Geotechnical Examples using **OpenSees**

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Outline

- **Take advantage of tcl scripting!!**
  - OpenSees Wiki Geotechnical Examples
  - Useful links

- **Take advantage of pre- and post- processors**
  - **GID**, just one possible alternative ☺

- **Some recent research projects completed using OpenSees**
  - Dynamic analysis of piles
  - Analysis of complete bridge system
  - 3D analysis of piles
  - 3D Analysis of bridge abutment

Take advantage of tcl scripting!!

- **tcl** can be used to develop scripts for geotechnical applications.
- Possible applications:
  - Laterally Loaded Pile Foundation – (similar to **lpile)**
  - One-Dimensional Consolidation
  - Total Stress Site Response Analysis of a Layered Soil Column- (similar to **shake**)
  - Effective Stress Site Response Analysis of a layered Soil Column
  - Dynamic Effective Stress Analysis of a Slope
  - Excavation Supported by Cantelever Sheet Pile Wall
  - Other ….

OpenSees Wiki Geotechnical Examples

http://opensees.berkeley.edu/wiki/index.php/Examples

Practical Examples

Geotechnical Examples

- Simulating a Centrifuge Test
- Laterally-Loaded Pile Foundation (Static Analysis)
- One-dimensional Consolidation
- 2D Total Stress Site Response Analysis of a Layered Soil Column
- 2D Effective Stress Site Response Analysis of a Layered Soil Column
- Dynamic Effective Stress Analysis of a Slope
- GiD ProblemTypes for 2D Slope Analysis Input File Generation
- Excavation Supported by Cantilevered Sheet Pile Wall
- 3D Site Response Analysis of Sloping Ground
- Deep Foundation Subject to Lateral Spreading (p-y spring analysis)

Structural Examples

- Infill Wall Model and Element Removal
- Pushover Analysis of 2-Story Moment Frame (without panel zones)
- Dynamic Analysis of 2-Story Moment Frame (without panel zones)
- Pushover and Dynamic Analyses of 2-Story Moment Frame with Panel Zones and RBS
- Dynamic Analyses of 1-Story Moment Frame with Viscous Dampers
- Parameter Study using Parallel Processing
- SCBF Model

Parallel Examples

- Simple Parameter Study

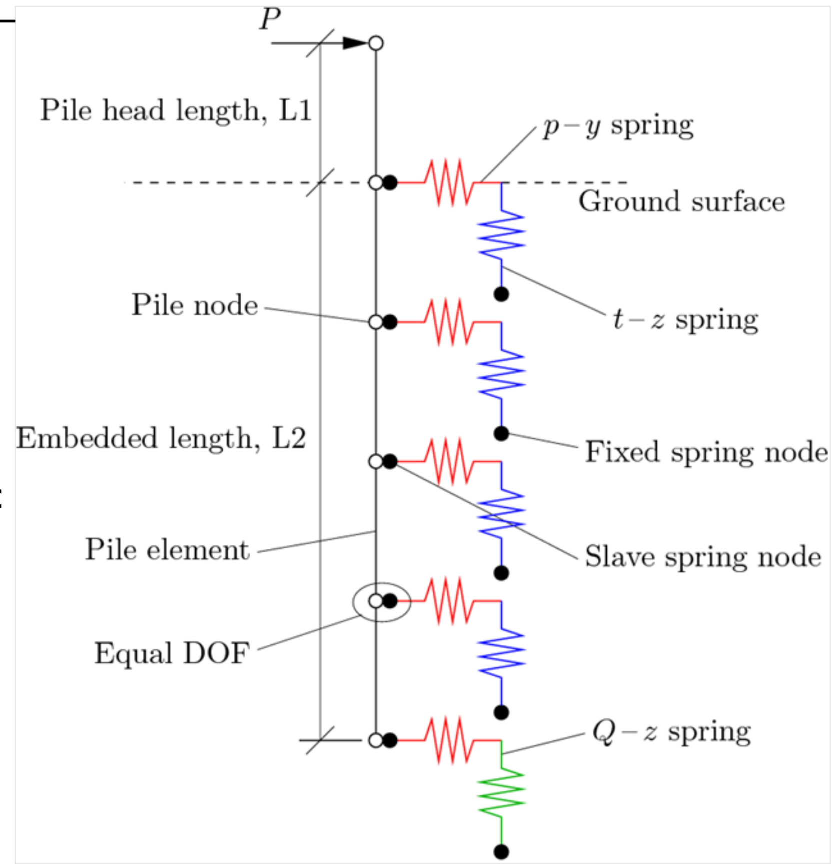
Interesting Articles

- Rigid Diaphragm Consequences
- Calling Matlab from a Scipt

Other useful **tcl** scripts @

- **http://opensees.berkeley.edu/**
- **http://sokocalo.engr.ucdavis.edu/~jeremic**
- **http://cyclic.ucsd.edu/opensees/**
- **http://www.ce.washington.edu/~geotech/opensees/PEER/davis_meeting/**
- **http://opensees.berkeley.edu/wiki/index.php/Examples**

Pseudo-Static Pile Pushover Analysis



This example describes how to run a pushover analysis of a pile in OpenSees.

The model is created in 3D. Pile nodes have 6 DOF, and the soil nodes have 3 DOF.

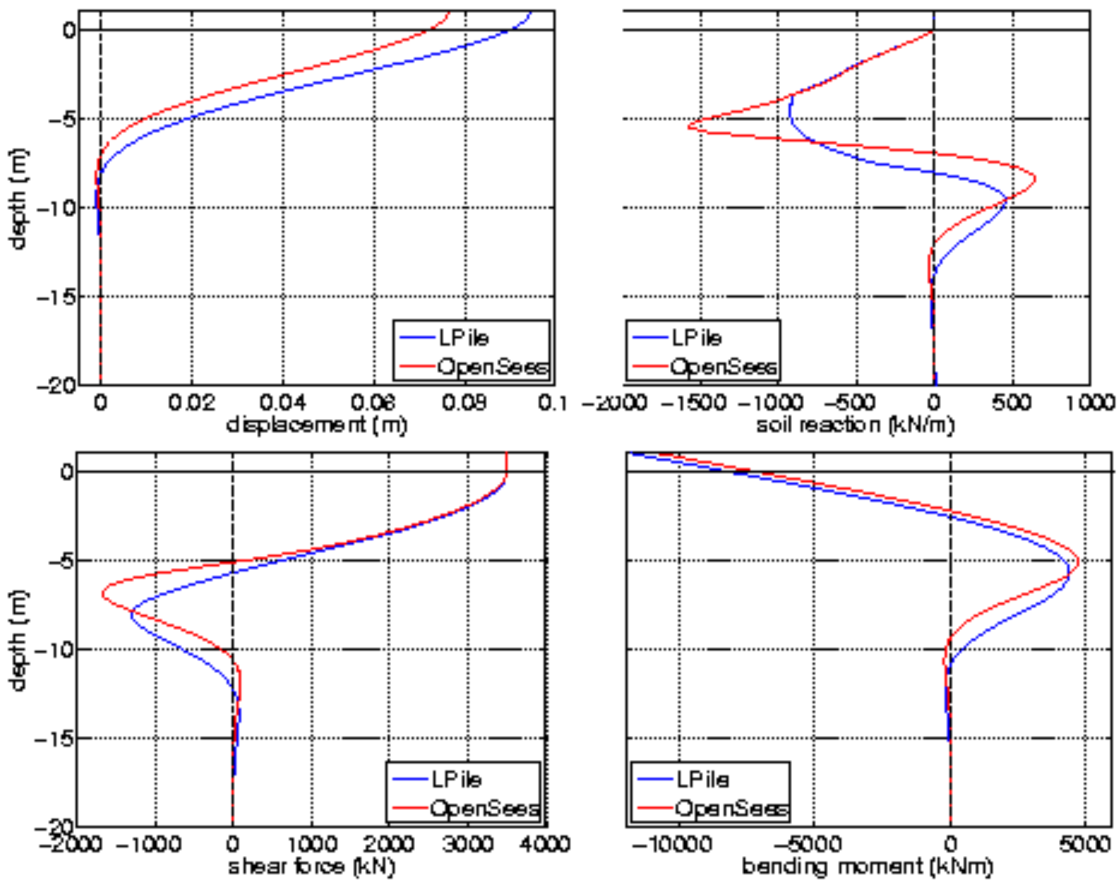
The pile is modeled using the *dispBeamColumn* element with an elastic *fiber* section for linear elastic constitutive behavior.

The soil is represented by *p-y*, *t-z*, and *Q-z* springs using the *PySimple1*, *TzSimple1*, and *QzSimple1* uniaxial materials with *zeroLength* elements.

The pile and spring nodes are tied together using the *equalDOF* command.

Pseudo-Static Pile Pushover Analysis

results of pushover analysis for a fixed-head pile

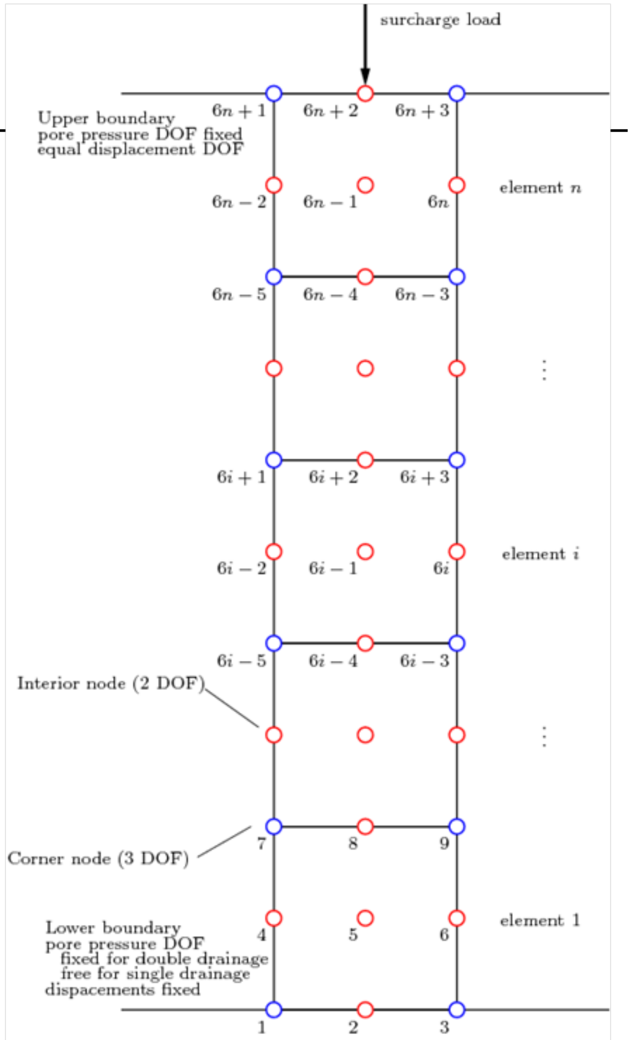


1D Consolidation

This example describes how to run a total 1D soil consolidation analysis in OpenSees.

