Efficient modelling of pile foundations in the Finite Element Method

Ronald B.J. Brinkgreve
Plaxis / Delft University of Technology

Outline

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Introduction

Finite Element Method (FEM) in geotechnical engineering:

- Numerical solution of boundary value problems:
  - Deformation (stress, strain) analysis (SLS) and ULS design
  - Groundwater flow analysis
  - (Geo)thermal analysis
  - Thermo-Hydro-Mechanical coupling

- Realistic simulation of soil, structure, soil-structure interaction and construction process
Introduction

FEM modelling piles:

- **2D:**
  - Axisymmetry: Axially loaded single pile
  - Plane strain: Pile (beam) becomes a wall
  - New: *Embedded pile row* in 2D

- Most practical applications involving pile foundations require a 3D model!

Introduction

Modelling options of piles in 3D FEM:

- **Solid elements:**
  - ‘Expensive’
  - Poor mesh quality
  - No structural forces

- **Beam elements:**
  - No pile volume
  - No surface area
  - Unrealistic pile-soil interaction
Introduction

Embedded pile (3D)

Efficient 3D modelling feature: Embedded pile elements

- Pile as beam elements
- Pile-soil interaction (shaft friction, end bearing)
- Arbitrary crossing of soil elements
Embedded pile (3D)

Skin stiffness:
- $k_s$: axial stiffness
- $K_n,k_t$: lateral stiffness

Skin tractions:
- $t_s = q_s / \text{length} = k_s (u^s_{pile} - u^s_{soil}) \leq t_{\max}$
- $t_n = q_n / \text{length} = k_n (u^n_{pile} - u^n_{soil})$
- $t_t = q_t / \text{length} = k_t (u^t_{pile} - u^t_{soil})$

Base stiffness:
- $k_b$: base/foot stiffness

Base/Foot force:
- $F_b = k_b (u_b^s_{pile} - u_b^s_{soil}) \leq F_{\max}$

Embedded pile:

- Beam nodes: Real nodes; 6 d.o.f’s per node ($u_x, u_y, u_z, r_x, r_y, r_z$)
- Interface nodes: Virtual nodes, 3 d.o.f’s per node ($u_x, u_y, u_z$), expressed in volume element shape functions
Embedded pile (3D)

Bearing capacity = \( \frac{1}{2} (T_{top} + T_{bot}) \times L_{pile} + F_{max} \)

Embedded pile – Deformation behaviour

Pile bearing capacity is *input* and not result of FEM calculation

Global pile response from soil modelling and pile-soil interaction
Embedded pile – Elastic region

- Around shaft
- Around foot

Soil stress points inside elastic region are forced to remain elastic

Embedded pile – Output

Displacements, bending moments, axial forces, shaft friction, foot force
Embedded pile – Validation by TUGraz (Tschuchnigg, 2009)

2D model: 72 mm

3D model - volume piles: 70 mm

3D model - embedded piles: 74 mm
Embedded pile – Validation by TUDelft (Dao, 2011)

Lateral movement of pile in horizontal soil slice:
- Embedded pile almost behaves as volume pile due to elastic region

Lateral force at pile top:
- Graph showing bending moment and pile depth with three curves indicating different scenarios:
  1. Volume pile without interface
  2. Volume pile with interface
  3. Embedded pile model

Images and graphs illustrating the concepts described.
**Embedded pile (3D)**

Conclusions embedded pile:

- Efficient 3D modelling of pile foundations (bored piles, piled rafts)
- Realistic pile-soil interaction (shaft friction, end bearing, group effects)
- Pile capacity is *Input* (not a result)
- Since 2005 many applications in practice (pile foundations, ground anchors)

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**Embedded pile row (2D)**

How to model a row of piles (out-of-plane) in 2D?
Embedded pile row (2D)

‘Conventional’ 2D options:

- Beam (plate):
  - Continuous out-of-plane
  - Prevents ‘soil flow’ between piles

- Two-node spring (N2N anchor):
  - No bending stiffness
  - No pile-soil interaction

Embedded pile row (2D)

New 2D modelling option:

- Embedded pile row:
  - Continuous ‘soil’ mesh
  - Pile as a superimposed beam element (axial stiffness, bending stiffness)
  - Pile and soil can move independently
  - Pile-soil interaction (interface) (shaft friction, end bearing)
  - Out-of-plane spacing (Ls)
Embedded pile row (2D)

Calibration of interface stiffness from 3D calculations

(Sluis, 2012)
Embedded pile row (2D)

Calibration of interface stiffness from 3D calculations

(out-of-plane)
Embedded pile row (2D)

Case study: Bridge abutment

Comparison 2D vs. 3D

3D detail
Embedded pile row (2D)

Conclusions embedded pile row:

- Efficient 2D modelling of pile rows (out-of-plane)
- Pile and soil can move independently
- Realistic pile-soil interaction (shaft friction, end bearing)
- Calibration of interface stiffness, based on out-of-plane spacing (Ls)
- Successful validation
- Since 2012 several applications in practice (piles and ground anchors)

Applications of embedded piles

Quay wall
Applications of embedded piles
Foundation of high-rise building in Frankfurt (Japan Centre)

(Courtesy of Prof. Y. El-Mossallamy)

Applications of embedded piles
Foundation of high-rise building in Singapore
Applications of embedded piles

Railway station in Vienna

~500 m
~400 m

47464 elements

(Courtesy of Prof. H.F. Schweiger)

Applications of embedded piles

Railway station in Vienna

Model without soil
(bottom view)

615 Piles
- Different pile lengths
- Different pile inclinations
(Rest is modelled as blocks)
Applications of embedded piles

Railway station in Vienna

axial force  shaft friction

Applications of embedded piles

Excavation in Monaco (Odeon Towers)

(i.c.w. Terrasol, France; Plaxis Bulletin 29, 2011)
Ongoing research

Research on installation effects of driven piles at TUDelft:

- Idea: Impose modified stress and density on ‘wished-in-place’ pile

(Engin, 2013)

Ongoing research

Research on large deformation analysis (MPM) due to pile installation
Conclusions

- Efficient modelling of piles in FEM:
  - Embedded pile row (2D)
  - Embedded pile (3D)
- Realistic pile-soil interaction (shaft friction, end bearing)
- Pile capacity is Input (not a result)
- Meanwhile many applications in practice (piles and ground anchors)
- Ongoing research:
  - Installation effects
  - Pile penetration using MPM

References

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