Use and Misuse of Numerical Modeling in Geotechnical Engineering Applications

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Acknowledgements

- To the many colleagues in Academia and Practice….

- GeoVirginia Organizers
Outline

- Historical Perspective & Background
- Examples of use
- Examples of misuse
- Looking ahead
- Considerations in engineering practice
- Concluding remarks
It is not new…. Terzaghi

THEORETICAL SOIL MECHANICS

By
KARL TERZAGHI

JOHN WILEY AND SONS, INC.
NEW YORK LONDON

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It is not new…. Poulos and Davis

ELASTIC SOLUTIONS FOR SOIL AND ROCK MECHANICS

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University of Sydney

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Professor of Civil Engineering
(Soil Mechanics)
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UNIVERSITY OF SYDNEY

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Why Numerical Modeling?

**Problem:**
- Design of new facilities
- Understanding of observed behavior/failure
- Basic studies of engineered system response

**Approach:**
- Empirical relations (case histories)
- Simplified/closed form/analytical solutions (e.g. elastic solutions, earth pressure, failure theories)
- Numerical solutions (e.g. slope stability, FE and FD)
Why Numerical Modeling?

- Limitations of empirical and simplified solutions
  - Complex geometries, load condition, soil profiles
  - Non-linear, inelastic soil behavior
  - Staged Construction
  - New types of construction
  - Dynamic Behavior

- Numerical Solutions
  - Computer revolution
  - Very powerful, versatile tool
  - Provide an additional tool for the design engineer
Role of Model Simulation

Engineering Design Objectives:
- Develop a facility economically
- Meet design and performance requirements

Estimation (models) of ground response
Coupled with detailed field & Lab investigations

Adjustment of engineering design & construction activities
Control deformations

Update simulation model of Performance of next stages
Intelligent systematic update

Data Storage and Display
GIS – heterogeneous data sets

Field data acquisition
Near real time sensors, wireless

Construction activities
Detailed records

- Not a substitute for good engineering and judgment
- Not a substitute for detailed field exploration and laboratory testing programs
Classes of Geotechnical Analysis Problems

- **Elasticity Problems**: Problems involving *stresses* and *deformations*, with *no failure* of the soil (linear elasticity, soil is highly non-linear even at small strains)

- **Stability Problems**: Problems dealing with the ultimate failure of a soil mass (e.g. theory of *perfect plasticity*)

- **Elasto-Plastic Problems**: The essential connection between elasticity problems and stability problems. Allow the *transition* from initial linear elastic state to the ultimate state of plastic flow

- **Time-dependent Problems**: Long term settlement and consolidation problems
Two Components of Numerical Modeling

I) **Domain Equations:**
   1- Equilibrium equations
   2- Equations relating displacements to strains
   3- Equations relating stresses to strains

II) **Boundary Conditions:**
    What happens on the surface of the model.

The combination of the domain equations and boundary conditions define a **Boundary Value Problem (BVP)**
Boundary Value Problems

Global Equilibrium due
to externally applied
load/construction

Stress - strain
relationships
in the medium

Soil Behavior

- **Types of Analyses:**
  - Total stress analysis
  - Effective stress analysis
  - Saturated and partially saturated analysis
  - Static
  - Dynamic
Field Equations of BVP

Soil Behavior/Constitutive Relation

Compatibility, equilibrium and conservation

\[ n_s + n_f = 1 \]

\[ \dot{n}_s + n_s \dot{u}_{i,i}^s = 0 \]

\[ \dot{n}_f + n_f \dot{u}_{i,i}^f = 0 \]

\[ \dot{\varepsilon}_{ij}^s = \frac{1}{2} \left( \frac{\partial \dot{u}_i^s}{\partial x_j} + \frac{\partial \dot{u}_j^s}{\partial x_i} \right) \]

\[ \sigma'_{ij} = \sigma_{ij} + \delta_{ij}p \]

\[ p_i + R_i + b_i^f = \rho_f n_f \ddot{u}_i^f \]

\[ \sigma_{ij,j} + b_i = \rho_s n_s \ddot{u}_i^s + \rho_f n_f \ddot{u}_i^f \]

