Better ZSOIL, Better Geotechnical Analysis

——Excavation and foundation settlement analysis of a 700m+ high-rise

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2. GEOFEM
CONTENTS

- General information of the analysis
- Pre-process of the analysis
- Post-process of the analysis
- Discussion
General information of the analysis
- Project information
- Problems to be analyzed
- Analysis strategy
General information of the analysis

Project information

- The high-rise locates in SuZhou, JiangShu Province, China
- Architectural Renderings of the high-rise Left
  - About 598m (structural height)
  - 700m+(architectural height)
  - International architecture consultant **Gensler**
  - International structure consultant **Thornton Tomasetti**
  - Geotechnical consultant **SGIDI**
General information of the analysis

Project information

Nearby project of B plot

Subway station

Project location

General information of the analysis

Project information

Nearby project of B plot

Subway station

Project location
General information of the analysis

Project information

Structural framing plan and pile foundation plan
General information of the analysis

Project information

- **Pile foundation plane**
  - Tower pile: 1100mm Dia., about 70m length, cast-in-place concrete pile, end & side-grouting, bearing layer is No. 13. Compressive capacity characteristic value is 13000kN. 876 piles total.
  - Podium compressive pile: 1000mm Dia., about 55m length, cast-in-place concrete pile, end & side-grouting, bearing layer is No. 13. Compressive capacity characteristic value is 10000kN.
  - Podium tension pile: 800mm Dia., about 25m length, cast-in-place concrete pile, end & side-grouting, bearing layer is No. 10. Tension capacity characteristic value is 1800kN.
General information of the analysis

Project information

Tower pile: 1000mm dia. , CIP, length=76~81m

Podium pile: 700/800mm dia. , CIP, length=33/53m
General information of the analysis

Project information

- Excavation plane
  - Athwart construction method (top-down construction method) is employed here. B0~B4F floor is designed to play the role of strut system.
  - Diaphragm wall bears the horizontal water and earth pressure.
  - To speed up the efficiency of excavation, “big” circular and rectangle holes for vertical soil transportation are designed.
General information of the analysis

Project information

Tower area: excavation depth 34.9m

Podium area: excavation depth 29.5m

B2F area: excavation depth 12.9m

Area of foundation pit: 26260 m²
General information of the analysis

Project information

- Diaphragm wall, $B=1.0m, H=34.0m$
- Diaphragm wall, $B=1.2m, H=62.5m$
- Diaphragm wall, $B=1.0m, H=62.5m$
- Large circular hole set for vertical soil transportation
General information of the analysis
Project information

Tunnel, buried depth 8~9m

8~9m, tunnel to the diaphragm wall

diaphragm wall, B=1.0m, H=34.0m

B0~B4F act as strut system

diaphragm wall, B=1.2m, H=62.5m
General information of the analysis

Project information

3m, from our project dia. wall to nearby project (B plot) dia. wall

Dia. wall, B=0.8m, H=30m

Dial wall, B=1.2m, H=62.5m
General information of the analysis

Problems to be analyzed

- The displacement/internal force influence on nearby structure (tunnel, subway station and structure of B plot) caused by the excavation of the deep foundation

- The displacement/internal force influence on nearby structure caused by the settlement of the building
General information of the analysis

Analysis strategy

- Excavation and foundation settlement is analyzed separately
  - We still do not have enough experience to estimate the value of bottom heave of excavation.
    - Some heave value will be “excavated” during the stage construction of foundation pit, while ZSOIL cannot model this yet.
    - Stage construction of excavation consumes much more time than only settlement calculation. Sometimes clients only care about settlement
    - We have more confidence in settlement assumption than bottom heave of excavation
    - Bad bottom heave assumption may contaminate the settlement value of the building
Pre-process of the analysis
- Challenge of establish ZSOIL model
- Soil parameters
- FEM model for excavation
- FEM model for settlement calculation
Pre-process of the analysis
Challenge of establish ZSOIL model

- Constitutive model: HSS model vs. HS model (only settlement analysis)
  - HSS seems to consume more time
  - The results may be very different
  - How to judge the result?

