FINITE ELEMENT ANALYSIS IN OFFSHORE GEOTECHNICS – A 30-YEAR RETROSPECTIVE

J. S. Templeton, III
SAGE USA, Inc.

SIMULIA Community Conference
Providence, Rhode Island
May 15-17, 2012.
FINITE ELEMENT ANALYSIS IN OFFSHORE GEOTECHNICS

Outline

• Milestones
• Piles and Well Conductors
  - Performance under lateral loading
  - Suction Foundations, total stress analysis
  - Suction Foundations, long term holding
• Jack-up Rigs
  - Performance in Severe Storms
  - Performance in Earthquakes
• Conclusions
• Further Developments
• Acknowledgements
MILESTONES  
(global)

• 1962, First published foundation FEA (Clough and Wilson) 
  (the second published paper to have “Finite Element” in the title)
• 1968, Roscoe and Burland modified Cam Clay theory of Critical 
  State Soil Mechanics (Schofield and Wroth).
• 1970, Hibbitt, Marcal and Rice (1970) established rigorous basis 
  for large strain FEA. McMeeking and Rice (1975) further elucidated.
• 1974, Nagtegaal, Parks and Rice (1974), resolved the problem of 
  shear locking of finite elements under large deformations.
• 1978-9, Miller, Murff and Kraft, as well as Carter, Randolph and Wroth 
  applied Modified Cam Clay to the problem of pile setup.
• 1980, Nystrom proposed incorporation of soil mechanics 
  capabilities into Abaqus.
• 1981, Abaqus soil mechanics capabilities released.
MILESTONES
(personal)

• 1967, Dynamic FEA of Saturn-Apollo vehicles in pre-NASTRAN era
• 1981, Early Abaqus foundation analyses
• 1985, Analysis of geologic history of Mississippi Canyon soils
• 1986, First Abaqus analysis of offshore GBS foundation consolidation
• 1991, First Abaqus analysis of offshore subsidence effects.
• 1992, First FEA analysis to explain observed pile skin friction in sand
• 1996, Abaqus continuum dynamic FEA of wave propagation in soils
• 2002, Defined role of FEA in suction pile design.
• 2003, First FEA for offshore foundation under vortex-induced vibration
• 2004, First FEA of long term holding uplift capacity for suction caissons
• 2006, Standard setting publication on use of Abaqus for jack-up rigs
• 2008, First published FEA of continuum soil and structure EQ response
• 2009, Abaqus analysis plus centrifuge tests changed lateral pile practice.
• 2011, First dynamic FEA to match jack-up hurricane wave response including foundation hysteretic damping effects
Early Abaqus offshore foundation analyses concentrated on issues related to axial capacity of slender driven piles (aspect ratios ~ 50 : 1 or > 100 : 1).

More recent work has concentrated on lateral performance issues and on suction piles (aspect ratios typically 7 : 1 or less).

New issues:
- different installation problems
- more complex soil/pile interaction
- axial and lateral capacities interact
- reverse end bearing
- long term uplift holding capacity
DOUBLE-BLIND Abaqus analysis and centrifuge test results agreed extremely well, but both indicated substantially greater capacity than current recommended practice.
SUCTION FOUNDATIONS

Installation by suction gets progressively more effective as water depth increases, while driving becomes more problematic and more expensive.
Anchor point penetration = 6.4 m
Anchor point penetration = 8.0 m
Anchor point penetration = 9.2 m
Anchor point penetration = 11.0 m
Abaqus results with pile loaded above midpoint and low water depth resulted in little separation and negligible effect on performance.

With a high attachment point, and an inclined load, soil can separate from pile here - even in clay, if water is not too deep.
Results from Abaqus (A) and comparison program (C) for pullout performance of suction pile with 5:1 aspect ratio, 26-degree inclined load and low (3/4) attachment point.
Pore Pressure Dissipation with time near tip of pile during long term hold of uplift load

At start of hold
After 11,000 days
Results for Uplift Holding Capacity vs. Hold Time
JACK-UP RIGS
(Bottom Founded Mobile Offshore Drilling Units)

Independent Leg

Mat Supported
MODELS FOR JACK-UP RIG ANALYSIS
SINGLE SPUD CAN PENETRATION ANALYSIS

CEL

Standard

Finite Element Penetration Analysis
ML 116 C, initially embedded at 55 ft
preloaded to 62 ft, debalasted and reloaded
SINGLE SPUD CAN PERFORMANCE

Force and Moment Capacity Interaction

FEA Results Compared to Interpolation from Parabola to Ellipse

Vertical Force Capacity, Relative to Maximum

Moment Capacity, Relative to Maximum

FEA Results, D/B = 1.7

FEA Results, D/B = 1.2

FEA Results, D/B = 0.3

b = 1, Ellipse

b = 0.8

b = 0.6

b = 0.4

b = 0.2

b = 0, Bulletin 5-5 Parabola

Finite Element Penetration Analysis

ML 116 C, initially embedded at 55 ft preloaded to 62 ft, debalasted and reloaded

Penetration, Ft

Vertical Load, kips

Penetration

Curve, Example,

GOM Clay

F. E. Analysis

rotational hysteresis

vertical

horizontal

stiffness reduction

Cyclic FEA Analysis Results

Complete Cyclic Reversal:
Low Stiffness, High Damping

Partial Cyclic Reversal: High Stiffness, Low Damping
SINGLE SPUD CAN PERFORMANCE
INTO SIMPLIFIED SPUD CAN FOUNDATION MODEL