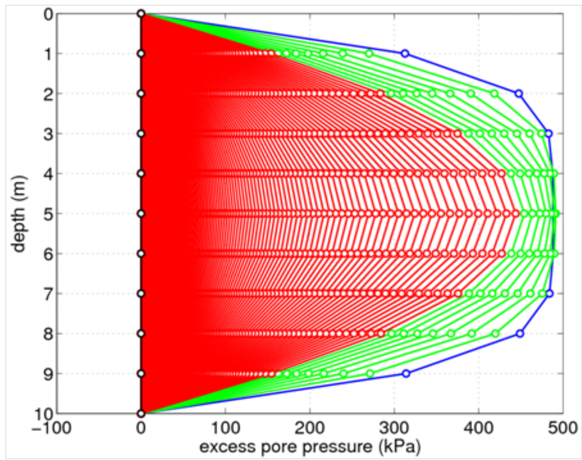
A column of soil is modeled in 2D using the *9_4_QuadUP* element. This element has nine nodes. The nodes in the corners of the element have an additional degree-of-freedom for pore pressure.

The surcharge load is applied as a *constant* timeseries inside of a *plain* load pattern. A *transient* analysis is conducted due to the time-dependent nature of consolidation.

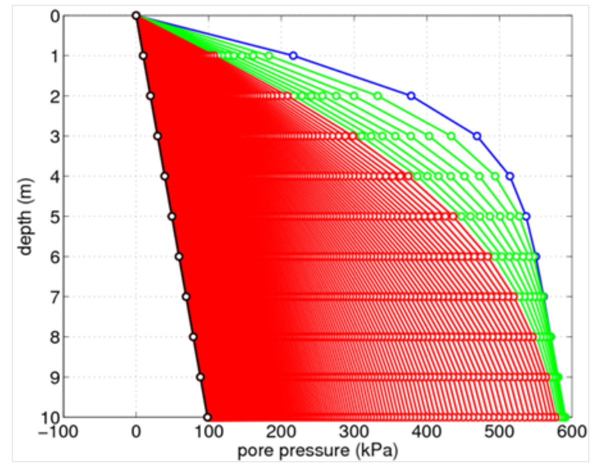


1D Consolidation

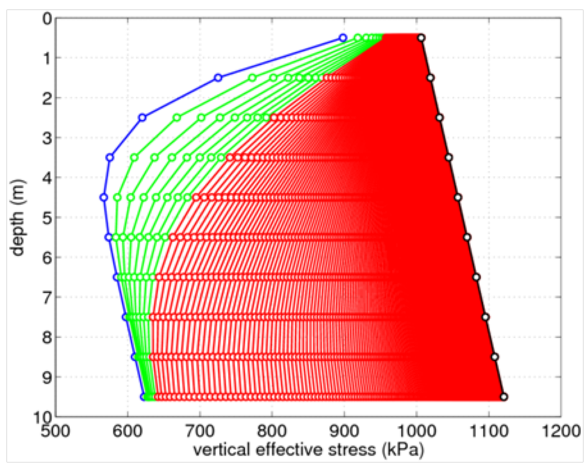
excess pore pressure: double drainage



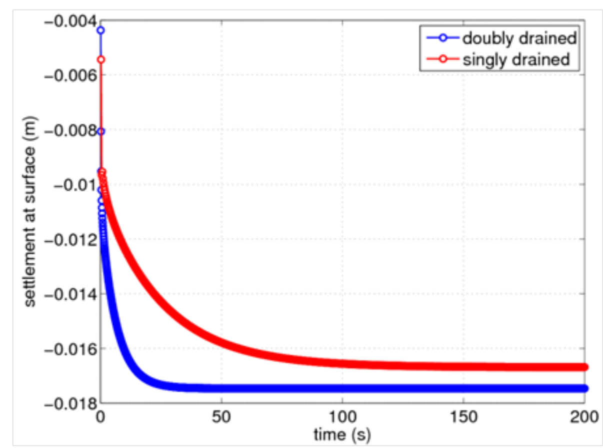
single drainage



other results: vertical effective stress



vertical settlement



Total Stress Site Response Analysis

This example describes how to run a total stress site response analysis in OpenSees.

A layered soil profile is modeled in 2D using nodes with 2 DOF.

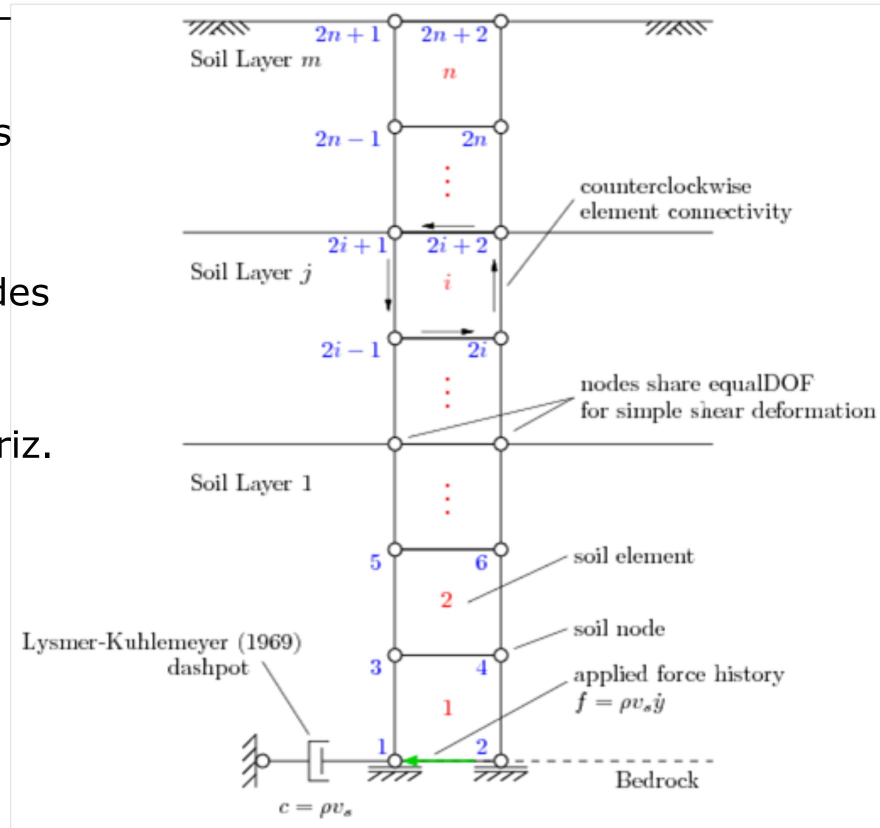
Periodic boundary conditions are enforced in horiz. direction using the *equalDOF* command

The plane strain formulation of the 4-node quadrilateral element *quad* is used for the soil.

Soil constitutive models include:

PressureDependMultiYield
PressureIndependMultiYield

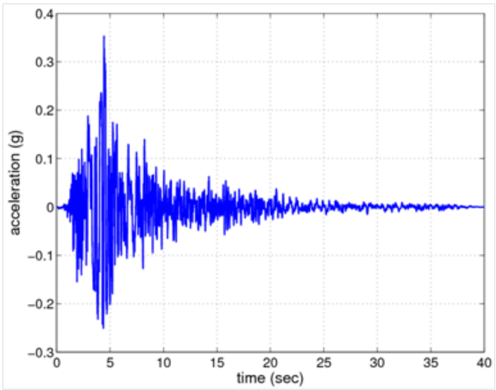
A compliant base is considered using a viscous dashpot modeled using a *zeroLength* element and the *viscous* uniaxial material.



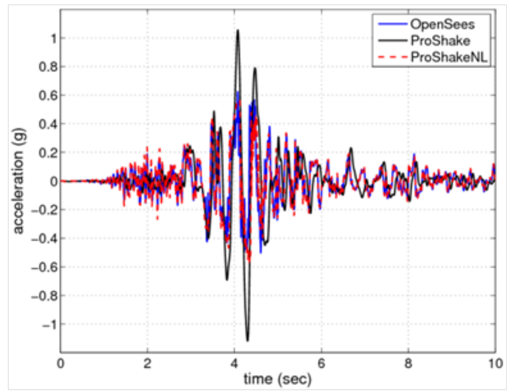
Total Stress Site Response Analysis

comparison with other analytical methods

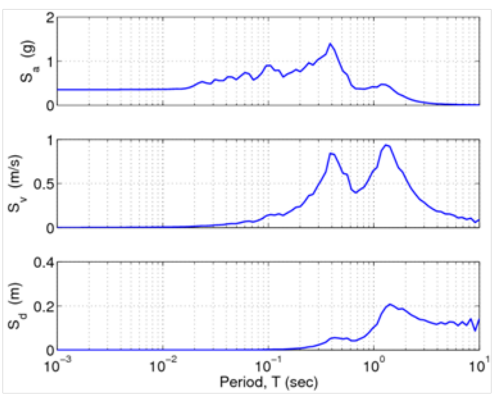
Input motion



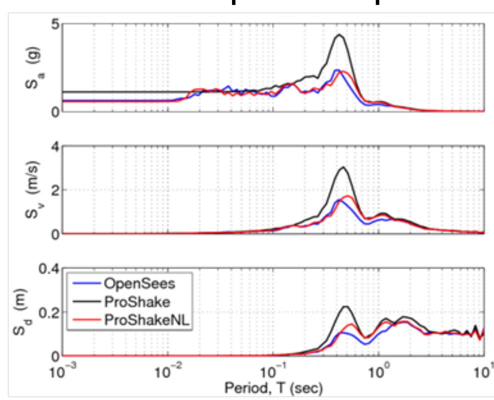
surface acceleration



surface response spectra

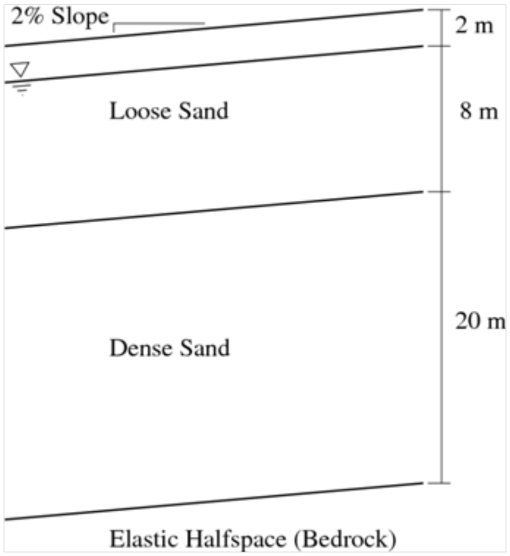


surface response spectra



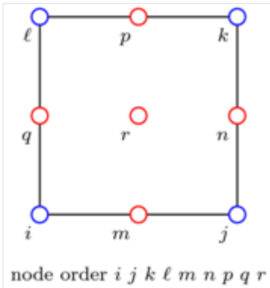
Effective Stress Site Response Analysis

This example describes how to run an effective stress site response analysis in OpenSees.



The approach is similar to the total stress analysis. A layered soil profile is modeled in 2D with periodic displacement boundary conditions enforced using the *equalDOF* command and a compliant base is considered using a viscous dashpot modeled using a *zeroLength* element and the *viscous* uniaxial material.