- How to gain parameters for HS/HSS
  - Only preliminary geotechnical investigation is finished yet
  - Empirical method is employed to estimate the parameters for soil model
How to establish such huge model

- We can assemble each part (subway station, tunnel, nearby underground structure, etc.) into a whole model with "kinematic constraint"
  - Efficiency vs. accuracy
- We can connect raft, column, shear wall, floor, beam, piles with "nodal link"
  - Model with node compatible consumes too much time. Sometimes compatible models are mission impossible for quick analysis
  - ZSOIL->nodal link save us
- Great passion, clear routine and strong mind are necessary
Pre-process of the analysis
Challenge of establish ZSOIL model

- How to solve such huge problem
  - About 1,500,000 equations
  - ZSOIL.PC X64
    - Parallel computation is supported
    - Choose a more efficient algorithm, BFGS?
  - Powerful computer is necessary
    - 2 or more CPU, more physical memory, etc.
  - Great patience, carefully established model without any mistake, kind boss and patient client
  - Above all, we must cut lot of branches with both hand, mind and courage
Pre-process of the analysis
Soil parameters

- Bore hole of CPT see below
  - The CPT value of each soil layer is plotted
  - Parameters for HSS/HS ($E_s, E_{ur}, E_0, E_{50}$) derive from CPT, SPT and lateral loading test according to empirical formula of SGIDI
    - Of course, hundreds of empirical formula available
  - $E_s = E_{50}$ and $E_0 = 3\sim5E_{ur}$ are taken for lack of tri-axial test data and other advanced experiment in preliminary analysis
① Fill back
④ silty clay
⑤ silt
⑥ silty clay
⑧ 1 silty clay
⑧ 2 silty clay with silt
⑨ silt with silty clay
⑩ silty clay
（11）silt with silty clay
（12）1 clay
（12）2 silty clay
（13）1 silt with silty clay
（13）2 fine sand
Pre-process of the analysis

Soil parameters

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>weight (kN/m³)</th>
<th>void ratio</th>
<th>water content</th>
<th>cohesion (kPa)</th>
<th>friction angle (deg.)</th>
<th>E₀₉₁₀·₂ (kPa)</th>
<th>Eᵤᵤ (kPa)</th>
<th>E₀ (kPa)</th>
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Pre-process of the analysis
FEM model for excavation

- Detailed construction stage is modeled
  - See pics of stage construction
  - Elaborate model of underground structure of nearby project (B plot) is established to get more reliable additional displacement and internal force caused by excavation and settlement of our project.
Pre-process of the analysis
FEM model for excavation
Pre-process of the analysis
FEM model for excavation

- Subway station
- Foundation pit of nearby project
- Tunnel
- Dia. wall
- Circular hole for vertical soil transportation
- B0F
- Underground structure of nearby project
Pre-process of the analysis
FEM model for excavation

- Circular hole for vertical soil transportation
- Rectangle hole for soil transportation
- Foundation pit of nearby project
- B0F
- B4F
- Podium compressive pile
- Column
- Tower piles
- Podium tension pile
Pre-process of the analysis
FEM model for excavation

- Column & supporting pile
- Shear wall
- Reinforced beam for circular hole
- Column
- Strut system of foundation pit nearby
Pre-process of the analysis
FEM model for excavation

Pile plan (dxf file) -> input to zsoil.pc -> convert circles to points -> extrude points to lines -> generate piles on lines -> OK
Pre-process of the analysis
FEM model for excavation
Pre-process of the analysis
FEM model for excavation

Nodal links are used to connect different objects

Kinematic constraints are used to combine different parts
Pre-process of the analysis
FEM model for settlement calculation

- Interaction of super structure, foundation and soil is considered in the model
  - It is unnecessary to establish a 150 floors building in the model. B5F + 5F can represent the stiffness distribution of the super structure.
  - Elaborate model of underground structure of nearby project (B plot) is established to get more reliable additional displacement and internal force caused by our project.
Pre-process of the analysis
FEM model for settlement calculation
Pre-process of the analysis
FEM model for settlement calculation

- **Surface load** exerted on mega column
- **Linear load** exerted on shear wall of core tube
Post-process of the analysis