Soil Model

\[ \dot{\sigma}'_{ij} = C_{ijkl} \dot{\varepsilon}_{kl}^s \]

\[ R_j = n_f K_{ij}^{-1} \left( \dot{u}_i^f - \dot{u}_i^s \right) \]

e.g. deep excavation

Variables:

\[ n_f, n_s \] (2)

\[ u_i^f, u_i^s \] (6)

\[ \varepsilon_{ij}, \sigma_{ij} \] (12)

\[ \sigma_{ij}', \sigma_{ij} \] (6)

\[ p \] (1)

\[ R_i \] (3)

?? (30)

Eq. (21+9)
The boundaries in BVP

Rules:
- displacements or stresses
- pore pressure or flow

$u_1 = 0$

$u_1 = 0, u_2 = 0$

$P = \text{constant}$

$C_L$

$Q = \text{constant}$
BVP idealization of Surface & Body Forces

Hashash (2016) - Numerical Modeling in Practice
Initial Conditions: State of Stress in Soil

Every element of soil is in equilibrium under the initial state of stress.

\[
\sigma_v = Z\gamma \\
\sigma'_h = K_0 \sigma'_v
\]

Where \( K_0 \) is the coefficient of earth pressure at rest.

Local Equilibrium & relationship to unit weight
Change in the (initial) state of stress

**Construction activities & deformations**

A new state of equilibrium

\[ \text{initial state} + \text{incremental change} = \text{in equilibrium} \]

\[ \text{incremental change} = \text{satisfies equilibrium} \]

Horizontal Shaking

\[ \Delta \sigma_v, \quad \Delta \sigma_h \]

Hashash (2016) - Numerical Modeling in Practice
Discretization of BVP

- Numerical Solution of system of differential equations
- Compute solution at discrete points, use interpolation/shape functions for in-between locations
Geotechnical software... The early years

SOILSTRUCT

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Implementation of Numerical Methods

- Finite Element Method (FEM)
- Finite Difference Method (FDM)
- Boundary Element Method (BEM)
- Discrete Element Methods (DEM)
- Commercial software:
  - FLAC, PLAXIS, ABAQUS...

Also:
Hybrid Methods (such as Discrete Finite Element Method, DFEM)
Coupled Methods (such as Hydro-Mechanical, Thermo-Hydro-Mechanical, etc)
Soil Behavior: Stress and Strain in Soil

Load & displacement

stress & strain
Soil Model: Multi-Phase Nature of Soil

Two Phase Soil: solids and water (100% saturated) with fluid flow

$u_1^S$, $u_2^S$, $u_3^S$
DEM simulation with Polyhedral Particles

Soil-bucket interaction simulation
(Nezami et al., 2007)

~3 hours per 1 sec. simulation w/ 25000 particles*

Triaxial compression tests
(Lee et al., 2012)

2~3 days to shear each sample up to 10% of $\varepsilon_{\text{axial}}$ w/ 9000 particles‡

Bearing tests on JSC-1A bed
(Lee et al., 2011)

~2 hours per 1 sec. simulation w/ 17000 particles‡

Direct Shear Box tests
(Huang et al, 2011)
Complexity of Soil Behavior: Stress-Strain-Strength Relations

- Static (monotonic) vs. Dynamic (cyclic)
- Soil vs. Rock
- Lab Shear Tests vs. Field Shearing Modes
- Strain Rate Effects
- Consolidation effects
- Continuum vs. discontinuum effects
Multitude of shearing modes

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<td>(e)</td>
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\[ b = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} \]

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DSC: Directional Shear Cell
TC: Triaxial Compression
TE: Triaxial Extension
PS: Plane Strain
TSHC: Torional Shear Hollow Cylinder
TTA: True Triaxial Apparatus
Simplified: Isotropic Linear Elasticity