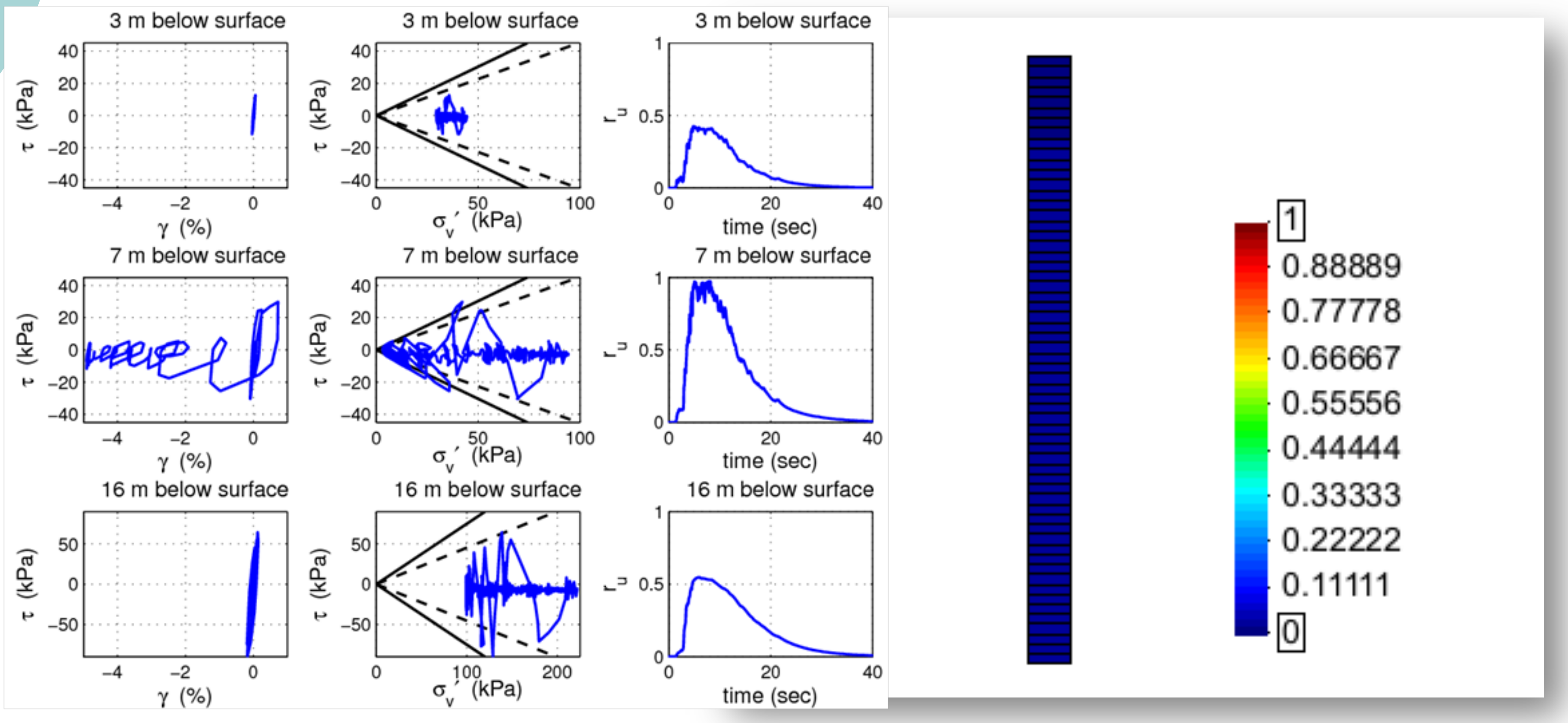
The *9_4_QuadUP* element is used to model the soil. This element considers the interaction between the pore fluid and the solid soil skeleton, allowing for phenomena such as liquefaction to be modeled.



The *PressureDependMultiYield02* constitutive model is used for the soil.

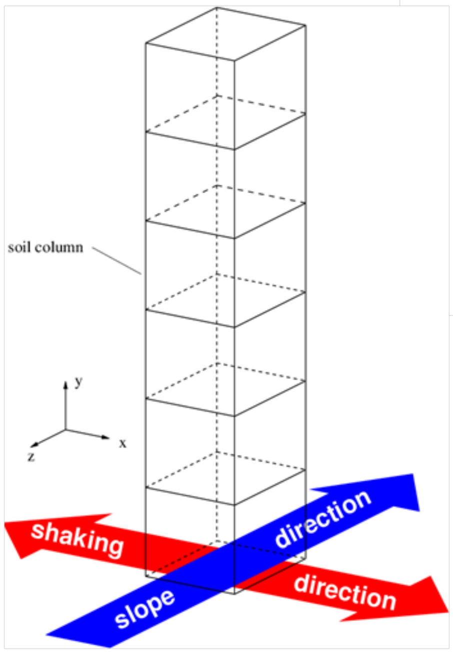
Effective Stress Site Response Analysis

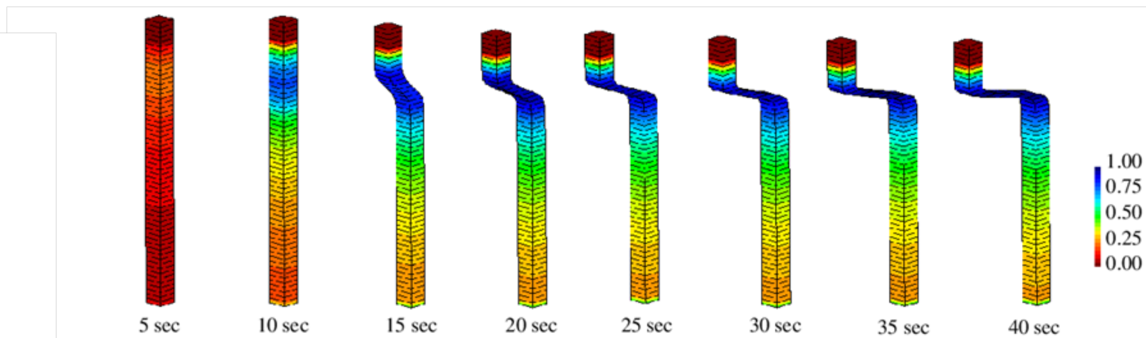
summary of soil behavior at three depths within the soil profile

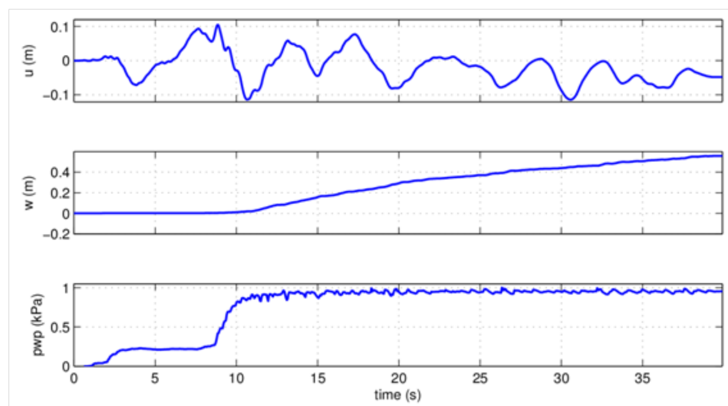


3D Effective Stress Site Response Analysis

displacement of soil column during analysis with contours of excess pore pressure ratio

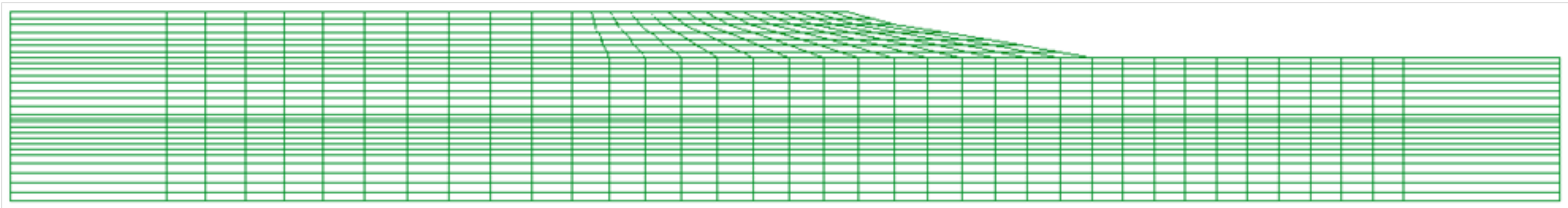






Dynamic Analysis of 2D Slope

Finite element mesh:



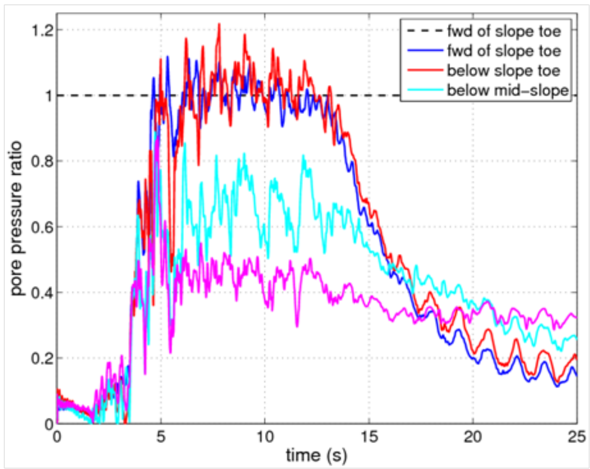
This example presents a 2D effective stress analysis of a slope subject to an earthquake ground motion.

The elements and constitutive models match those used in the site response analysis examples.

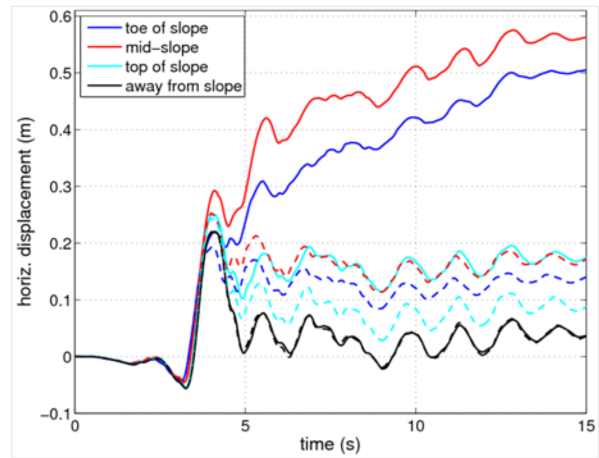
The free-field soil response is applied to the model using free-field columns which are much more massive than the adjacent soil.

