Soil-Foundation-Superstructure Interaction for Combined Piled-Raft Foundations

MIDAS Geotechnical Engineering Seminar

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Soil-Foundation-Superstructure Interaction for Combined Piled-Raft Foundations

Part 1. Definitions ........... 02
Part 2. Process of Foundation Design ........... 10
Part 3. Soil Modeling for Structural Design ........... 15
Part 4. Pile Foundation Modeling ........... 24
Part 5. Case Study ........... 57
Part 6. Final Remarks ........... 83
Definitions

Foundation Differential Settlements

- Differential settlements due to gravity loads
- For tall towers even small differential settlements can offset the top by meters and overstress the structure
- A special study is needed to determine differential settlements
Soil Modeling for Structural Design

Structural Approach
Winkler Springs Model

Geotechnical Approach
Continuum Model
Raft Foundations

• A raft consists of a reinforced-concrete slab that supports the columns and walls of a structure, and distributes the loads to the underlying soils.

• Raft foundations are considered when:
  – Individual footings cover more than about half of the building area.
  – Total and differential settlements are too high.
Combined Pile-Raft Foundations

- Combined Pile-Raft foundations are considered when:
  - Settlements and differential settlements are too high when using only raft foundations.
Definitions

Piled Raft - Overview

• Combination of raft + piles
  – Raft to provide adequate bearing
  – Piles to reduce total and differential settlements

• Piled-raft consists of a limited number of piles strategically located below heavily loaded area (e.g.: shear walls)
Piled Raft - Overview

Kuala Lumpur, Malaysia

Brooklyn, N.Y., US

Brooklyn, N.Y., US

Kuala Lumpur, Malaysia
Settlement Comparison between Raft only and Piled-Raft

- Project: Brooklyn, N.Y., US

Raft Only
Max $\Delta / L = 1/335$

Piled-Raft
Max $\Delta / L = 1/630$
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Project Team for Towers

- Developer
- Architect
- Structural Engineer
- Geotechnical Engineer

+ 

- Local Consultants
- Peer Reviewers
- Specialty Foundation Contractors
Developing Foundation System

- Geotechnical Investigation
- Structural Engineer Provides Initial Tower Loads
- Initial Studies (Bearing Capacity, Settlement) by Geotechnical Engineer
- Refinement of Studies (Determine Constructability, Iterative Process between Structural + Geotechnical Engineer)
- Peer Review Process
- Contractor Selection Process
- Local Authorities Approval Process
Iterative Process General Steps - RAFTS

- COLUMN LOADS
- WINKLER SPRINGS, FOUNDATION SETTLEMENTS + STRESSES
- REVISED FOUNDATION SETTLEMENTS + STRESSES
- NEW WINKLER SPRINGS, NEW FOUNDATION SETTLEMENTS + STRESSES

Structural Engineer → Geotechnical Engineer

Structural Engineer

Geotechnical Engineer
Iterative Process – Combined Pile-Rafts

In addition to Raft Settlements, require convergence on

• Pile Loads
• Pile/Subgrade Load Sharing
• Column/Wall Loads
### Soil-Foundation-Superstructure Interaction for Combined Piled-Raft Foundations

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Soil Modeling for Structural Design

Structural Approach
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Elastic Space

Inelastic Space
Determination of Soil Springs (K-value)

- The K-value (a.k.a. Winkler Spring or Modulus of Subgrade Reaction) is the ratio of pressure over displacement

\[ K = \frac{p}{\delta} \]
Foundation Response

• Significant differences in response between Winkler and Continuum models.
  – Contact pressure beneath “rigid” foundations
  – Settlements beneath “flexible” foundations
Foundation Response – Rigid Raft

Structural Approach
Winkler Springs Model

Geotechnical Approach
Continuum Model

\[ p = kw \]

Settlements

Stress Distribution
Foundation Response – Flexible Raft

Winkler

\[ w = \frac{p}{k} \]

Continuum

Settlements

Stress Distribution

\[ E, \nu \]
Foundation Response

• Solution:
  - Stiffness of outermost springs should be increased to account for increase in soil rigidity.
  - For “stiff” soil, outer springs may increase 30-40%.
  - For “soft” soil, they may need to increase 2-3 times!
Determination of Modulus of Subgrade Reaction (K-value)

