Overview of Pile Foundation Design & Construction - Chapt. 2 & 3
Aaron S. Budge, Ph.D., P.E.
A Little About Me!

- B.S. Utah State University - 1998
- M.S. Utah State University - 2000
- Ph.D. Utah State University and UT Austin – 2004
- Licensed Professional Engineer in MN – 2009
- Sabbatical Leave with BARR Engineering and MnDOT
- I LOVE being back in Logan!
A Quick Item of Interest - Foundations Utilized?

• MnDOT-funded survey to State DOT’s
• 41 out of 50 States eventually responded (with some prodding!)
• One of several questions – How much do states use driven piles, vs. drilled shafts, vs. shallow foundations for transportation applications?
• Of those 41 respondents, the following results were obtained…

(Full report available online through MnDOT)
### Results of the State DOT Setup Survey

1 – For transportation applications in your state, which of the following best describes the use of Driven Piles:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Description</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0%</td>
<td>Our agency never uses Driven Piles for transportation applications</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2%</td>
<td>Our agency rarely uses Driven Piles for transportation applications (AZ)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5%</td>
<td>Our agency occasionally uses Driven Piles for transportation applications (HI &amp; NV)</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>83%</td>
<td>Our agency often uses Driven Piles for transportation applications (LOTS)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10%</td>
<td>Our agency almost exclusively uses Driven Piles for transportation applications (ND, SD, IA &amp; WY)</td>
<td></td>
</tr>
</tbody>
</table>
Results of the State DOT Setup Survey

2 – For transportation applications in your state, which of the following best describes the use of Drilled Shafts:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0%</td>
<td>Our agency never uses Drilled Shafts for transportation applications</td>
</tr>
<tr>
<td>3</td>
<td>7%</td>
<td>Our agency rarely uses Drilled Shafts for transportation applications</td>
</tr>
<tr>
<td>22</td>
<td>54%</td>
<td>Our agency occasionally uses Drilled Shafts for transportation applications</td>
</tr>
<tr>
<td>16</td>
<td>39%</td>
<td>Our agency often uses Drilled Shafts for transportation applications (AZ, NV, HI, others)</td>
</tr>
<tr>
<td>0</td>
<td>0%</td>
<td>Our agency almost exclusively uses Drilled Shafts for transportation applications</td>
</tr>
</tbody>
</table>
3 – For transportation applications in your state, which of the following best describes the use of Shallow Foundations:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0%</td>
<td>Our agency never uses Shallow Foundations for transportation applications</td>
</tr>
<tr>
<td>8</td>
<td>20%</td>
<td>Our agency rarely uses Shallow Foundations for transportation applications</td>
</tr>
<tr>
<td>17</td>
<td>41%</td>
<td>Our agency occasionally uses Shallow Foundations for transportation applications</td>
</tr>
<tr>
<td>16</td>
<td>39%</td>
<td>Our agency often uses Shallow Foundations for transportation applications</td>
</tr>
<tr>
<td>0</td>
<td>0%</td>
<td>Our agency almost exclusively uses Shallow Foundations for transportation applications</td>
</tr>
</tbody>
</table>
Design Considerations

- Insertion of piles generally alters soil character, and intense stresses are set up near piles
- Complex soil-pile interaction

*Therefore, it is necessary to use practical, semi-empirical design methods*
Solution Requires Thorough Information & Understanding of:

1. Foundation loads
2. Subsurface conditions & soil/rock properties
3. Current practices in pile design & construction
Strength Considerations

Two Failure Modes

1. Pile structural failure
   - controlled by allowable stresses

2. Soil (geotechnical) failure
   - controlled by factor of safety

In addition, the ability to drive the pile, evaluated by wave equation
Serviceability Considerations

- Factors arising from the action of service loads
  - i.e., Settlement
Establish Requirements for Structural Conditions and Site Characterization

Obtain General Site Geology

Collect Foundation Experience From Area to Identify Possible Foundation Types

Determine Preliminary Substructure Loads and Load Combinations at Foundation Level

Develop and Execute Subsurface Exploration and Laboratory Testing Program

Evaluate Information and Determine Foundation Systems for Further Evaluation

Deep Foundations

Shallow Foundations - w/o Ground Improvement - with Ground Improvement

Select Candidate Driven Pile Foundations Types and Sections For Further Evaluation

Evaluate Other Deep Foundation Systems
9. Select Static Analysis Method and Calculate Ultimate Axial Capacity vs Depth

10. Plot and Evaluate Ultimate Capacity vs Depth and Cost per MN vs Depth to Identify Most Economical Candidate Piles

11. Driveability of Candidate Pile Types to Pile Penetration Depth(s) and Ultimate Capacity Sufficient?

- Yes
  - 12. Select 1 to 2 Candidate Pile Types, Ultimate Capacities and Pile Penetration Depths for Trial Pile Group Sizing

- No
  - Return to Block 8

13. Evaluate Group Capacity, Settlement, Performance, and Cost of Trial Pile Group Configurations

14. Size and Estimate Cost of Pile Cap for Trial Groups

15. Summarize Total Cost of Candidate Pile Types, Group Configurations and Pile Caps

16. Select and Optimize Final Pile Type, Ultimate Capacity and Group Configuration

Continued on Next Page
Does Optimized Design Meet Performance, Constructability and Driveability Requirements?

