NON LINEAR SOIL STRUCTURE INTERACTION : IMPACT ON THE SEISMIC RESPONSE OF STRUCTURES

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OUTLINE OF PRESENTATION

• Review of existing foundation design practice
  ➢ Required changes in design philosophy

• Examined foundation behavior during cyclic loading
  ➢ Modeling aspects through dynamic macroelement

• Assess the impact of foundation non-linearities and variability of seismic motion on structural behavior

• Draw some preliminary conclusions
FOUNDATION DESIGN PHILOSOPHY

• Foundations are designed to remain elastic during earthquakes
  - foundation cannot be easily inspected and repaired after an earthquake

• Ductility demand restricted to superstructure

• Alternative approach
  - Accept permanent (limited and controlled) displacements at foundation
  - Performance based design $\Leftrightarrow$ displacement based design
MOTIVATION FOR DISPLACEMENTS EVALUATION

• Soil structure interaction plays a dominant role in seismic response of the structure
  - Beneficial or detrimental?? Controversial but all linear elastic studies

• Permanent foundation displacements affect the performance of the structure
WHY CONSIDERING FOUNDATION NONLINEARITY / INELASTICITY?

• Recent records revealed very strong seismic shaking
  
  ➢ 1994 Northridge : 0.98 g, 1.40 m/s
  ➢ 1995 Kobe : 0.85 g, 1.50 m/s

  and SA values reaching 2 g

• Retrofitting of existing/damaged structures impossible to accomplish elastically
MOSS LANDING
(Loma Prieta, 1989)
MEXICO (Michoacan, 1985)
IMPLICATIONS OF NON LINEARITIES GEOTECHNICAL EARTHQUAKE ENGINEERING

• Sliding of foundation

• Foundation uplift

• Partial loss of bearing capacity
CENTRIFUGE TESTS

(Gajan et al., 2005)
DIFFICULTIES OF NON LINEAR DYNAMIC ANALYSES

• Analyses are time consuming & expensive to run
  ➢ Especially if soil is modeled (3D continuum)

• Results are very sensitive to small changes in input data
  ➢ Input motion
  ➢ Structural characteristics
  ➢ Soil characteristics
Nonlinearities:
- Geometrical (interface behavior) → Uplift model
- Material (elasto-plastic soil behavior) → Plasticity model

Wave propagation:
- Dissipation of radiation energy
- Dynamic elastic impedances
GENERALIZED FORCES AND DISPLACEMENTS

Rigid circular footing under planar loading

\[
\mathbf{Q} = \begin{bmatrix}
Q_N \\
Q_V \\
Q_M 
\end{bmatrix} = \frac{1}{DN_{\text{max}}} \begin{bmatrix}
DN \\
DV \\
M 
\end{bmatrix}
\]

\[
\mathbf{q} = \begin{bmatrix}
q_N \\
q_V \\
q_M 
\end{bmatrix} = \frac{1}{D} \begin{bmatrix}
u_z \\
u_x \\
D\theta_y 
\end{bmatrix}
\]

\[
\dot{\mathbf{q}} = \dot{\mathbf{q}}^\text{el} + \dot{\mathbf{q}}^\text{up} + \dot{\mathbf{q}}^\text{pl}
\]
<table>
<thead>
<tr>
<th>MECHANISM</th>
<th>DISSIPATION</th>
<th>REVERSIBILITY</th>
<th>NON-LINEARITY</th>
<th>MACROELEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity</td>
<td>No</td>
<td>Reversible</td>
<td>No</td>
<td>Elasticity</td>
</tr>
<tr>
<td>Uplift</td>
<td>Non - dissipative</td>
<td>Reversible</td>
<td>Geometric</td>
<td>Non-linear elastic model</td>
</tr>
<tr>
<td>Soil Yielding</td>
<td>Dissipative</td>
<td>Irreversible</td>
<td>Material</td>
<td>Associated Plasticity model</td>
</tr>
</tbody>
</table>

Possible load states are limited by ultimate bearing capacity of foundation.
Phenomenological non-linear elastic model

\[ \ddot{Q} = K(q) \dot{q} \]