- The K-value can be obtained through:
  - **Method A**: Plate load tests
  - **Method B**: Tables of typical values / correlations (based on plate load tests)
  - **Method C**: Modeling of the loaded foundation
Determination of Modulus of Subgrade Reaction (K-value) – Method C

- Estimate settlements and bearing pressures at many points within the raft
- Determine the K-value from:
  \[ K = \frac{p}{\delta} \] (pressure/settlement)
- Draw K-value contours
- If piles are present, pile springs can be determined as pile force/pile settlement at the pile locations
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Line-to-Solid Interface Elements for Pile Foundation Modeling
Approaches:

**Three pile modeling approaches are available:**

- Solid Element Model
- Beam-Solid Connectivity Model
- Line-to-Solid Interface Model
Solid Element Model

Model = Soil (solid) + Pile (solid) + Interface (surface)

Nodal connectivity is required on pile outer surface
Solid Element Model

Surface interface elements for solid-to-solid connection:

(a) topology  (b) displacements

Drawbacks of solid element models:

- Model definition and mesh-generation are elaborate.
- Many elements in model → large computation times.
- Pile forces and moments are not directly available in post-processing.
Beam-Solid Connectivity Model

Model = Soil (solid) + Pile (beam) + Interface (line)

Nodal connectivity is required along pile length
Beam-Solid Connectivity Model

Line interface elements for beam-to-solid connection:

(a) topology  
(b) displacements

Drawbacks of beam-solid element models:

- The nodal compatibility requirement makes geometry modeling and meshing of the soil elaborative.
- For piled rafts with large number of piles, this technique produces large models $\rightarrow$ large computation times.
Line-to-Solid Interface Model

Model = Soil (solid) + Pile (beam) + Interface (line-to-solid)

No Nodal connectivity required
Line-to-Solid Interface Element for Shaft Friction

Line-to-solid interface elements for beam-to-solid connection:

Characteristics of line-to-solid interface modelling in GTS:

- Pile and soil geometries and meshes can be specified independently
- Intersections of line and solid elements are calculated automatically
- Nonlinear friction-slip properties for line-solid interface elements
- Mesh refinement requirements for the soil are minimum → reduced computation time
Point-to-Solid Interface Element for Pile Tip Capacity

Model = \text{Soil (solid)} + \text{Pile (beam)} + \text{Interface (point-to-solid)}

The pile tip can be arbitrarily placed in the solid element.

It acts as an orientated spring connecting the soil to the pile tip.
## Comparison of 3 Approaches for Shaft Friction

<table>
<thead>
<tr>
<th></th>
<th>Solid Elements</th>
<th>Beam-Solid Connectivity</th>
<th>Line-to-Solid Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface type</td>
<td>Surface</td>
<td>Line</td>
<td>Line-to-solid</td>
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<tr>
<td>Nodal connectivity</td>
<td>Required</td>
<td>Required</td>
<td>Not required</td>
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<tr>
<td>Shear law</td>
<td>Coulomb friction</td>
<td>Relation between friction force per meter and slip displacement</td>
<td>Relation between friction force per meter and slip displacement</td>
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<tr>
<td></td>
<td>plasticity</td>
<td></td>
<td></td>
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<tr>
<td>Friction stress –</td>
<td>Local</td>
<td>Averaged over circumference</td>
<td>Averaged over circumference</td>
</tr>
<tr>
<td>Slip disp.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transversal behaviour</td>
<td>Gap opening</td>
<td>Rigid</td>
<td>Rigid</td>
</tr>
<tr>
<td></td>
<td>possible</td>
<td>(high elastic stiffness)</td>
<td>(high elastic stiffness)</td>
</tr>
<tr>
<td>Variation over pile</td>
<td>Considered</td>
<td>Not considered</td>
<td>Not considered</td>
</tr>
<tr>
<td>circumference</td>
<td></td>
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</table>
### Comparison of 3 Approaches for Pile Tip Capacity