Prepare Plans and Specifications Including Field Capacity Determination Procedure

Contractor Selection

Perform Wave Equation Analysis of Contractor's Equipment Submission, Accept or Reject

Drive Test Piles and Evaluate Capacity

Adjust Driving Criteria or Design

Construction Control. Drive Production Piles, Resolve Any Pile Installation Problems

Post-Construction Evaluation and Refinement for Future Designs

Return to Block 12

Foundation Design Process (3 of 3)


**Design Phase**

1. Collect and Evaluate Design Information
2. Perform Pile Design Including Driveability
3. Prepare Specifications and Select Contractor
4. Evaluate Equipment
5. Verify Capacity
6. Drive Production Piles

**Construction Phase**

**Foundation Design Process (condensed)**
Types of Lab Tests

- Soil classification & index
- Shear strength
- Consolidation
- Electro chemical classification
ESTABLISHMENT OF A NEED FOR PILE FOUNDATION
SITUATIONS WHERE A DEEP FOUNDATION IS NEEDED

(a) Rock

(b) Soft Strata

(c)

(d)
SITUATIONS WHERE A DEEP FOUNDATION IS NEEDED

(e)  

(f)  

(g)  

(h)
SITUATIONS WHERE A DEEP FOUNDATION IS NEEDED
SELECTION OF PILE TYPE AND SIZE FOR FURTHER STUDY
STATIC ANALYSIS METHODS

Static analysis methods and computer solutions are used to:

- Calculate pile length for loads
- Determine number of piles
- Determine most cost-effective pile type (\( \$ / \text{ton} \))
- Calculate foundation settlement
- Calculate performance under uplift & lateral loads
STATIC ANALYSIS METHODS

Static analysis methods and computer solutions are an integral part of the design process.

Static analysis methods are necessary to determine the most cost-effective pile type.

For a given pile type:
- calculate capacity
- determine pile length
- determine number of piles

Bid Quantity
EXAMPLE SOIL PROFILE

Layer 1
SAND
(subject to scour)

Layer 2
SOFT CLAY
(unsuitable)

Layer 3
SUITABLE
SUPPORT
MATERIALS

Embedded Pile Length, D

Q_u

R_s1

R_s2

R_s3

R_t
The Commonly Referenced Factor of Safety Relates To Slip Of The Pile Relative To The Soil Without Structural Failure In The Pile
The factor of safety used in a static analysis should be based on the construction control method specified.

<table>
<thead>
<tr>
<th>Construction Control Method</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static load test with wave equation analysis</td>
<td>2.00</td>
</tr>
<tr>
<td>Dynamic testing with wave equation analysis</td>
<td>2.25</td>
</tr>
<tr>
<td>Indicator piles with wave equation analysis</td>
<td>2.50</td>
</tr>
<tr>
<td>Wave equation analysis</td>
<td>2.75</td>
</tr>
<tr>
<td>Gates dynamic formula</td>
<td>3.50</td>
</tr>
</tbody>
</table>
Stress Zones from a Single Pile and Pile Group

a.) Single Pile
b.) Pile Group
Special Design Considerations

- Negative Shaft Resistance or Downdrag
- Lateral Squeeze
- Scour
- Soil and Pile Heave
- Seismic Considerations
Additional Design Considerations

- Time effects on pile capacity
- Effects of predrilling, jetting, and vibratory hammer use on capacity
- Effects of site dewatering on pile capacity
- Densification effects on pile capacity
- Plugging of open pile sections
- Pile-driving-induced vibrations and noise
- Pile driveability
PILE DRIVEABILITY

Pile driveability should be checked during the design stage for all driven piles.

Pile driveability is particularly critical for closed-end pipe piles.
PILE DRIVEABILITY EVALUATION DURING DESIGN STAGE

1. Wave Equation Analysis
   Computer analysis that does not require a pile to be driven.

2. Dynamic Testing and Analysis
   Requires a pile to be driven and dynamically tested.

3. Static Load Tests
   Requires a pile to be driven and statically load tested.
Parts of a Foundation Report

- Table of contents
- Introduction
- Scope of explorations
- Interpretation of subsurface conditions
- Design soil parameters
- Design analysis
- Geotechnical conclusions & recommendations
- Construction considerations
- Appendices & graphical presentations
Project Plans

- Location of piles
- Designation to identify piles
- Pile cutoff elevation
- Est. pile toe elevation
- Min. pile toe elevation
- Required pile batter & direction
- Orientation of H-Piles
- Ultimate pile capacity
- Location of soil borings
- Results of subsurface exploration
Pile Specs - Major Sections

- Pile material
- Driving system
- Pile installation
- Method of determining capacity
- Method of measurement (payment)
Construction Considerations

- Success depends largely on relating static analysis results to dynamic methods of field installations.