\[
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{23} \\
\sigma_{31}
\end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix}
1-\nu & \nu & \nu & 0 & 0 & 0 \\
\nu & 1-\nu & \nu & 0 & 0 & 0 \\
\nu & \nu & 1-\nu & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{(1-2\nu)}{2} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2}
\end{bmatrix} \begin{bmatrix}
\epsilon_{11} \\
\epsilon_{22} \\
\epsilon_{33} \\
\gamma_{12} \\
\gamma_{23} \\
\gamma_{31}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{23} \\
\sigma_{31}
\end{bmatrix} = \frac{(K + \frac{4}{3}G)}{(K - \frac{2}{3}G)} \begin{bmatrix}
(K - \frac{2}{3}G) & (K - \frac{2}{3}G) & 0 & 0 & 0 \\
(K + \frac{4}{3}G) & (K - \frac{2}{3}G) & 0 & 0 & 0 \\
(K + \frac{4}{3}G) & (K + \frac{4}{3}G) & 0 & 0 & 0 \\
G & 0 & 0 & G & 0 \\
G & 0 & 0 & G & 0 \\
G & G & G & G & G
\end{bmatrix} \begin{bmatrix}
\epsilon_{11} \\
\epsilon_{22} \\
\epsilon_{33} \\
\gamma_{12} \\
\gamma_{23} \\
\gamma_{31}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{23} \\
\sigma_{31}
\end{bmatrix} = \begin{bmatrix}
\lambda + 2\mu & \lambda & \lambda & 0 & 0 & 0 \\
\lambda & \lambda + 2\mu & \lambda & 0 & 0 & 0 \\
\lambda & \lambda & \lambda + 2\mu & 0 & 0 & 0 \\
0 & 0 & 0 & \mu & 0 & 0 \\
0 & 0 & 0 & 0 & \mu & 0 \\
0 & 0 & 0 & 0 & 0 & \mu
\end{bmatrix} \begin{bmatrix}
\epsilon_{11} \\
\epsilon_{22} \\
\epsilon_{33} \\
\gamma_{12} \\
\gamma_{23} \\
\gamma_{31}
\end{bmatrix}
\]
Stiffness Nonlinearity at Small Strains

- Burland 1989 – Small is Beautiful


- $V_s$ as a fundamental geotech parameter

- Representation of nonlinearity now more readily available in commercial software (e.g. PLAXIS)

---

**Figure:**
- SASW testing, TTC, SF
- After Simpson et al. 1979
Material Constitutive Models: Plasticity

→ **Plasticity based models**, concept of a loading criterion, different behavior of loading and unloading

**Flow theory of plasticity:**
- Initial yield surface
- Evolution of the yield surface (hardening rule), perfect plasticity → no evolution
- Flow rule

Can represent:
- Dilatancy
- Nonlinear hysteretic behavior
Yield and Failure Surfaces

(a) 2-D plot showing the yield surface projection and the flow vector. Normality of the associated flow rule illustrated with the arrow perpendicular to the yield surface at current plastic state.

(b) 3-D Plot showing the yield surface (ellipsoid) and failure cone with respect to the stress path.
Ex.: MIT-E3 Plane Strain Tests Simulations

\[ \frac{(\sigma_y + \sigma_x)}{2\sigma_y} \]

\[ \frac{\tau}{\sigma_y} \]

MIT-E3 Peak Strength Envelope

\[ \sigma = \frac{1}{2} \sqrt{(\sigma_y - \sigma_x)^2 + 4\tau^2} \]

Maximum Shear Stress

Maximum Shear Strain, \( \gamma \) (%) vs. Major Principal Stress Direction at Failure, \( \delta_f \) (°)

Hashash (2016) - Numerical Modeling in Practice
Executing a numerical analysis

I) Pre-Processing Stage:
1- Simplify the geometry to fit the modeling capabilities
2- Discretize the simplified geometry (FE, FD, DE, etc)
3- Define geometric and hydraulic boundary conditions
4- Define initial state of stress and pore pressure
5- Define material profile and properties

II) Processing Stage:
1- Impose variations to the model (e.g., staged construction)
2- Compute the response of the model

III) Post-Processing Stage:
1- Reduce and process the resulting data
2- Display the results (visualization)
2- Analyze the results

Essential Component: Engineering Experience, Judgment and Good Intuition
Example Uses of Numerical Modeling

- Urban Excavation
- Reactivated landslide
- Deep ground freezing
- Blasting in confined space
Deep Excavation in an Urban Area
Garage at Post office Square, Boston, MA

Design Problem:
- Top-down construction, 1st of its kind in Boston
- Load in support system
- Water inflow into excavation
- Adjacent structures
Deep Excavation in an Urban Area
Garage at Post office Square

**Approach:**
- Empirical relations: charts, not for keyed in walls, limited precedence
- Simplified/closed form/Analytical solutions: None
- Numerical solutions: construction staging, coupled stress-flow analysis
Empirical Relations

After Clough and O’Rourke 1990

...dependent on details of construction process
...require more comprehensive monitoring
...need for higher fidelity numerical model
Deep Excavation in an Urban Area