Dynamic Analysis of 2D Slope

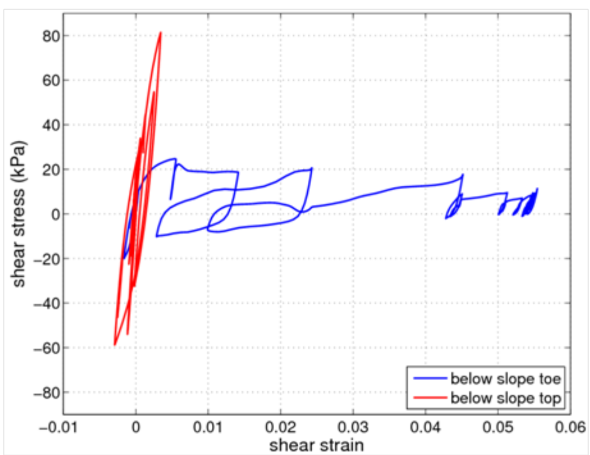
excess pore pressure ratio



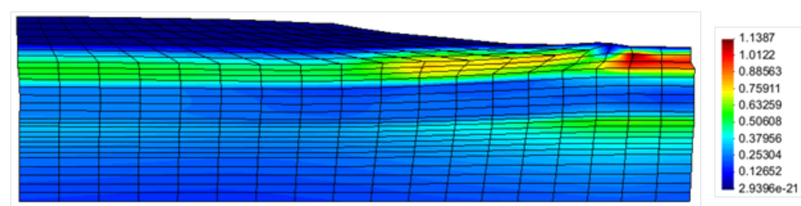
lateral displacement



shear stress-strain

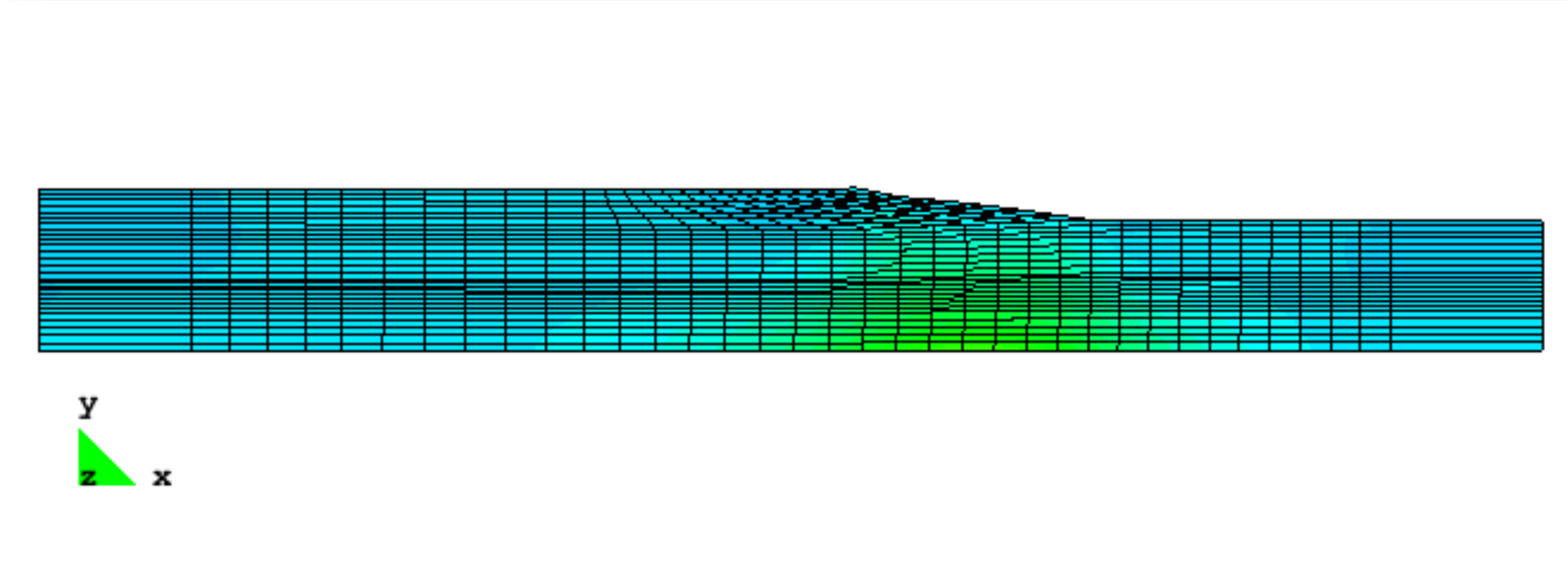


excess pore pressure ratio
contours near slope



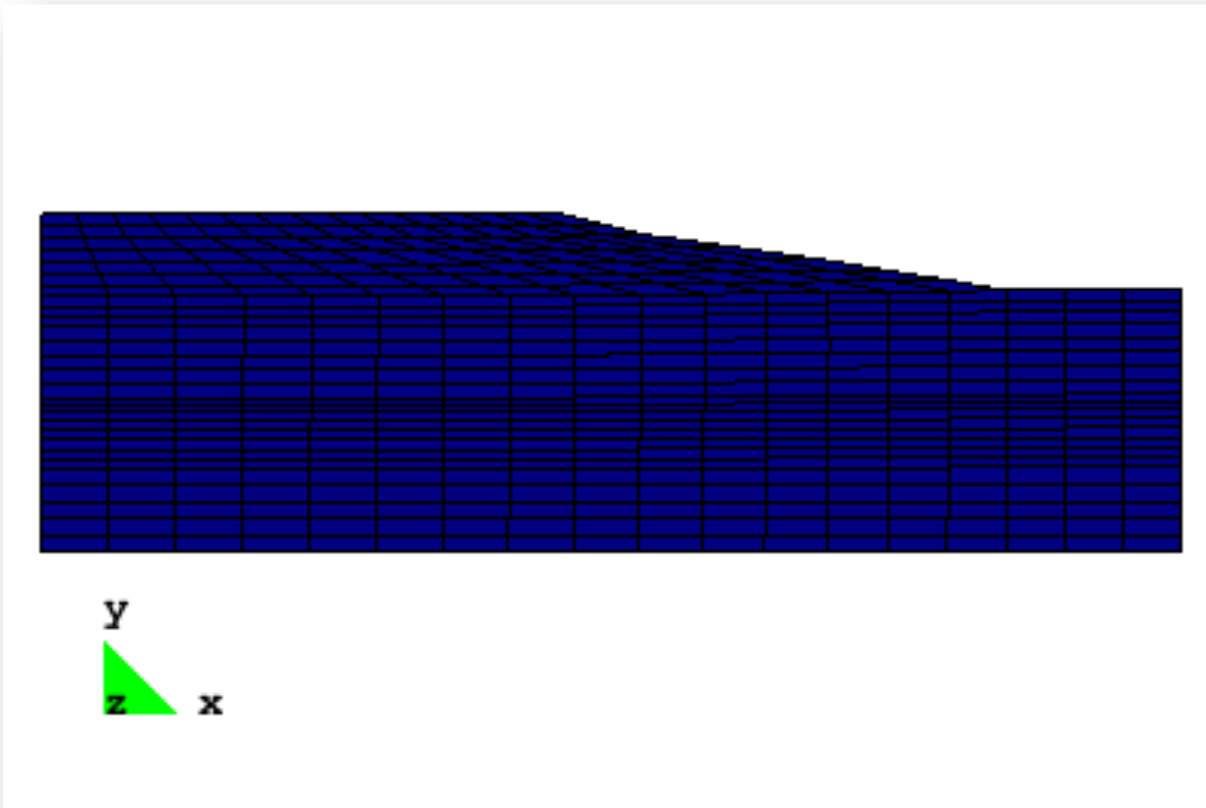
Dynamic Analysis of 2D Slope

displacement of full mesh during analysis showing propagation of shear stress waves



Dynamic Analysis of 2D Slope

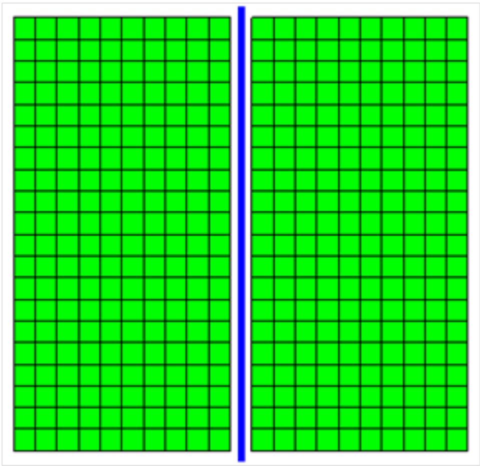
displacement near the slope with contours of excess pore pressure ratio
(red is r_u = 1.0)



Excavation Analysis

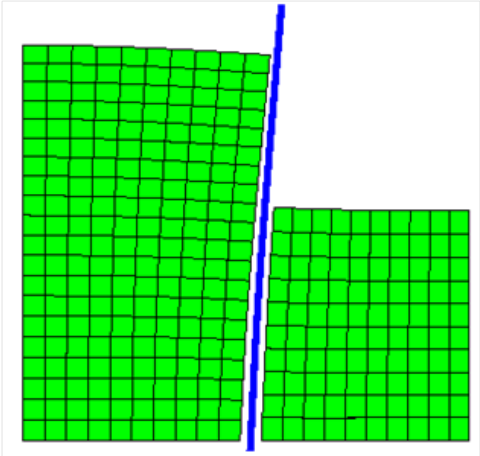
This example presents a simulated excavation supported by a sheet pile wall using OpenSees.

The sheet pile wall is modeled using the *dispBeamColumn* element with an elastic *fiber* section for linear elastic constitutive behavior.



The soil-wall interface is modeled using the *BeamContact2D* element.

The *InitialStateAnalysis* feature is used to create the gravitational state of stress in the model without accompanying displacements.

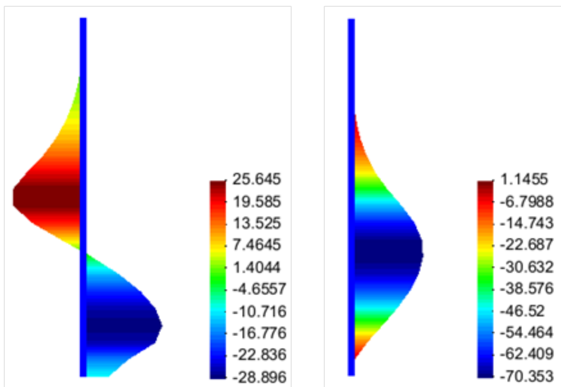


The plane strain formulation of the *quad* element is used for the soil with the *PressureDependMultiYield* nDMaterial for constitutive behavior.

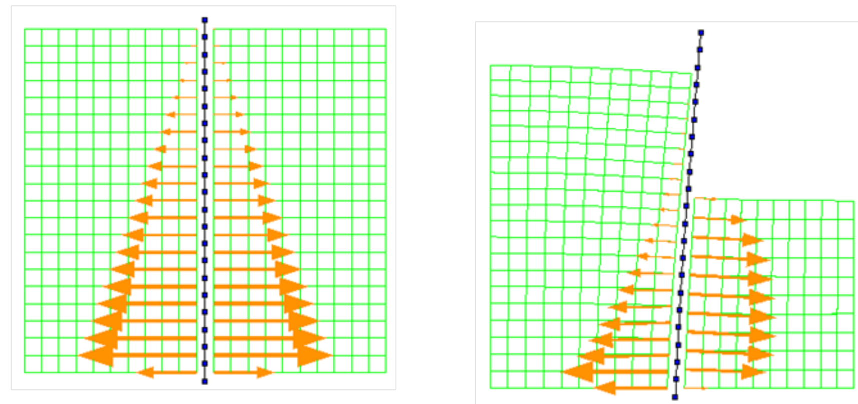
Soil elements to the right of the wall are progressively removed to simulate an excavation.