- Pile must be driven to a resistance, or predetermined length.

- Avoid pile damage by excessive driving.
Construction Considerations (cont.)

- Knowledge supervision & inspection is **KEY** to proper installation

- Post construction review of driving results vs. predictions of blow count, pile lengths, field problems, etc. is essential
**Construction Phase**

1. Contractor Selection
2. Perform Wave Equation Analysis of Contractor’s Equipment Submission, Accept or Reject
3. Drive Test Piles and Evaluate Capacity
4. Adjust Driving Criteria or Design
5. Construction Control. Drive Production Piles, Resolve Any Pile Installation Problems
6. Post-Construction Evaluation and Refinement for Future Designs
Dynamic Soil Resistance =
Static Resistance + Damping Force

Static Resistance Component is the Capacity Developed by the Pile to Resist Static Loads

Both Components Must be Considered in a Drivability Analysis
Dynamic Formula or Wave Equation
Dynamic Test
Inspection of Pile Installations

<table>
<thead>
<tr>
<th>FEET</th>
<th>BLOWS</th>
<th>STROKE / PRESSURE</th>
<th>REMARKS</th>
<th>FEET</th>
<th>BLOWS</th>
<th>STROKE / PRESSURE</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>55-56</td>
<td></td>
<td></td>
<td>1-2</td>
<td>55-57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>57-58</td>
<td></td>
<td></td>
<td>3-4</td>
<td>58-59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-5</td>
<td>59-60</td>
<td></td>
<td></td>
<td>5-6</td>
<td>60-61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-7</td>
<td>61-62</td>
<td></td>
<td></td>
<td>7-8</td>
<td>62-63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-9</td>
<td>63-64</td>
<td></td>
<td></td>
<td>9-10</td>
<td>64-65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-11</td>
<td>65-66</td>
<td></td>
<td></td>
<td>11-12</td>
<td>66-67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-13</td>
<td>67-68</td>
<td></td>
<td></td>
<td>13-14</td>
<td>68-69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-15</td>
<td>69-70</td>
<td></td>
<td></td>
<td>15-16</td>
<td>70-71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16-17</td>
<td>71-72</td>
<td></td>
<td></td>
<td>17-18</td>
<td>72-73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18-19</td>
<td>73-74</td>
<td></td>
<td></td>
<td>19-20</td>
<td>74-75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-21</td>
<td>75-76</td>
<td></td>
<td></td>
<td>21-22</td>
<td>76-77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22-23</td>
<td>77-78</td>
<td></td>
<td></td>
<td>23-24</td>
<td>78-79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24-25</td>
<td>79-80</td>
<td></td>
<td></td>
<td>25-26</td>
<td>80-81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26-27</td>
<td>81-82</td>
<td></td>
<td></td>
<td>27-28</td>
<td>82-83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-29</td>
<td>83-84</td>
<td></td>
<td></td>
<td>29-30</td>
<td>84-85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30-31</td>
<td>85-86</td>
<td></td>
<td></td>
<td>31-32</td>
<td>86-87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32-33</td>
<td>87-88</td>
<td></td>
<td></td>
<td>33-34</td>
<td>88-89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34-35</td>
<td>89-90</td>
<td></td>
<td></td>
<td>35-36</td>
<td>90-91</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PILE SUPPLIER: PILE CAST OR ROLLING DATE:
PILE TOE ATTACHMENTS: FINAL PILE HEAD CONDITION:
FINAL ALIGNMENT: FINAL PLUMBINESS: INTERNAL INSPECTION:
INSPECTORS NAME AND SIGNATURE:
Proper construction control requires effective communication between the Design and Field Engineers.

Variations of pile items from plans & specs should be discussed with the Designer.

Feedback of construction monitoring data to the Design Engineer is necessary.
## CONSTRUCTION-STAGE COMMUNICATION

<table>
<thead>
<tr>
<th>Subject</th>
<th>Structural</th>
<th>Geotechnical</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establish Appropriate Methods of Construction Control and Quality Assurance.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Perform Wave Equation Analysis of Contractors Driving System to Establish Driving Criteria.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Perform Static Load Test(s) and/or Dynamic Monitoring and Adjust Driving Criteria.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Resolve Pile Installation Problems / Construction Issues.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>