Garage at Post office Square

- Mismatch in estimated lateral movement
- Mismatch in settlements
- Should we change stiffness?
- Concrete shrinkage
- Drainage

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Deep Excavation in an Urban Area
Garage at Post office Square

Finite Element Results:
- Base Case Prediction
- Modified Analysis
- Modified Analysis Stage 32

Stage 10
Stage 19
Stage 28
Stabilization of an Ancient Landslide
Hoover Slide, Upper Provo Canyon, Utah

**Design Problem:**
- load on drilled caissons
- reduction in ground movement
- Impact of roadway construction

![Diagram of the Hoover Slide](image)

- Alluvial Deposits
- Great Blue Limestone
- Provo River Fill
- US-189
- Inclinometer U-12
- Slide Debris
- Weathered Manning Shale (Shear Zone)
- Intact Manning Shale

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Stabilization of an Ancient Landslide

**Approach:**
- Empirical relations: engineering estimate, similar cases in Washington
- Simplified/closed form/Analytical solutions: ??
- Numerical solutions: construction staging, coupled stress-pile analysis
Stabilization of an Ancient Landslide
Hoover Slide, Upper Provo Canyon, Utah

- Calibrate creep model without stabilization measures and roadway.

- Add roadway fill and compute deformations

- Add stabilizing shaft and compute deformations
Stabilization of an Ancient Landslide
Hoover Slide, Upper Provo Canyon, Utah

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Ground Freezing in a Uranium Mine

**Cigar Lake mine, Saskatchewan, Canada**

*Design Problem:*
- load on adit support system
- extent of freeze zone
- deformations

---

**Diagram:**
- **Sandstone** (High Permeability)
  - Free Supply of Water
- **Ore Body** (Low Permeability)
- **Basement Rock** (Low Permeability)
  - Limited Supply of Water
- **Frozen Sand**
  - Cutoff of free water
- **Freeze Tube**
- **Tube Insulation**
- **Frozen Rock**
- **Frozen Level**
- **Production Level**

---

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Ground Freezing in a Uranium Mine

Cigar Lake mine, Saskatchewan, Canada

Approach:
- Empirical relations: some charts, no precedence
- Simplified/closed form/Analytical solutions: None
- Numerical solutions: construction staging, coupled stress-flow analysis
Ground Freezing in a Uranium Mine

Cigar Lake mine, Saskatchewan, Canada

- Experimental freezing program
- Temperature measurements
- Lining stress measurements
- Calibrate a user developed temperature dependent water freezing model

Temperature contours
Ground Freezing in a Uranium Mine
Cigar Lake mine, Saskatchewan, Canada

- Compute forces on lining in multi adit configuration

- Forces limited mostly by overburden pressures
Munitions Disposal in an Adit: Nevada Test site

**Design Problem:**
Effect of repeated blasting on integrity of tunnel walls.
Munitions Disposal in an Adit: Nevada Test site

**Approach:**
- Empirical relations: no precedence, perform full scale field trials
- Simplified/closed form/Analytical solutions: 1-D wave propagation
- Numerical solutions: tunnel geometry & blast pressure distribution
Munitions Disposal in an Adit

Nevada Test site

- Model of the tunnel
- Model of the pressure wave development

Results:
- Areas of tensile failure
- Invert uplift

Is this reasonable?

Yielding of Rock
Tensile failure
Munitions Disposal in an Adit

Nevada Test site

Yielding of Rock - Tensile failure

Significant damage caused by reflected (tensile) wave

Observed damage – Shotcrete spalling
Ex: Misuse of Numerical Modeling

- Excavation
- Ground Improvement
Case 1: Braced Excavation vs SEM

- Congested urban area
- Many historic structures, sensitive to deformations
- Design: braced excavation, T-wall (for added stiffness) and bracing at 6-8 ft vertical spacing
Case 1: Exc. vs SEM – Value Eng’g

- Value Engineering Proposal:
  - Sequential excavation method
  - Roof with pipe Stabilize face, and shotcrete
  - Deformations less than those from braced excavation
  - Backed up with boxes of Finite Element Analysis output

Hashash (2016) - Numerical Modeling in Practice
Case 1: Exc. vs SEM - Reviewers

- Braced diaphragm walls – Stiff ground support system
- SEM- relies on ground relaxation – Flexible Support system
  - Therefore, $\delta_{\text{SEM}} > \delta_{\text{Braced}}$

- However, Numerical model says $\delta_{\text{SEM}} < \delta_{\text{Braced}}$

- Contractor confident that numerical analysis is correct

- Is there a disconnect?