Excavation Analysis

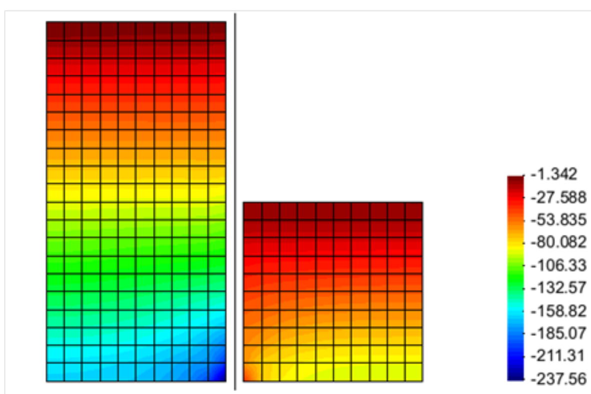
shear and moment in the wall



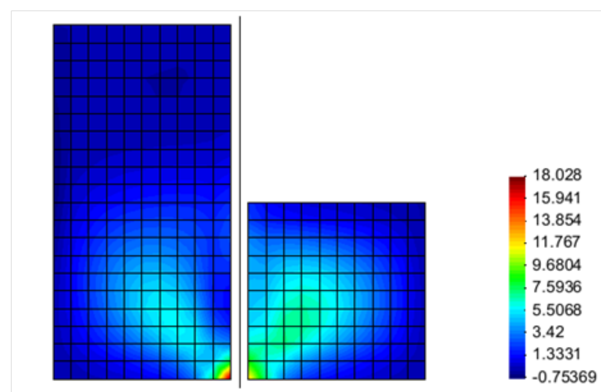
wall-soil contact forces



vertical stress contours

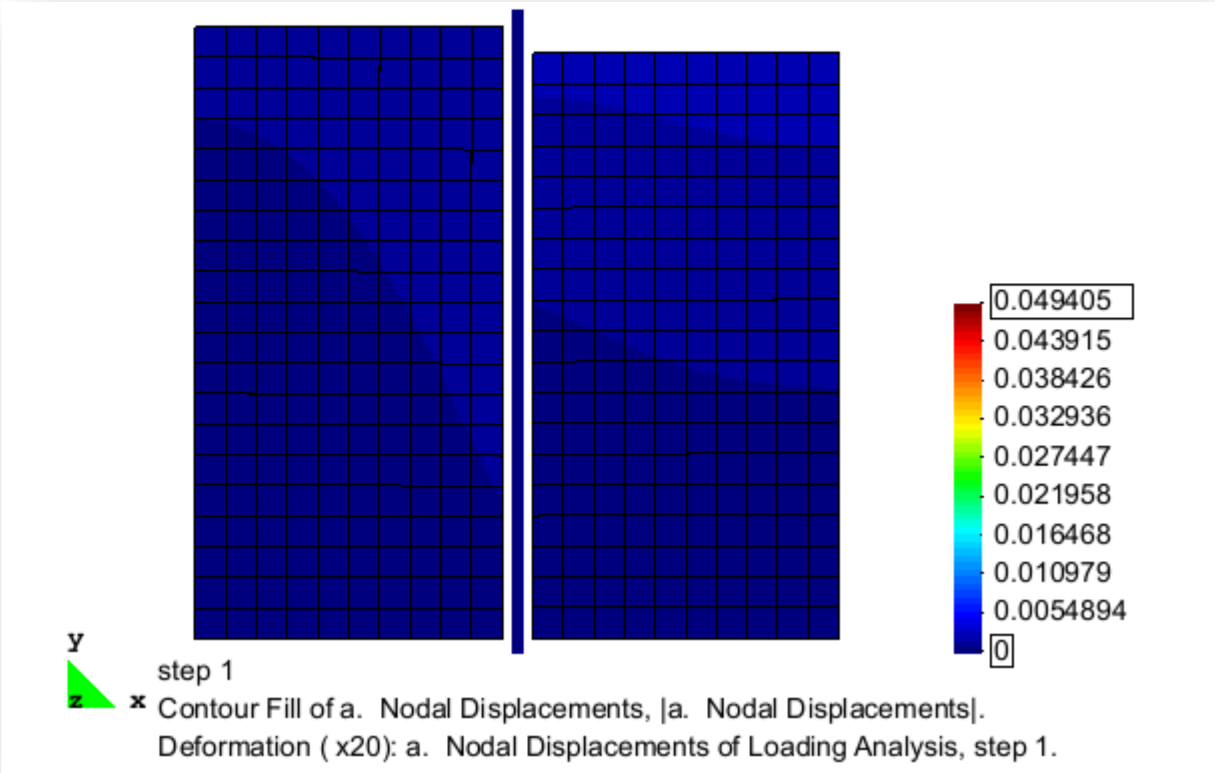


shear stress contours



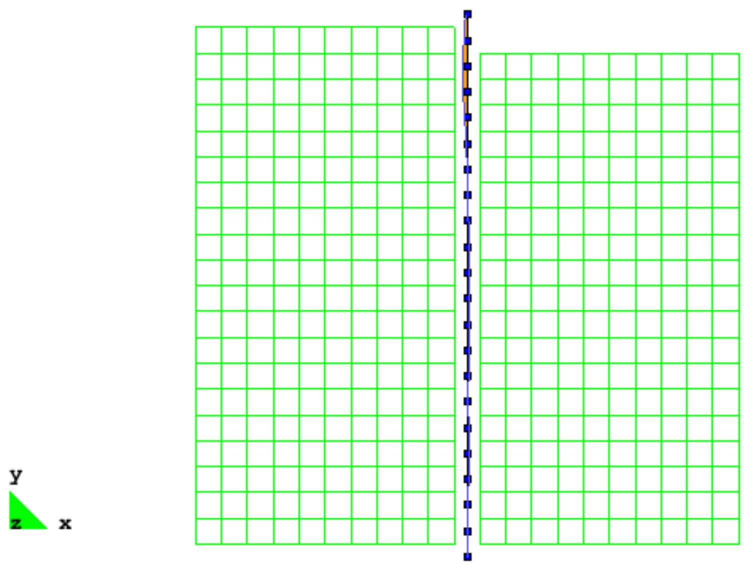
Excavation Analysis

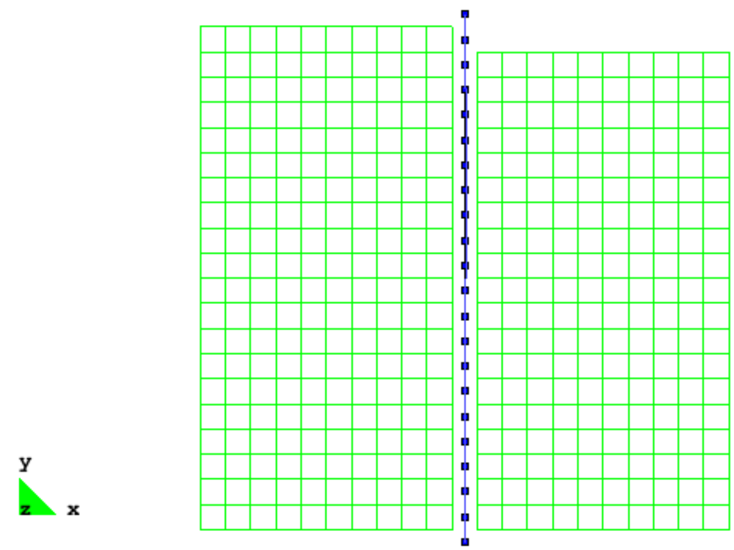
Nodal displacement magnitude during the excavation analysis



Excavation Analysis

shear and moment in the wall during the excavation analysis



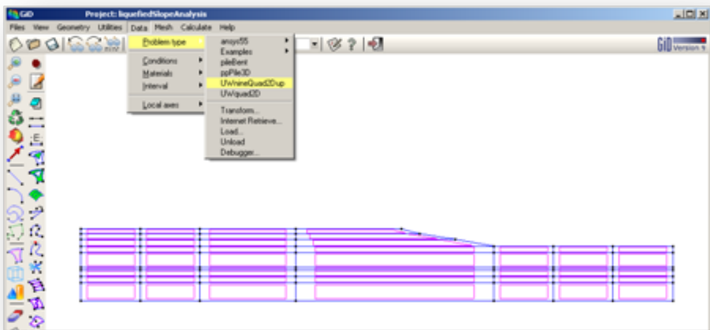


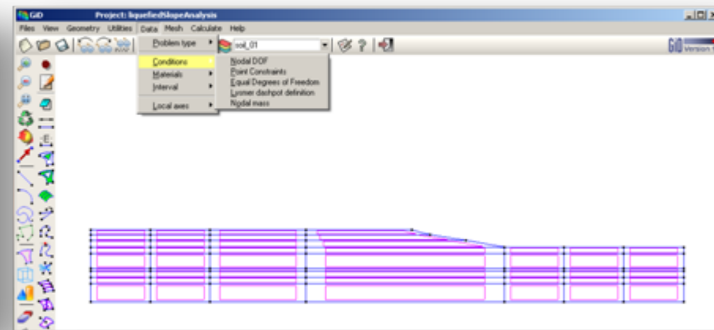
Take advantage of pre- and post-processors

- Difficult to create **tcl** scripts for complex boundary value geotechnical problems.
  - complex foundation configurations
  - embankments
  - wharves
  - bridges
  - 3-D analysis
- Need to use pre- and post processors to create meshes and visualize results
- **GID**, just one possible alternative ☺

