2}}{\text{2nd and 3rd layers - geotextile}} \)

**Check Serviceability (creep-limited strength at 5% strain)**

\[
T_{u} = \begin{cases} 1440 & \text{lb} \\ \frac{601}{R} & \text{lb/ft} \end{cases}
\]

- \( g_{1} = \text{Minifl Geotext H5400} \)
- \( g_{2} = \text{Minifl H50031} \)

- \( T_{u1} \)
- \( T_{u2} \)

- \( T_{u} \) creep-limited strength at 5% strain

- \( \text{Check}_1 = \frac{T_{u} \leq T_{u1}}{\text{bottom layer - geotextile}} \)
- \( \text{Check}_2 = \frac{T_{u} \leq T_{u2}}{\text{2nd and 3rd layers - geotextile}} \)
Numerical Analysis – Overall Design Approach

**Soil-RI-LTP Interaction**

- Accounts for the relative movement between:
  - LTP and RI
  - RI and Soil
- Load transfer between soil and RI

Locate neutral axes

Determine stress in RI

Total settlement and ‘dimpling’
Numerical Analysis – Overall Design Approach

- Stability of embankment or tank
- Lateral loads or bending moments on elements

How to model the discrete elements?
- Volume?
  - Change thickness
- Strength
  - Change material properties?
- Embedded pile option
Where did you put it?

What did you put into the ground?

How did you do it?
RI Load Testing

- Individual element tests
  - Use ASTM D1143 as guideline regarding measurement and spacing

What should the test load be?

This interaction does not occur during test
Apply true loading conditions to the system

Verify stress concentration in elements and anticipated settlement

Full Scale Embankment Test
Ohio River Bridge Project
ORB - Design Verification

Clay and Silt  Sand

LEGEND
- EARTH PRESSURE CELLS
- SETTLEMENT CELL
- PREMETERS
- (SUPER LOCATION)
- INFILTRATION CELL
- TIMBER STONE COLUMN

SBT Fr Normalized
MAI = 1
1990

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70

Gravelly Sand to Sand
Sand Mixture: Silty Sand to Sandy Silt
Silt Mixture: Clay Silt to Silty Clay
Clayey Clay to Silty Clay
Clayey Clay to Silty Clay
Clayey Clay to Silty Clay
Clayey Clay to Silty Clay
Clayey Clay to Silty Clay
Clayey Clay to Silty Clay
Clayey Clay to Silty Clay
Clayey Clay to Silty Clay

EP11 - EP24 LOCATED ABOVE PLATFORM

1" = 20'-0"
ORB – Test Embankment
Remote access to data
  - Settlement/PP response to loading
## ORB - Design versus Performance

<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>
</tr>
</thead>
<tbody>
<tr>
<td>12 x 12 SC</td>
<td>12’ Square</td>
<td>9.32”</td>
<td>6.88”</td>
<td>6.13”</td>
<td>-11%</td>
</tr>
<tr>
<td>10 x 10 SC</td>
<td>10’ Square</td>
<td>9.56”</td>
<td>6.56”</td>
<td>6.97”</td>
<td>+6%</td>
</tr>
<tr>
<td>9 x 9 SC</td>
<td>9’ Square</td>
<td>11.99”</td>
<td>7.02”</td>
<td>5.99”</td>
<td>-14%</td>
</tr>
<tr>
<td>8 x 8 SC</td>
<td>8’ Square</td>
<td>10.71”</td>
<td>5.91”</td>
<td>6.93”</td>
<td>+17%</td>
</tr>
<tr>
<td>8 x 8 RI</td>
<td>8’ Square</td>
<td>11.80”</td>
<td>2.26”</td>
<td>2.40”</td>
<td>+6%</td>
</tr>
</tbody>
</table>
RI Testing

- Individual elements may also be PIT tested
  - Qualitative check of RI integrity
  - PIT results may show indications of:
    - Necking
    - Bulging
    - Cracking
Rigid Inclusion Construction
RI System Installation Overview

1. Working platform preparation and control
2. RIs are installed using displacement method to advance the element and grouted on withdrawal of the tool
3. Tops of RIs are lowered (as needed)
4. Load transfer platform (LTP) is installed per design
How are RIs Installed?