- Who is right, wrong, both or neither?
Let us review SEM

Heading and bench carried together (I, II, III) or (IV, V, VI)
Heading and bench excavation, Shotcrete and lattice girder support
Excavate top heading: one round
Place initial layer of shotcrete: 1 to 2 in.

Set lattice girder
Encapsulate lattice girder with shotcrete: ~ 8 in. +
SEM

Drive, or drill and grout, spiles ahead of face
Excavate first bench
Place initial layer of shotcrete:

Extend lattice girders
Encapsulate lattice girder with shotcrete
SEM

Excavate second bench
Place initial layer of shotcrete:

Extend lattice girders
Encapsulate lattice girder with shotcrete
Tunnel- Ground Interaction

Hashash (2016) - Numerical Modeling in Practice
Tunnel- Ground Interaction

- Tunneling front
- Tunnel convergence
- Ground deformations ahead of tunnel face
Case 1: Exc. vs SEM – It’s in the Details

- Numerical model of tunnel was 2-D
- Tunnel supports installed in the same analysis step of tunnel excavation.
- Analyses did not incorporate the 3-D ground relaxation.
- Analysis wishes the tunnel support in place, hence minimal deformations are computed.
- Analysis results are correct... based on the input
- Input to the analysis is incorrect.

*It’s not the software, it’s the engineer*
Case 2: Soil Mixing for Excavation

- Excavation in soft marine soils.
- Soil Mixing in support of excavation and unbalanced load.

Plan view – Ribs/walls
Case 2: Soil Mixing for Excavation

- Numerical modeling to estimate stresses in soil mix ribs
- Required soil coverage let us say 50%
- Criteria: stresses exceeds unconfined compressive strength of the soil mix.

Driving Earth Pressure

Resisting Earth Pressure

Depth below Excavation bottom ~100ft

Soil Mix Ribss

Ground Surface
Case 2: Soil Mixing for Excavation

- Interpretation: maximum/major principle stress larger than unconfined compressive strength of the soil mix mass.

- Concern: cost, expensive to do so much treatment

- Peer review: engineering judgement and simple calculation would indicate this might be excessive

- Are we missing something?
Case 2: Soil Mixing for Excavation

- Where is the controlling maximum principles stress?
  - At the bottom corner of the “wall” (structural engineering view)

- Is it a wall or deep soil mix?
Case 2: Soil Mixing for Excavation

- Recall Mohr Circle of stress

![Mohr Circle diagram](image)

- Soil Mix UC Strength
- Normal Stress
- Shear Stress

$\sigma_1$, $\sigma_3$
Case 2: Soil Mixing for Excavation

- It’s a deep mixed soil – confining pressure
- Significantly reduced % coverage of mixing
- Saving ~$10 Million
- Lesson: proper interpretation
Looking Ahead
Deep Learning- Inverse Analyses

- Strong relationship between soil model and displacements around an excavation

- Parameter Optimization
  - Optimize parameters of a pre-existing soil model
  - Limited by the versatility of the existing model
  - Can use readily available commercial software

- Self learning simulations
  - Soil behavior evolves from measurements
  - Can learn new soil behavior such as anisotropy and small strain nonlinearity
  - Requires greater user expertise
Self-Learning Simulations

- Inverse analysis framework to learn soil behavior from field measurements

1. Field Measurements

2. SelfSim Learning FEM, iterated

- Initial stress-strain data from:
  1. Linear elastic
  2. Laboratory tests
  3. Case histories
  4. Constitutive models

- Stress-Strain Pairs

- Neural Network
- Constitutive Soil Model

- Forward FEM analysis with trained NN material model

3. Forward FEM analysis with trained NN material model

- Next excavation stage / other locations within the excavation or Similar excavation

Hashash (2016) - Numerical Modeling in Practice
Ford Center Excavation – 3-D Modeling