1. Matrix \( K \) depends explicitly on \( q \)
2. No influence of \( Q_V \) on uplift

[Crémer et al (2001)]
[Wolf (1985)]
FOOTING BONDED ON A COHESIVE SOIL
No uplift allowed

Ellipsoidal bounding surface

$Q_N, Q_M, Q_V$

Hypoplastic bounding surface plasticity
1. Cyclic loading
2. Continuous variation of plastic modulus
3. Numerical implementation

Associative flow rule
DEFINITION OF ULTIMATE LOADS

Soil: Undrained Conditions

Interface: Uplift

Uplift

Associated Plasticity

Zero dissipation

\[ \sigma \]

\[ \tau \]
SURFACE OF ULTIMATE LOADS

(Chatzigogos et al, 2007)
UPLIFT – PLASTICITY COUPLING

Ellipsoidal Bounding Surface

Total footing detachment

Ultimate surface

Elastoplastic response with uplift

Toppling limit

Elastoplastic response

Uplift Initiation

[Chatzigogos et al, 2010]
SWIPE TESTS
Imposed Horizontal Displacement

Test GG03
\( N = 1600[N] \)

Test GG07
\( N = 200[N] \) \( N = 1600[N] \)

Mohr-Coulomb branch \( \phi_{int} = 21^\circ \)
DIFFICULTIES OF NON LINEAR DYNAMIC ANALYSES

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  ➢ Especially if soil is modeled (3D continuum)

• Results are very sensitive to small changes in input data
  ➢ Input motion
  ➢ Structural characteristics
  ➢ Soil characteristics
INCREMENTAL DYNAMIC ANALYSIS (Cornell, 2002)

• Series of nonlinear time histories analyses
  ➢ Same time history scaled to increasing amplitudes
  ➢ Track of characteristic quantities of the response

• IDA curve is a plot of selected IM vs selected DM

• IDA curve set: collection of IDA curves
  ➢ Several time histories representing one EQ scenario for one selected IM and DM
EXAMPLES OF IDA CURVES

IDA curve

IDA curves set
INCREMENTAL DYNAMIC ANALYSES

• Series of non linear time history analyses
  ➢ 30 records representing an earthquake scenario
    M=6.5-6.9  d=20-30km
  ➢ Time histories scaled up according to Intensity Measures (IM)
    • pga , SA(T_s) , SA(T_{SSI}) , CAV

• Damage measures (DM) calculated
  ➢ Foundation settlements (residual or maximum)
  ➢ Foundation rotations (residual or maximum)
  ➢ Deck drift (residual or maximum)
  ➢ Structural ductility demand ......
EXAMPLE : BRIDGE PIER

(a) Bridge deck
Bridge pier (circular section)
Circular surface footing
Seismic excitation
Homogeneous purely cohesive soil

(b) Bridge pier: Non-linear beam elements
Macroelement 2-node link element

$md$
$h$
$m$
$mf$
EXAMPLE OF SYSTEM RESPONSE

Single analysis

IDA curves $\mu = f(CAV)$
STRUCTURAL DUCTILITY DEMAND $\mu = f(CAV)$
Price to pay for change in ductility demand
No sign of distress even for increasing motion
RESULTS OF NUMERICAL ANALYSES

• Consideration of non linear soil structure interaction beneficial
  ➢ drastically reduces the ductility demand in the structure
• Counterbalanced by
  ➢ larger displacements and rotations at the foundation
    ✓ May become unacceptable
• Variability in the response becomes large as more demand is placed on the foundation
REMAINING ISSUES

• Increased variability
  - care must be exercised before accepting to transfer the ductility demand from the structure to the foundation
  - thorough investigation of the variability of the response

• Requires careful definition of acceptable criteria for the foundation performance

• IDA may represent a convenient tool for analysis
CONCLUSION

• It is time to move from the concept of
  ➢ ductility demand restricted to the
    superstructure
  ➢ elastic behavior of foundations

• To
  ➢ controlled share of ductility demand between
    the superstructure and the foundation