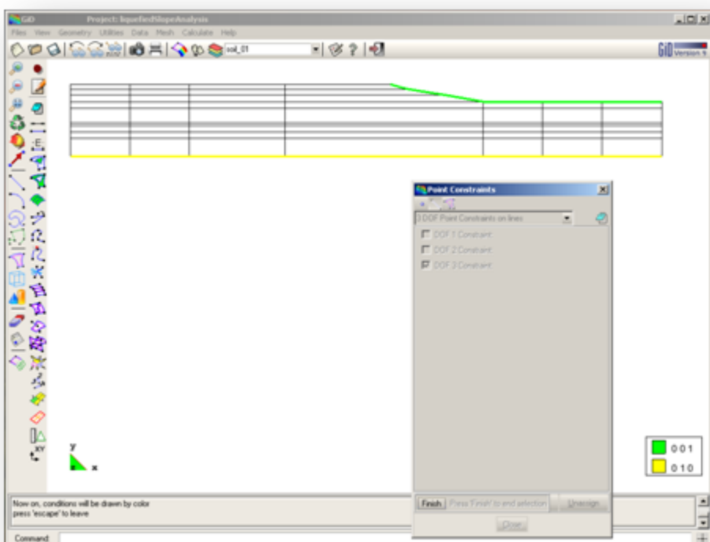
GiD Problem Type for 2D Analysis

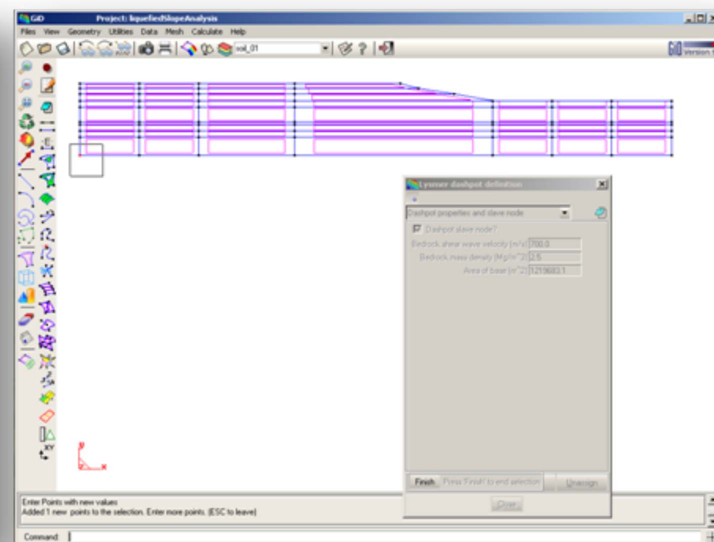
Create geometry and select problemType





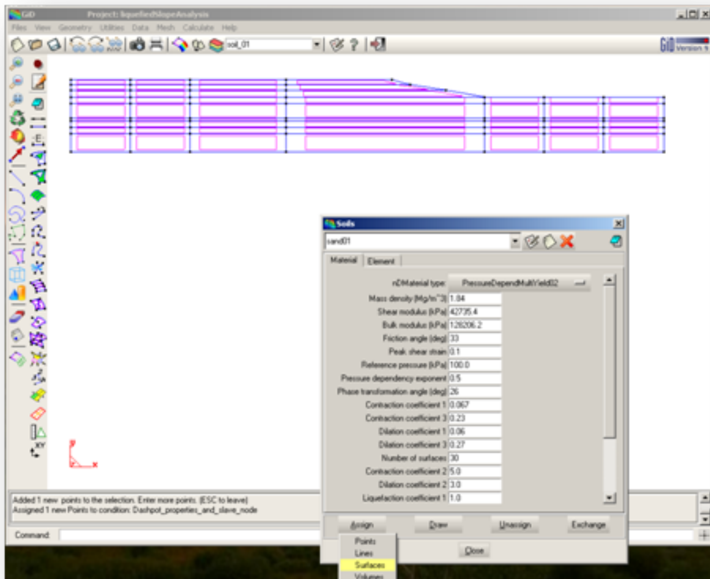
Assign boundary conditions

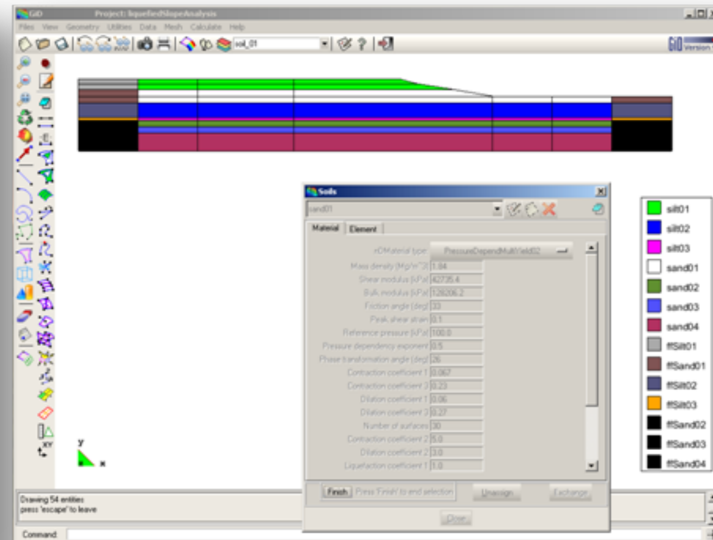




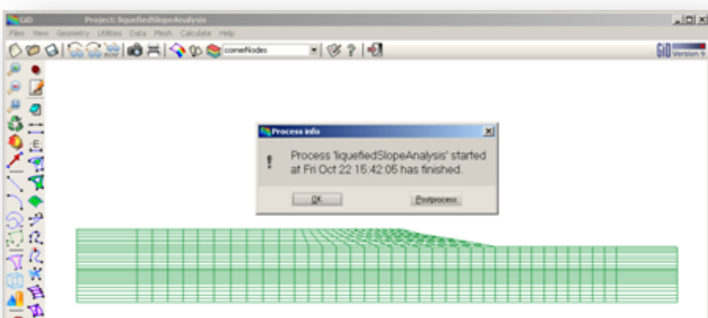
GiD Problem Type

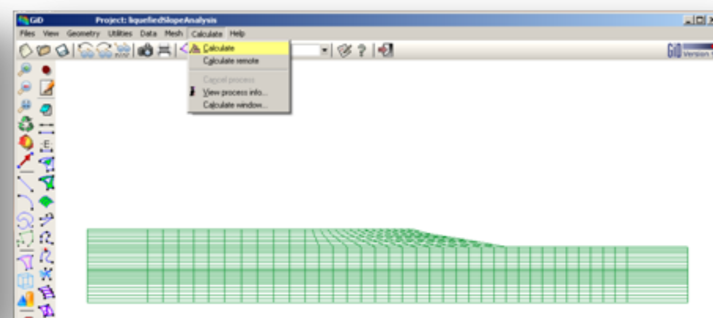
Assign materials to the geometry





Generate mesh and OpenSees input file

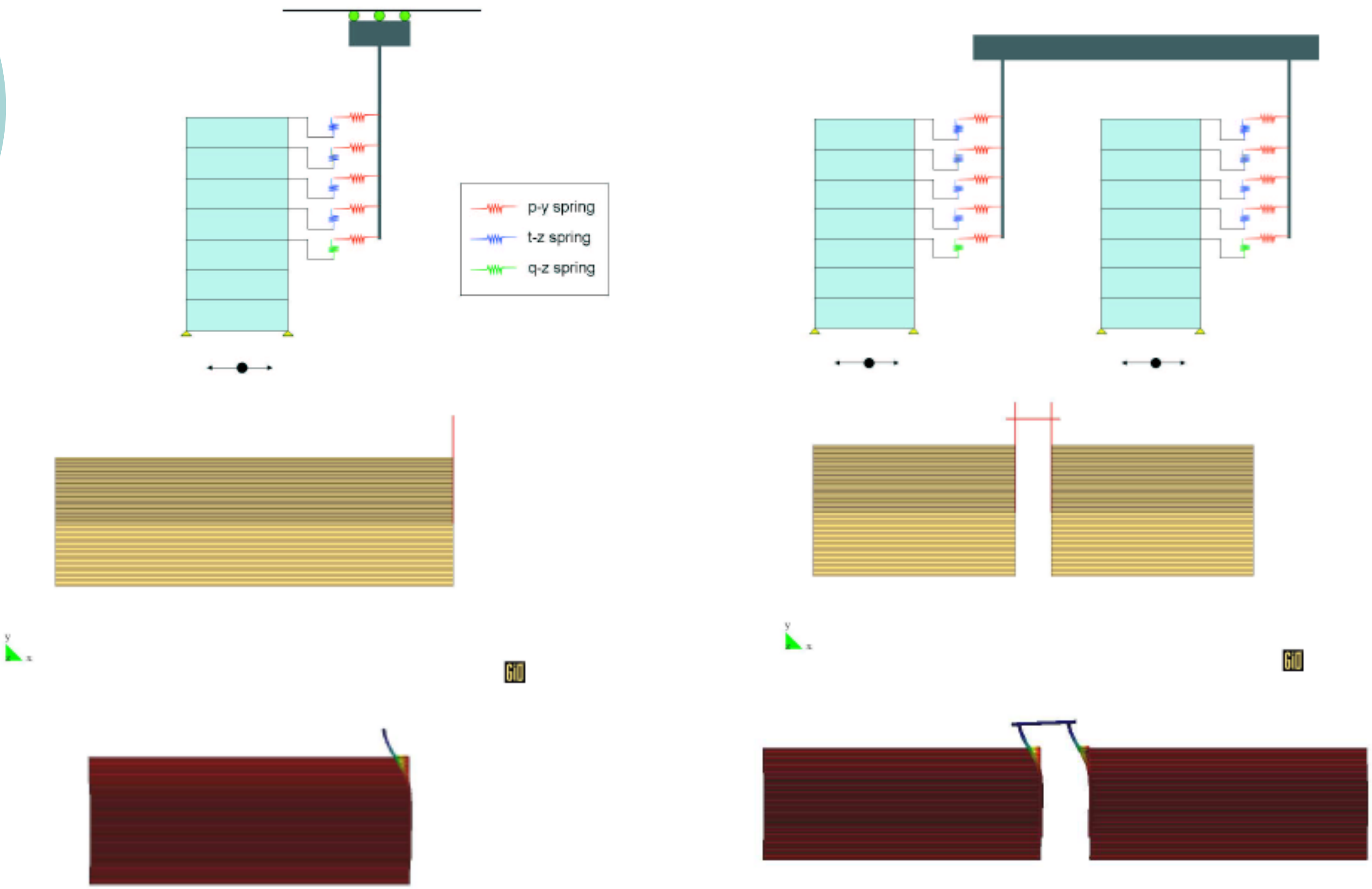




Some research projects completed using OpenSees

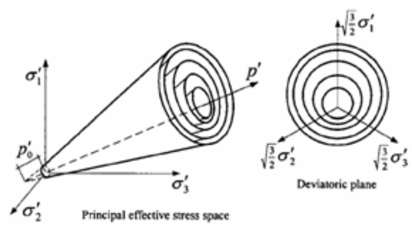
- Dynamic analysis of piles
- Analysis of complete bridge system
- 3D analysis of piles
- 3D analysis of bridge abutment

Dynamic Analysis of Piles in **OpenSees**



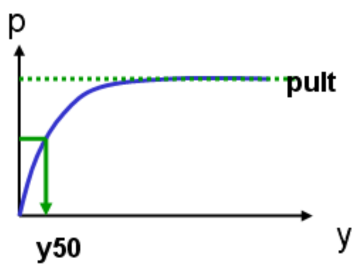
SPSI modeling in OpenSees

Soil model (by Yang & Elgamal)



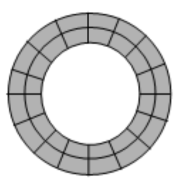
pressure dependent multi-yield material

P-y spring model (by Boulanger)

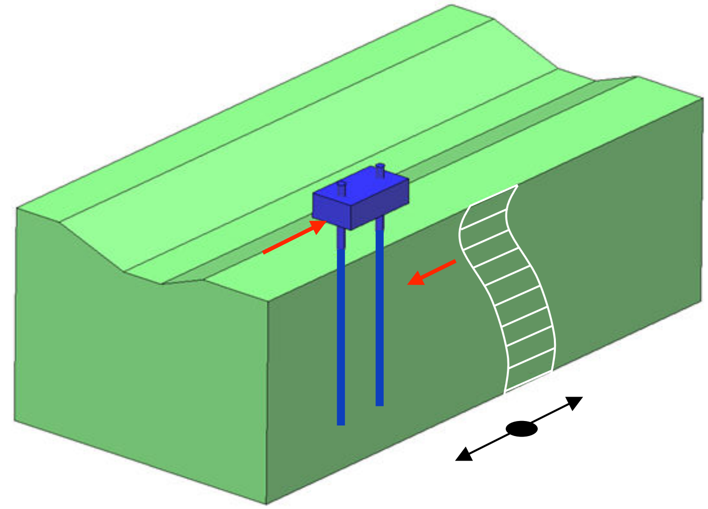


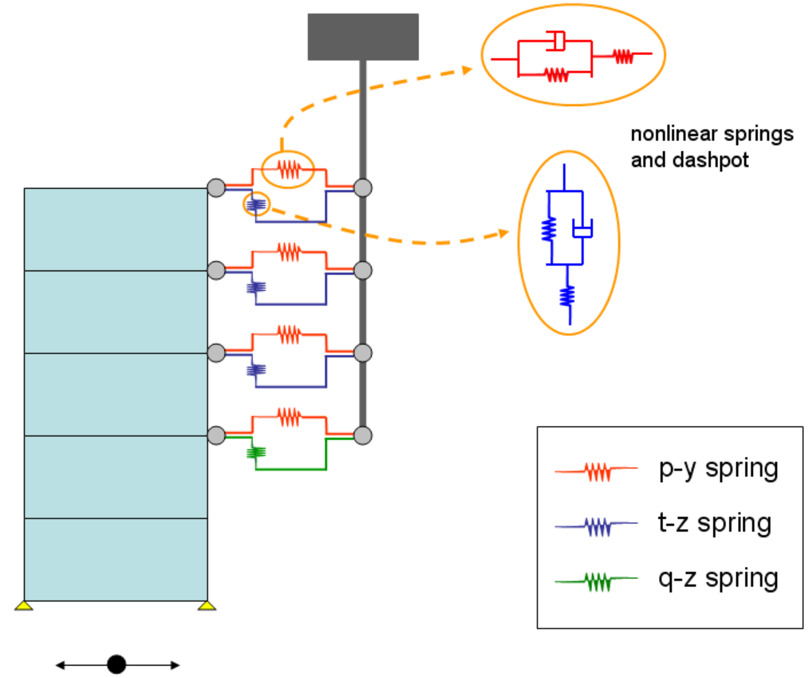
API (1993)