- Generally installed using *displacement* methods
- Typical diameters range from 12-inches to 18-inches
RI Tooling

Displacement tooling benefits:

- Increases lateral stress in the subsurface
- Produces localized densification of granular soils
- Little spoil generated

http://www.giefoundation.com/products.html
Typical RI Equipment (Vibratory Method)

- Fixed/Telescopic Mast-style (e.g. ABI, RTG) rig is preferred configuration

- Can hang from a crane also,
  - Improved reach
  - But more difficult to maintain verticality
Typical RI Equipment (Vibratory Method)
Typical RI Equipment (Vibratory Method)
Typical RI Equipment
(Displacement Auger Method)

- Fixed/Telescopic Mast-style (e.g. ABI, RTG, Bauer, SoilMec) rig is preferred configuration
Typical RI Equipment
(Displacement Auger Method)

Traditional Auger Displacement Tooling
100% Single Pass Displacement

Traction Compacting Tool (TCT) Schematic
~50% Insertion / 50% Extraction Displacement
(16 inch diameter tooling)
Typical RI Equipment (Displacement Auger Method)

http://www.soilmec.com/en/displacementpiles
Typical RI Equipment

- **Piston-type Concrete Pump**
  - Selected for concrete/grout mix properties and productivity

- **Telehandler and/or Loader**
  - Unload trucks during mob / demob
  - Move concrete pump, hoses, misc.

- **Manlift**
  - For maintenance of RI rig
  - Need manlift to safely access drill head

- **Skid-steer / mini-excavator / track-hoe for LTP / dipper**
  - Heave and work-platform management
Rigid Inclusion QC/QA
Drill and Tooling

- Confirm proper diameter of displacement tool

- Match drill rig size, crowd force / torque / vibratory energy for subsurface conditions and refusal criteria. *Best selected by contractors.*
Rigid Inclusion QC/QA Installation

- Confirm Location and Verticality
- Monitor adjacent locations
  - Communication
    - Ground movement
    - Grout rise
    - RI top deflection
  - If there is communication, where does it occur? How much grout rise, etc.?
- Confirm Penetration Depth
  - Does it meet predetermined design depth
  - Does it meet refusal/termination criteria
Rigid Inclusion QC/QA
Grouting

- Calibrate the grout pump
- If non-pressurized system is used, grout must be maintained with proper head level to build continuous grout column
- If pressurized system is used, determine the line loss and grout pressures
- Continually check grout quantities vs. delivered quantities
  - Does this match the theoretical volume (plus waste) of our element?
- Daily slump tests and cylinder preparation
  - Slump is typically 4 to 8 inches, but will vary with tooling and soil type
  - 28 day strength matches design strength
HBI Data Acquisition System (DAQ)

- HBI DAQ system
  - Installed to any rig
  - On-screen depth, strokes, pen. rate, inclination, etc.
  - Electronic and paper QC reports
Rigid Inclusion QC/QA Finishing

- Understand top-of-RI elevations vs. bottom of working elevation and Load Transfer Platform
  - Impacts constructability and design function

- Perform cut offs while grout is wet / fresh (typical)
  - Can be done after, with care
Rigid Inclusion Finishing
Rigid Inclusion QC/QA
Work Platform / LTP

- Load Transfer Platform
  - Correct elevations
  - Correct material
  - Placed in proper lifts
  - Compacted
  - Proper thickness

- Low bearing pressure equipment only for LTP construction
  - Until first layers of LTP have been constructed

- Static compaction
  - Vibratory rollers may damage RI elements
Constructability Considerations

- **Obstructions** – Offset, excavate, pre-drill
  - Boulders, steel, utilities, remnant foundations
  - Existing embankments*

- **Refusal Criteria**
  - Must reflect site geology
  - Expect variability
  - Displacement sequence may impede advance of tools with time, especially in granular materials.
Constructability Considerations

- Avoid the need to excavate around the RI elements
  - Non-reinforced
  - Easily broken
  - Leave slightly low when possible and backfill with stone
Constructability Considerations

- **Spoil and/or waste control**
  - Not critical with displacement methods, but still should be considered

- **Ground heave**
  - Displacement methods will usually heave the site
  - Grading control necessary
Constructability Considerations

- Work platform almost always required
  - 150,000 lb. crawler machine (typical)
  - Over-the-road ready-mix trucks
Comments on Specifications

- Define performance requirements clearly
- Allow for adjustment of refusal criteria based on ground conditions
- Avoid definition of grout/concrete fluid properties
  - Allow contractor to match with tools and soil conditions
- Minimize time for review cycle(s)
Comments on Measurement and Payment

- Unit Pricing consistent with Work
  - Linear Feet for RIs (from working grade to refusal elevation)
  - Volume or area for platform/LTP work
  - Account for different diameters, as appropriate
  - Allow for the difference between conventional and reinforced elements
  - Pre-drilling is not incidental, add a unit price

- Recognize that the specialty RI contractor will design but NOT construct the LTP. Accommodate the complimentary scopes.
THINK SAFE
WORK SAFE
GO HOME SAFE