<table>
<thead>
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<th>Solid Elements</th>
<th>Beam-Solid Connectivity</th>
<th>Line-to-Solid Interface</th>
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</thead>
<tbody>
<tr>
<td><strong>Interface type</strong></td>
<td>Surface</td>
<td>Point spring</td>
<td>Point-to-solid</td>
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<tr>
<td><strong>Nodal connectivity</strong></td>
<td>Required</td>
<td>Required</td>
<td>Not required</td>
</tr>
<tr>
<td><strong>Tip failure</strong></td>
<td>Relying on soil plasticity (high refinement required!)</td>
<td>Relation between tip reaction force and tip settlement</td>
<td>Relation between tip reaction force and tip settlement</td>
</tr>
<tr>
<td><strong>Bearing stress – Settlement disp.</strong></td>
<td>Local</td>
<td>Averaged over tip surface</td>
<td>Averaged over tip surface</td>
</tr>
<tr>
<td><strong>Transversal behaviour</strong></td>
<td>Coulomb friction over pile section</td>
<td>Slipping</td>
<td>Slipping</td>
</tr>
<tr>
<td><strong>Variation over Tip surface</strong></td>
<td>Considered</td>
<td>Not considered</td>
<td>Not considered</td>
</tr>
</tbody>
</table>
Pile Foundation Modeling

Automatic creation of line-to-solid interface elements in GTS

After meshing pile lines with a single beam element per pile, use the “Create Pile” function

Define pile-soil friction properties and pile tip bearing capacity

Create an attribute for the pile-soil friction interface

Model> Element > Create Pile...
Pile-soil friction law

**Input parameters:**

- **Ultimate shear force,** \( q_u \) [kN/m]
  per unit length of the pile, at reference depth.

- **Shear Stiffness Modulus,** \( K_t \) [kPa]
  Linear elastic penalty stiffness of the interface in the longitudinal direction of the pile.

- **Normal Stiffness Modulus,** \( K_n \) [kPa]
  Linear elastic penalty stiffness of the interface in the transversal direction.

- **Reference depth** for which the diagram as defined above is applicable

- **Slope of Friction-Rel. Disp. Curve,** \( S \) [kPa]

\[
S = \frac{q_u^{z_1} - q_u^{z_0}}{z_1 - z_0}
\]
Pile tip law

Input parameters:

- Tip Bearing Capacity, $Q_u$ [kN]
  Maximum bearing force allowed at the pile tip.

- Tip Spring Stiffness, $K_s$ [kN/m]
  Initial elastic stiffness used before pile tip failure.

- Function:
  Alternative option to ‘Tip Spring Stiffness’. It defines a multi-linear relation between the normalized tip reaction force and the relative axial displacement between the pile tip and the soil elements. The pile tip law is then based on the force-displacement diagram resulting from the multiplication of this normalized function (unit insensitive) by the specified tip bearing capacity (unit sensitive).
Piled foundation of a bridge pier

Exercise 5
1. Introduction

**Function Overview**

- Insert piles using the embedded pile concept (incompatible meshes)
- Connect piles to the pier footing
- Add loads and boundary conditions
- Define construction stage analysis
- Run analysis
- Investigate results

**Starting File Required**

- Bridge Pier on Piles_(Start).gtb
### 3. Specification of soil-pile interface

#### Values to be used in Exercise

<table>
<thead>
<tr>
<th>Property</th>
<th>Pile Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Pile</td>
</tr>
<tr>
<td>Ultimate Shear Force [kN/m]</td>
<td>1,000</td>
</tr>
<tr>
<td>Shear Stiffness Modulus, $K_n$ [kPa/m]</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Normal Stiffness Modulus, $K_n$ [kPa/m]</td>
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</tr>
<tr>
<td>Reference Depth</td>
<td>deactivated</td>
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<tr>
<td>Slope of Friction-Rel_DISP.Curve</td>
<td>deactivated</td>
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<tr>
<td>Function</td>
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<tr>
<td>Tip bearing capacity [kN]</td>
<td>500</td>
</tr>
<tr>
<td>Tip Spring Stiffness [kN/m]</td>
<td>1,000,000</td>
</tr>
</tbody>
</table>
4. Specification of pier-pile interface

Values to be used in Exercise

<table>
<thead>
<tr>
<th>Property</th>
<th>Pile Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Pile</td>
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<tr>
<td>Ultimate Shear Force [kN/m]</td>
<td>1.0E+10</td>
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<tr>
<td>Shear Stiffness Modulus, $K_n$ [kPa/m]</td>
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</tr>
<tr>
<td>Normal Stiffness Modulus, $K_n$ [kPa/m]</td>
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<tr>
<td>Reference Depth</td>
<td>deactivated</td>
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<tr>
<td>Slope of Friction-Rel.Disp.Curve</td>
<td>deactivated</td>
</tr>
<tr>
<td>Function</td>
<td>Not used</td>
</tr>
<tr>
<td>Pile Tip Spring</td>
<td>Not used</td>
</tr>
</tbody>
</table>
5. Complete pre-processing