- Results for excavation analysis
- Results for settlement analysis
Post-process of the analysis

Results for excavation analysis

B0F uplifts 4~6cm because of unloading

Weight of 7m thick raft cause 2.3cm settlement finally
Post-process of the analysis
Results for excavation analysis

Max. 4.4cm normal displacement occur at middle of the edge

Only 2.5cm normal displacement because of unloading of nearby foundation pit
Post-process of the analysis
Results for excavation analysis

Max. M1 moment 1475kNm
Post-process of the analysis

Results for excavation analysis

Max. M2 moment 1856kNm
Post-process of the analysis
Results for excavation analysis

Max. 1.66cm raft heave of nearby structure

Max. 1.5cm raft settlement of nearby structure
Post-process of the analysis
Results for excavation analysis

Max. additional M1 moment 407kNm
Post-process of the analysis
Results for excavation analysis

Max. 1.69cm dia. Wall
heave of nearby structure
Post-process of the analysis
Results for excavation analysis

Max. tunnel heave 8.67mm
Post-process of the analysis
Results for excavation analysis

Max. tunnel horizontal disp. 3.38mm
Post-process of the analysis
Results for excavation analysis

Conclusion for excavation analysis

- The excavation of a large and depth foundation pit will cause “heave” of nearby underground structure and tunnel
- Piles set before excavation will decrease bottom heave significantly
- Excavation of foundation pit nearby will decrease both normal displacement and internal force of our project
  - Excavation nearby is good for our project
  - Without 3D analysis, it is hard to judge the consequence of such situation
Post-process of the analysis
Results for settlement analysis

- Max. settlement 5.72cm, HSS model
- Max. settlement 11.02cm, HS model
- Influence range by settlement calculated with HS model seems wider than calculated with HSS
Post-process of the analysis

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Results for settlement analysis

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Post-process of the analysis

Results for settlement analysis

- Max. additional settlement of tunnel is about 1.31mm, HSS model
- Max. additional settlement of tunnel is about 9.08mm, HS model
Post-process of the analysis
Results for settlement analysis

- Max. additional horizontal displacement of tunnel is about 1.21mm, HSS model
- Max. additional horizontal displacement of tunnel is about 3.99mm, HS model
Post-process of the analysis
Results for settlement analysis

- Max. additional settlement of nearby underground structure is about 9.78mm, HSS model
- Max. additional settlement of nearby underground structure is about 37.5mm, HS model
- Influence range by settlement calculated with HS model seems wider than calculated with HSS
Post-process of the analysis
Results for settlement analysis

- Max. additional M1 moment of nearby underground structure (raft) is about 205kNm, HSS model

- Max. additional M1 moment of nearby underground structure (raft) is about 317kNm, HS model
Post-process of the analysis
Results for settlement analysis

- Max. additional normal displacement of dia. Wall of nearby underground structure is about 2.36mm, HSS model

- Max. additional normal displacement of dia. Wall of nearby underground structure is about 6.67mm, HS model
Post-process of the analysis
Results for settlement analysis

- Max. additional M1 moment of dia. Wall of nearby underground structure is about 99.7kNm, HSS model

- Max. additional M1 moment of dia. Wall of nearby underground structure is about 352.6kNm, HS model
Post-process of the analysis
Results for settlement analysis

■ Conclusion for settlement analysis
  □ Settlement of a high-rise will “drag” the nearby structure and tunnel to settle.
  □ The additional displacement and internal force of the structure nearby calculated with HSS is much smaller than HS.
  □ Influence range by settlement calculated with HS model seems wider than calculated with HSS
Discussion

- Which model can predict the result better? HSS or HS?
  - According to engineering experience, HS model seems to perform well this time.
  - No advanced experiment is conducted to gain parameters for HSS. Coarse parameters from my head may eliminate the advantage of HSS model.
  - For preliminary calculation, HS is more efficient than HSS.
Discussion

- To improve
  - Set shell hinge to model the joint of dia. Wall
  - Excavation + settlement in one model
  - Refine parameters for HS/HSS
For some reasons, not all of the details is published in the PPT.

Ideas maybe more important than numbers for geotechnical engineers.