Pile model

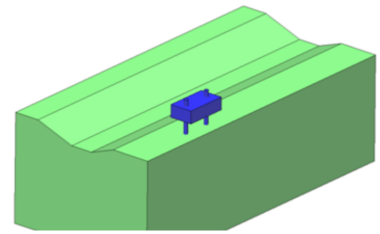


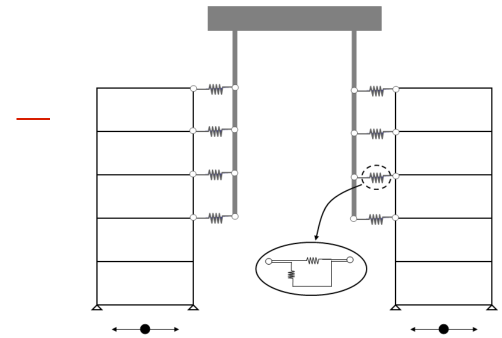
nonlinear beam column elements using fiber section

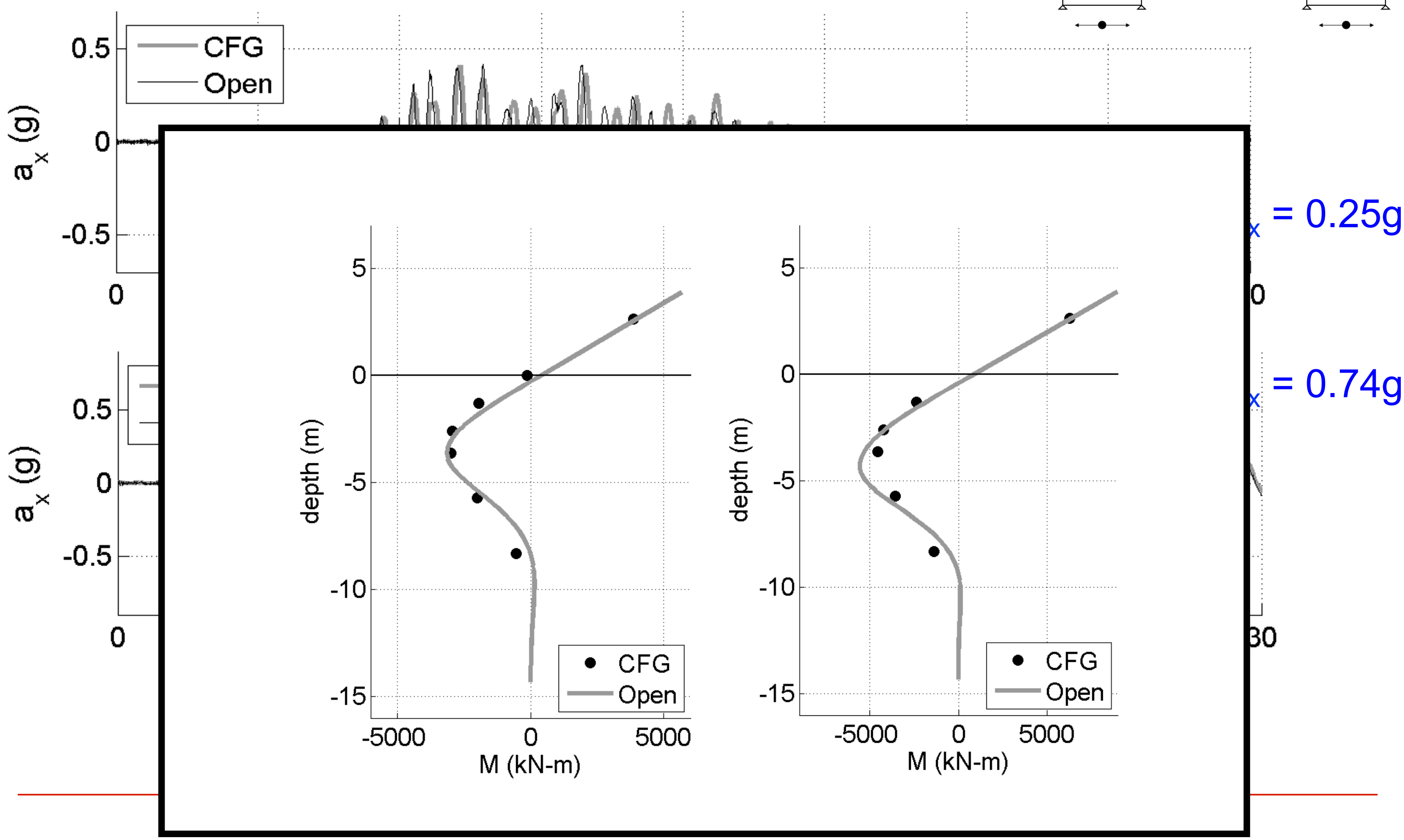




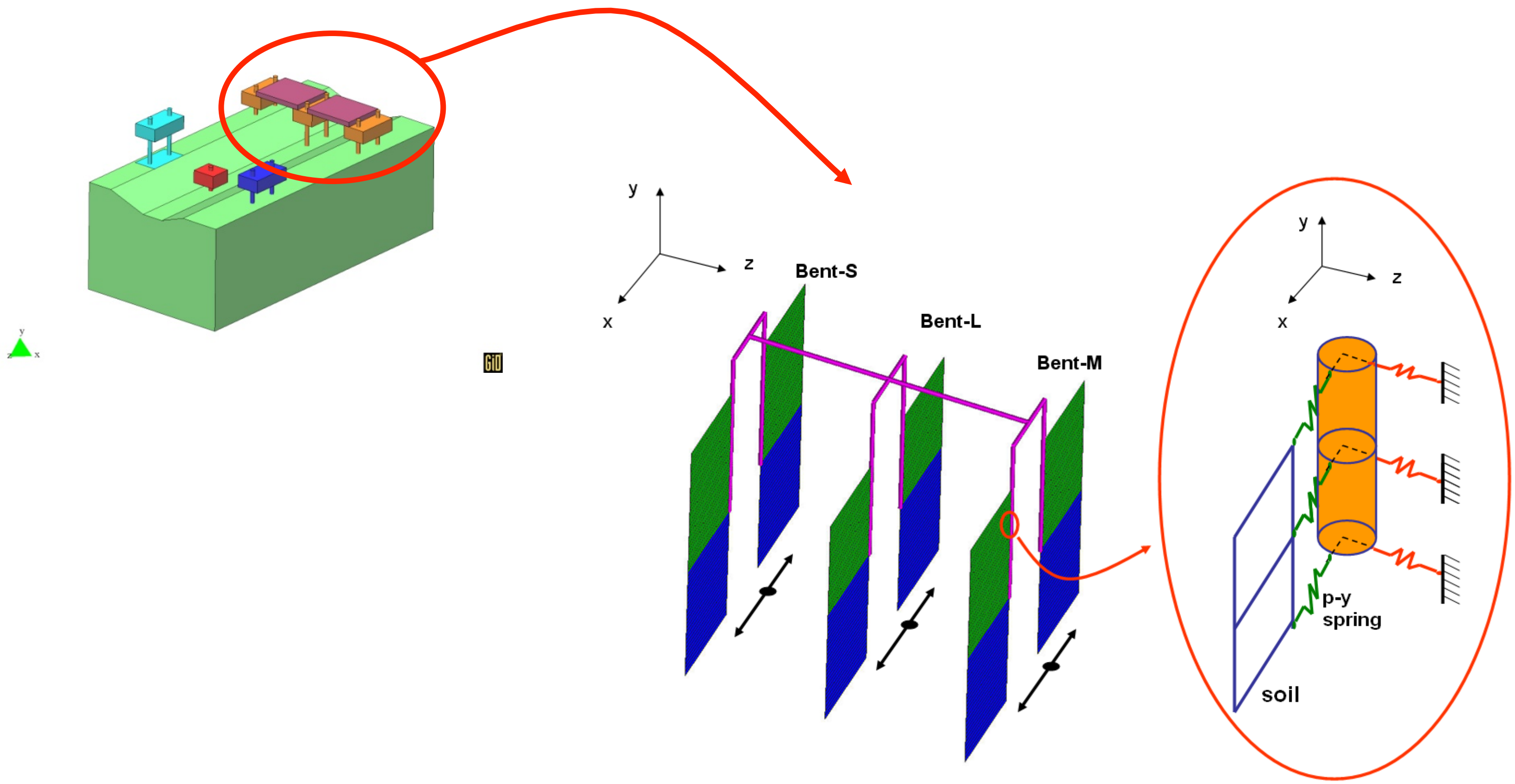
Two-column Bent



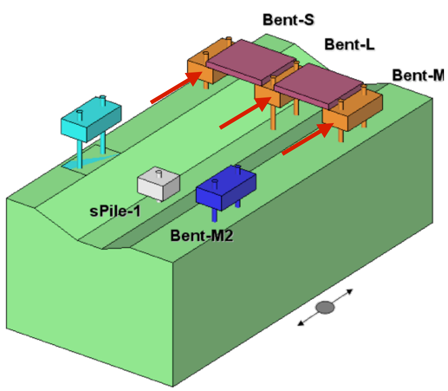


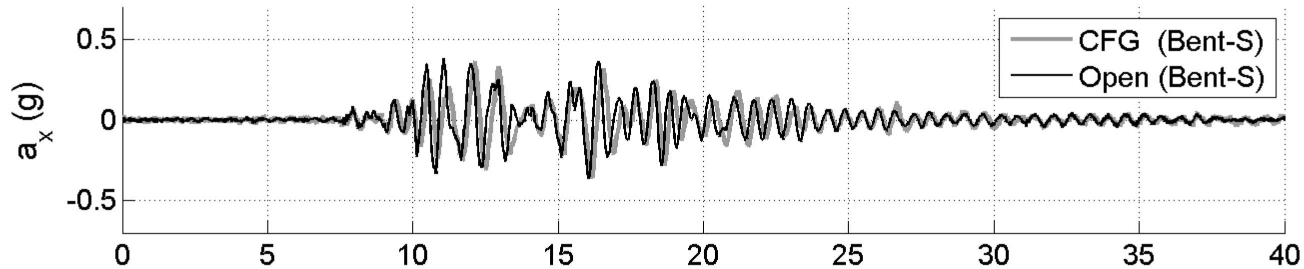


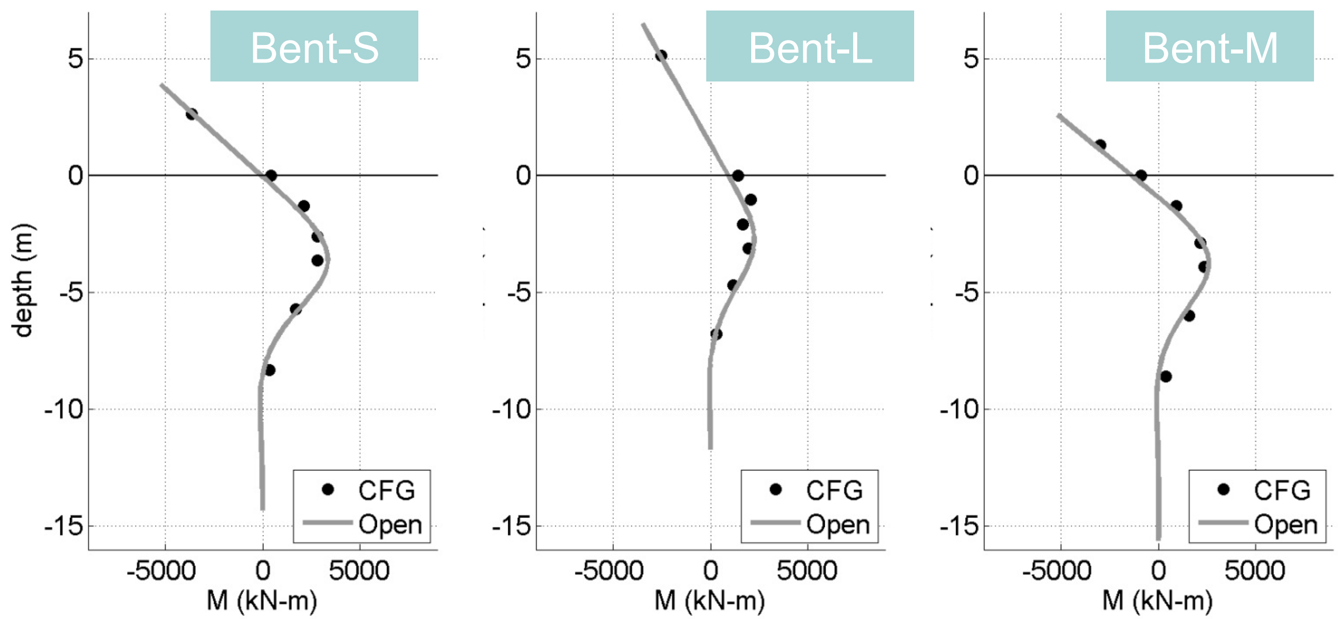
Two-span bridge



Two-span bridge