Mesh piles with beam elements

1. Hide all Mesh and Geometry and show pile curves only

Right click on Curves > Show all

2. Open "Bridge Pier on Piles_(Start).gtb"

Mesh > Auto Mesh > Edge...
Insert pile-soil friction interface elements

Select the 12 beam elements just created

Define pile-soil interface properties according to slide 5

Create an attribute for the pile-soil interface

Model > Element > Create Pile...

Note:
Pile creation can take some computing time as intersections with soil elements are calculated, piles are divided accordingly and line-to-solid interface elements are inserted.
Define properties of stiff connection between pile heads and pier footing

4. Copy and Modify the soil-pile interface properties to define the pier-pile interface properties

5. Copy and Rename (Modify) the soil-pile interface attribute to create the pier-pile interface attribute
Assign pile-pier interface properties for elements embedded in the pier footing

- Change interface element properties in pier footing
- Set the filter to 1D element
- Show only the pier and Friction-Interface Mesh sets
- Select the interface elements inside the pier footing (41 elements)

Model> Element > Change Parameter...
Pile Foundation Modeling

Define Loads

Gravity Load

Model > Load > Self Weight...

Self Weight

Load Set: Gravity

Self Weight Factor:
- X: 0.0000
- Y: 0.0000
- Z: -1.0000

Repeat the operation with the second pad specifying 2000 kPa

Model > Load > Pressure Load...

Hide all mesh sets and display pier solid only (geometry item).
Define non-symmetric pressure loads on pier bearing pads.
Apply 3000 kPa on the left pad.
Define Construction stages

11  Stress initialization

12  Pier construction and loading

Model > Construction Stage > Define Construction Stage...

The water level is not activated as dry conditions are assumed
Define analysis case and Run

13

Analysis > Analysis Case...

Add/Modify Analysis Case

Analysis Type: Construction Stage

Analysis Control

Construction Stage

Initial Stage for Stress Analysis

Restart Option

The analysis takes about 10 minutes to run
Vertical displacements [cm] in cross-section after bridge construction and loading
Settlement bowl [cm] – top view
Axial forces in piles
Pile Foundation Modeling

Bending moments $M_y$ in piles

[UNIT] kN, m
[DATA] CS: settlement analysis, Bridge construction-Last Step, Beam $M_y$
Shaft friction forces $q_x$ along piles
Soil-pile relative displacement $D_{u_x}$ along piles
### Pile Foundation Modeling

#### Local Traction

<table>
<thead>
<tr>
<th>TX, kN/m</th>
<th>Value</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>+5.00000e+002</td>
<td>33.3%</td>
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<tr>
<td>+4.65488e+002</td>
<td>0.0%</td>
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<tr>
<td>+4.30976e+002</td>
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<tr>
<td>+4.04650e+002</td>
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<td>+2.92929e+002</td>
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<tr>
<td>-1.76770e+001</td>
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<tr>
<td>-5.21888e+001</td>
<td>8.3%</td>
<td></td>
</tr>
</tbody>
</table>

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*Pile tip reaction forces Q_x*
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Geotechnical Investigation

- Geotechnical Borings
- In-situ Testing (i.e., SPT, Pressuremeter Tests)
- Laboratory Tests (Index properties, Triaxial, 1-D Consolidation, etc)
- Geophysical Methods
Model Parameter Selection

Determine **critical** parameters such as

- Raft thickness
- Locations, geometry of piles
- Soil Modulus of deformation
- Method of construction
- Pile/Soil interface strength
Hand Calculations

Method 1 - Fully-Grouted Foundation (2/3-1/3)

\[ \delta = 48 \text{ m} \]

Pressure & equivalent unit

\[ \delta_2 = \delta_1 \frac{A_1}{A_2} = 1.4 \times \frac{48}{90} \Rightarrow \]

\[ \Rightarrow \delta_2 = 0.34 \text{ MPa} \]

\[ \delta \approx 0.5 \times \delta_2 \times \frac{D_2}{E} \approx 0.5 \times 0.34 \times 98 \Rightarrow \]

\[ \Rightarrow \delta \approx 19 \text{ mm} \]