Plan view

- Element locations for stress paths (S)
- Settlemment Points
- Inclinometers


Data Courtesy of Prof. R. Finno, NWU
3-D Laser Scanning

- 13 scan sessions and 5 selected stages

Hashash (2016) - Numerical Modeling in Practice
FE Mesh Modeling Techniques

- 3D excavation model from laser scanned data
  - No Direct ways of importing/exporting
  - Finite element modeling: Brick element deleting scheme (C++)
  - Choose mesh dimension/density first → remove/add element according to the 3DLS data
Ford Center Excavation

- Learning from I-5, I-1 and I-2

After SelfSim

<table>
<thead>
<tr>
<th>Exc Stage</th>
<th>Target</th>
<th>SelfSim</th>
</tr>
</thead>
<tbody>
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<td>Jan. 30th</td>
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<td>March 12th</td>
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<td>April 14th</td>
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<td>May 7th</td>
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Data Courtesy of Prof. R. Finno, NWU
Ford Center Excavation

- Surface settlement profiles

### After SelfSim

<table>
<thead>
<tr>
<th>Stages</th>
<th>Predicted</th>
<th>Finno&amp;Roboski (2005)</th>
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<tr>
<td>Feb. 18th</td>
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<td>May 7th</td>
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Direct Site Specific Soil Model Development

Multiple Laboratory Tests
Lab Testing
Stress Paths with Complex Behavior

Development of Soil Model
Constitutive Modeling & Evaluation of Model

Solution of Boundary Value Problem
Application to BVP (Excavation)

Inverse Analysis
Soil Model
Lab Testing (DSS) as BVP

Extracted Constitutive Behavior

NN Based Constitutive Model

Current approach

Future approach
Modeling in Professional Practice

- Numerical modeling is an extension of conventional engineering calculations

- It is based on basic principles of equilibrium and compatibility

- It is a virtual representation of the planned structure.

- It is a versatile tool that complements available tools

- It may include 1, 2 and 3-D modeling, static and dynamic, multiphase, flow, thermal and chemical processes.

- It may provide higher fidelity estimates

- It supports performance based design
It’s all about the user - example

- Excerpt for PLAXIS manual

- DISCLAIMER: PLAXIS .... The accuracy at which reality is approximated depends highly on the expertise of the user regarding the modeling of the problem, the understanding of the soil models and their limitations, the selection of model parameters, and the ability to judge the reliability of the computational results. Hence, PLAXIS may only be used by professionals that possess the aforementioned expertise. The user
Issues to consider

1. Processes and interaction and team composition

2. Interaction between modeling team and other engineering team members

3. Relationship between numerical modeling, field and laboratory investigation and engineering design. Design aided by numerical modeling vs design by numerical modeling.

4. Soil-structure Interaction
   a. collaborative process between geotechnical and structural engineers
   b. shared information needs
   c. iterative analysis and model compatibility
Processes, interactions and team composition

- Modeling team leader part of the proposal preparation team

- Modeling activity involves three individuals:
  - Modeler (person behind the computer)
  - Modeling advisor (daily or every other day interaction and guidance)
  - Project Engineer (weekly interactions)

- Model checking during model development

- All three co-author the analysis report (do not leave it to the modeler).

- For large or important projects, external modeling advisor, and peer reviewer/panel are highly recommended
Numerical Modeling and Field and Laboratory Testing

- Develop a field investigation program compatible with the planned numerical modeling.

- Shear wave velocity is a key parameter for static and dynamic problems.

- High quality field and laboratory tests.

- Parametric studies are not a substitute for a good and comprehensive site investigation program.

- Numerical modeling may identify additional site investigation needs.
Soil-Structure Interaction

• A collaboration of geotechnical and structural engineers.

• Soil is not a spring, structure is not a pendulum.

• Higher fidelity geotechnical models interacting with higher fidelity structural models.

• The problem does not care whether you are a geotechnical or structural engineer. Important to extend beyond traditional boundaries…
Numerical Modeling and Engineering Design

• Design aided by numerical modeling vs design by numerical modeling.

• Develop a modeling plan with clear objectives, prepare to modify.

• Modeling shall inform engineering design.

• *Calculation packages for numerical models.*
Numerical Modeling Guidelines
For Geotechnical Applications

Prepared by Youssef Hashash
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Saturday, October 8, 2016

Version 2.0
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Concluding Remarks

- Numerical modeling is a powerful tool available to our profession.

- Numerical modeling can be an integral element of design & construction processes – Use and misuse.

- Not a substitute for good engineering and judgment, and detailed investigation programs.
Thank you.

Questions?