Vertical Force Capacity, Relative to Maximum
Moment Capacity, Relative to Maximum

FEA Results, D/B = 1.7
FEA Results, D/B = 1.2
FEA Results, D/B = 0.3

b = 1, Ellipse
b = 0.8
b = 0.6
b = 0.4
b = 0.2
b = 0, Bulletin 5-5 Parabola

n = -1.25 (N/A)
n = -1.0 (maximum sharpness), hyperbolic tangent
n = -0.75
n = -0.5
n = -0.25
n = 0, sand per original Bulletin 5-5, exponential function
n = 0.25
n = 0.5
n = 0.75
n = 1.0, clay per orig. Bul. 5-5 (min. sharpness), hyperbola
n = 1.25 (N/A)

SAGE FEA, work hardening GOM clay, with vertical load and preload
SAGE FEA, work hardening GOM clay, with vertical load but no preload
SAGE FEA, work hardening GOM clay, with no preload or vertical load

Finite Element Penetration Analysis
ML 116 C, initially embedded at 55 ft
preloaded to 62 ft, debalasted and reloaded

Penetration, Ft
Vertical Load, kips

rotational hysteresis

horizontal interaction

vertical stiffness reduction

partial

NEW STANDARD
ISO 19905

Complete Cyclic Reversal:
Low Stiffness, High Damping
Partial Cyclic Reversal:
High Stiffness, Low Damping
Deck accelerations were recorded on independent leg jack-up rig, Adriatic III, during it’s exposure to severe storm conditions in Hurricane Rita.

LeTourneau 116-C rig, Adriatic class
Photo, courtesy of Transocean

Adriatic III (+) on Hurricane Rita path (---). Map, courtesy of Transocean and Ken Schaudt
Adriatic III in Hurricane Rita
Abaqus Results from time domain random wave
dynamic analysis compared to field observation
surge displacement time history, 2 min. incl. max response

Abaqus results

Measured displacement
Time Domain Earthquake Analysis of Mat Supported Jack-Up Structure on Soft Clay

Maleo Producer, a Bethlehem 250 Mat supported jack-up, offshore, Indonesia, photo courtesy of Stewart Technology and Global Process Systems

“Soil Island” model for 3-D time domain nonlinear analysis of unified site soil response, soil-structure interaction and structural dynamic response
3-D Response to two times DLE 1 motions, Maleo Producer, Final Soils Contours of plastic strain on deformed mesh with 40x magnification Burgundy = 0.5% strain or greater; Navy Blue = .01% or less
Maleo Producer Acceleration Response Spectra
Sway direction motions for Ductility Level Event
3-D FEA results

Spectral response acceleration (5% damping), g
Deck, center of mass
Mat, center of mass
Mudline, far field
CONCLUSION

After over 30 years, Abaqus is still the leading program for high-end finite element geotechnical work

Top 10 reasons:
1. General quality.
2. History of successful use.
3. Extensive material behavior library.
4. Selection of element types and features.
5. Worldwide leadership in nonlinear FE analysis.
6. Rigorous large strain capabilities.
7. Unlimited 3-D feature applicability.
8. No program-imposed problem size limitations.
9. Level of program documentation, verification and technical support.
CONCLUSION
After over 30 years, Abaqus is still the leading program for high-end finite element geotechnical work.

Number one top reason:

1. **Substantial continuous improvement since 1981,**
e.g.:
   - Extensions to the Modified Cam Clay
   - Implementation of NLGEOM for soil models
   - Extended Drucker Prager
   - Contact surfaces
   - Drucker Prager Cap
   - Explicit dynamics
   - Mohr Coulomb yield
   - Combined hardening
   - Multiple exponential kinematic hardening
   - ALE adaptive meshing
   - Extended finite element method (XFEM)
   - Combined Eulerian-Lagrangian (CEL)
FURTHER IMPROVEMENTS NEEDED

- First order (Nagtegaal) elements in Explicit (and CEL)
- Pore pressure-enabled elements in Explicit (and CEL)
- Creep in combination with the parabolic yield surface in Drucker Prager
- Creep in combination with K values other than 1.0 in Drucker Prager
- Creep in combination with the extended finite element method (XFEM)
- Sub-yield kinematic hardening, in Drucker Prager and clay plasticity Is
- Update of Pi plane shape function in Drucker Prager and Clay Plasticity
- Update of the formulations in the Spud Can option of Elastic-Plastic Joint elements to conform with the new ISO 19905-1.

With developments like these, Abaqus seems likely to maintain its leadership position in geotechnical FEA well into the future.
ACKNOWLEDGEMENTS


Former colleagues at Exxon Production Research and McClelland Engineers

Present and former SAGE colleagues, M. K. Hossain, PhD., P.E., F. B. Biegler, Z. M. Oden Duffy, PhD., E. L. Templeton-Barrett, PhD., M. J. Barrett, A. A. Rahim, PhD., P.E. and X. Long, PhD., P.E. (on loan from GEMS)

Principals and staff of HK&S and Dassault Systèmes, particularly H. D. Hibbitt, E. P. Sorensen, J. C. Nagtegaal, and D. Datye
Abaqus Effective Stress Analysis of long term uplift capacity for suction piles/caissons

Soil modeled as elastic-plastic porous material with Modified Cam Clay constitutive theory.

Pile / Caisson modeled as elastic material with Young’s modulus and Poisson’s ratio representative of steel.