Method 2 - "Buter" Method (use pile skin friction)

\[ \delta = 48 \text{ m} \]

Equivalent pressure \( \delta_2 \) on pile tip.

\[ \delta_2 = \frac{\sin A_1 - \frac{D_2}{2} \times 0.75}{A_1} \Rightarrow \]

\[ \Rightarrow \delta_2 = 1.4 \times \frac{83}{15} \times 0.48 \Rightarrow \]

\[ \Rightarrow \delta_2 = 0.16 \text{ MPa} \]

\[ \delta \approx 0.5 \times 0.66 \times \frac{98}{150} \Rightarrow \]

\[ \Rightarrow \delta \approx 115 \text{ mm} \]
Finite Element Modeling

Input

- Geometry (raft, piles, stratigraphy)
- Material Properties (raft, piles, stratigraphy)
- Element Selection (Volume, area, line elements)
- Boundary Conditions
- Loading (Construction Staging, Self Weight, Tower Loads)
Case Study

RAFT: ~40m x 60m x 4m
PILES D=2m, L=75m
Typical Soil/Rock Constitutive Models

Soil
- Elastic \((E, \nu, \text{unit weight})\)
- Mohr-Coulomb (friction angle, cohesion)
- Modified M-C/Soil Hardening
- Soft Soil/ Modified Cam-Clay

Rock
- Elastic \((E, \nu, \text{unit weight})\)
- Mohr-Coulomb (friction angle, cohesion)
- Hoek-Brown
Typical Structure Models

Raft
- Elastic (E, ν, unit weight), Volume Elements
- Plate Elements (thickness)

Piles
- Volume Elements (w or w/o interface)
- Beam Elements (w or w/o interface)
- Embedded Beam Elements w interface
Typical Loading Conditions

- Soil/Foundation Self Weight
- Column/Wall Loads as
  - Point Loads
  - Line Loads
  - Pressure Loads
- Foundation Construction Stages
Settlement Results

~100mm

~35mm
Settlement Results

40 m

70 m
Soil Subgrade Stresses
Vertical Strains (Block Behavior)
Pile Settlements
Pile Axial Loads
Pile-Soil Relative (Slip) Displacement
Soil/Pile Springs Determination

- Determine Pile Springs (Reaction/Settlement)
- Determine Area Springs (Pressure/Settlement)
- Determine Pile/Raft Load Share
- Provide the above to Structural Engineer
Pile Loads + Settlements

Pile Loads

Raft Settlements
Case Study

Soil/Pile Springs

PILE SPRINGS

AREA SPRINGS

7.1 MN/m³
2.6 MN/m³
6.4 MN/m³
4.3 MN/m³
5.2 MN/m³
Winkler Springs Adjustment

Based on Structural Engineer’s

- Settlements
- Subgrade Stresses
- Pile Loads
- Pile/Raft Load Sharing
- Wall Loads

Re-run Foundation Model + adjust Area and Pile Springs appropriately
Comparisons: Iteration 1

Percent Change in Pile Load

Pile Loads > 20%
Settlements > 20%

Percent Difference in Settlements
Comparisons: Iteration 2

Percent Change in Pile Load

Pile Loads > 20%
Settlements >10%
Wall Loads >10%

Percent Difference in Settlements
Comparisons: Iteration 3

Pile Loads > 5%
Settlements >5%
Wall Loads >10%

Percent Change in Pile Load

Percent Difference in Settlements
Comparisons: Iteration 4

Pile Loads > 5%
Settlements >5%
Wall Loads <10%

Percent Change in Pile Load

Percent Difference in Settlements
Comparisons: Iteration 5

Pile Loads ~5%
Settlements ~5%
Wall Loads <10%
Shear-Wall Load Changes

RAFT EDGES

RAFT CENTER

Normalized Wall Load vs. Shear Wall #

Normalized Wall Load

1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39

STEP 1

STEP 3
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FINAL REMARKS

• The iterative process gives insight on the redistribution of column/wall loads.
• The redistribution is more pronounced when the superstructure is “stiff” compared to the foundation.
• The redistribution may necessitate “stiffening” the foundation.
Thank you!