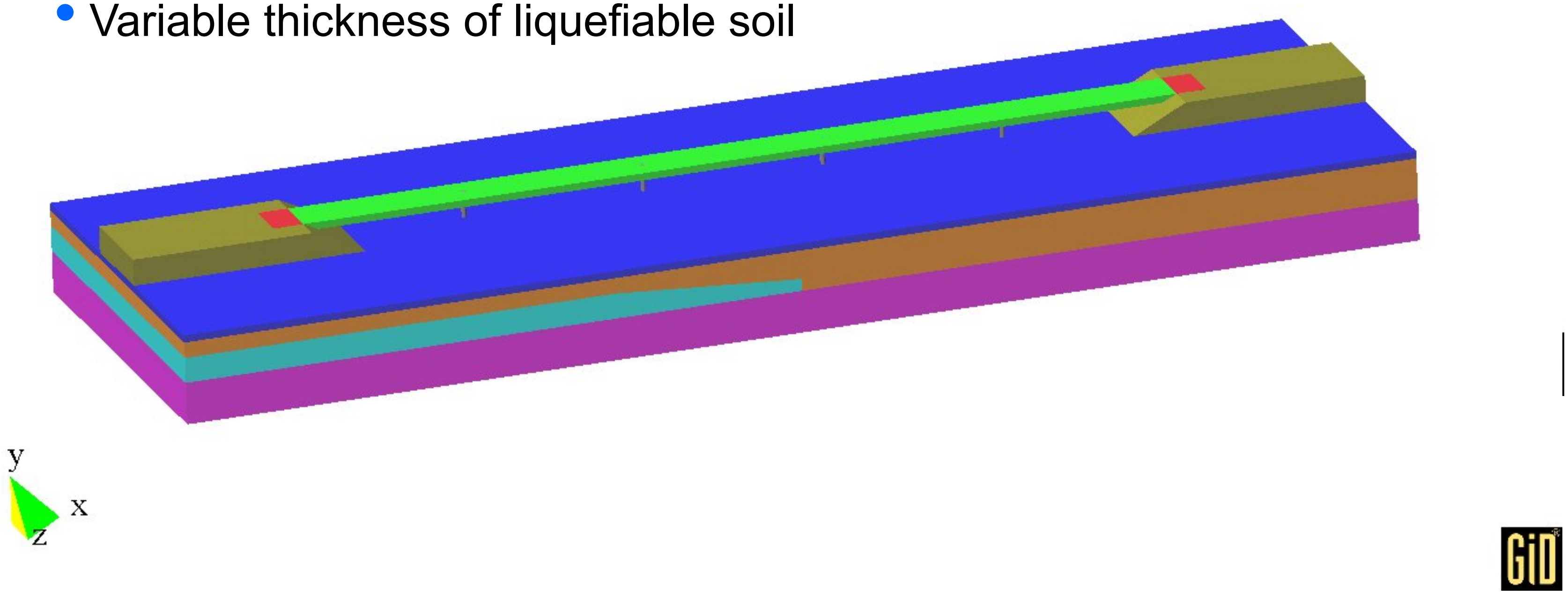
SPSI of a complete bridge system

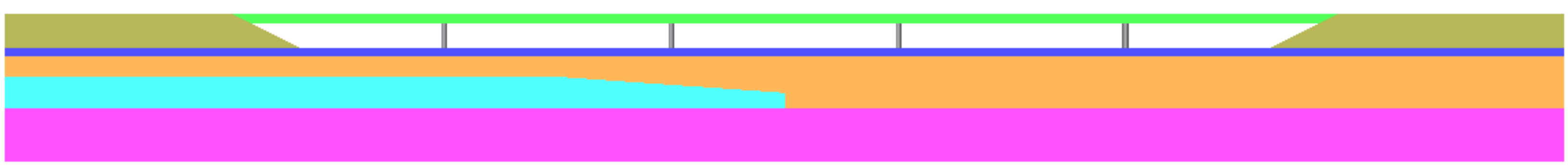
- Five-span bridge
- pile group foundation
- abutment
- liquefiable soil / various layers

- lateral spreading
- earthquake intensities
- uncertainties

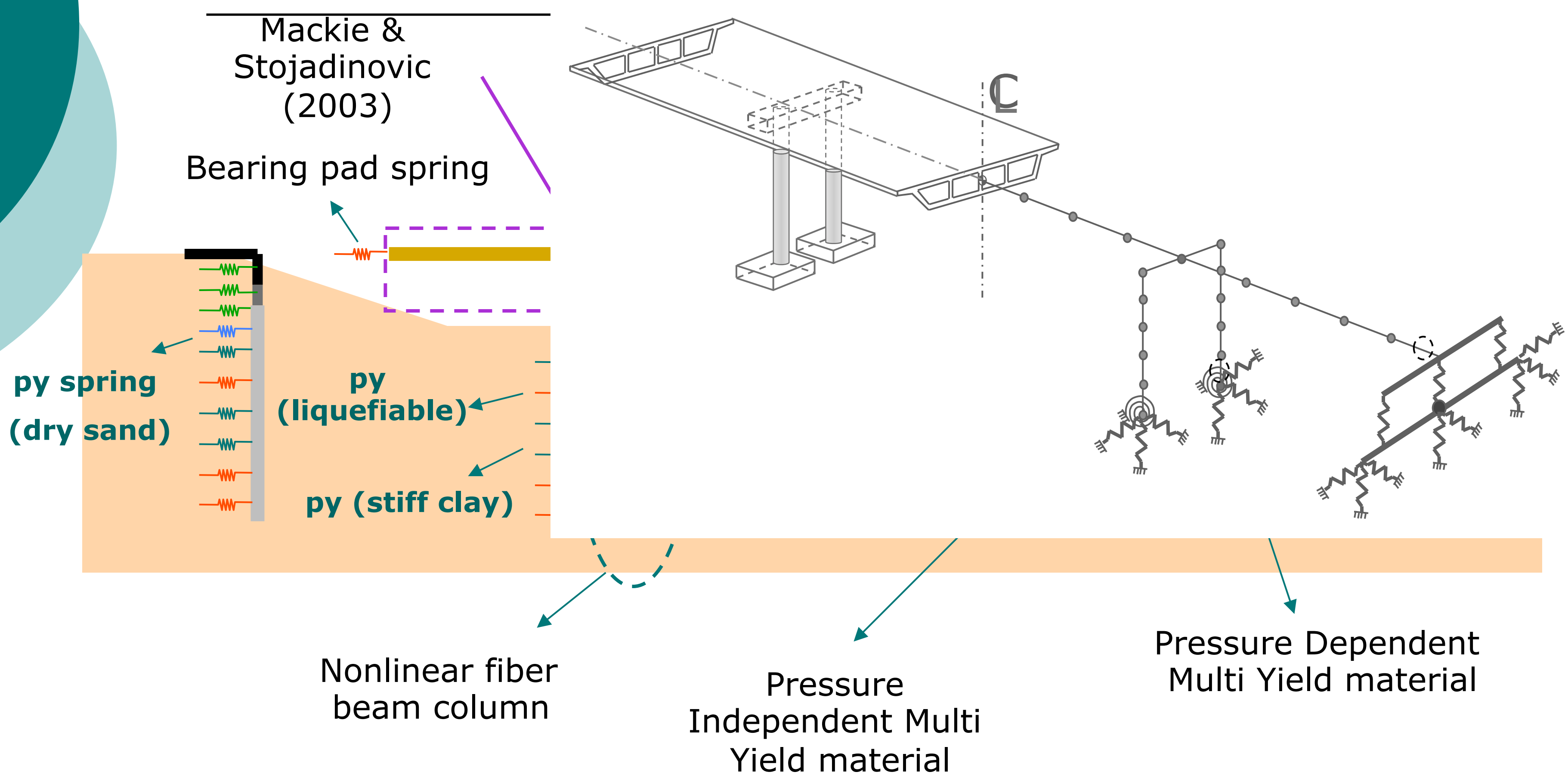
SPSI of a complete bridge system

- Five-span bridge
- Approach embankments
- Variable thickness of liquefiable soil



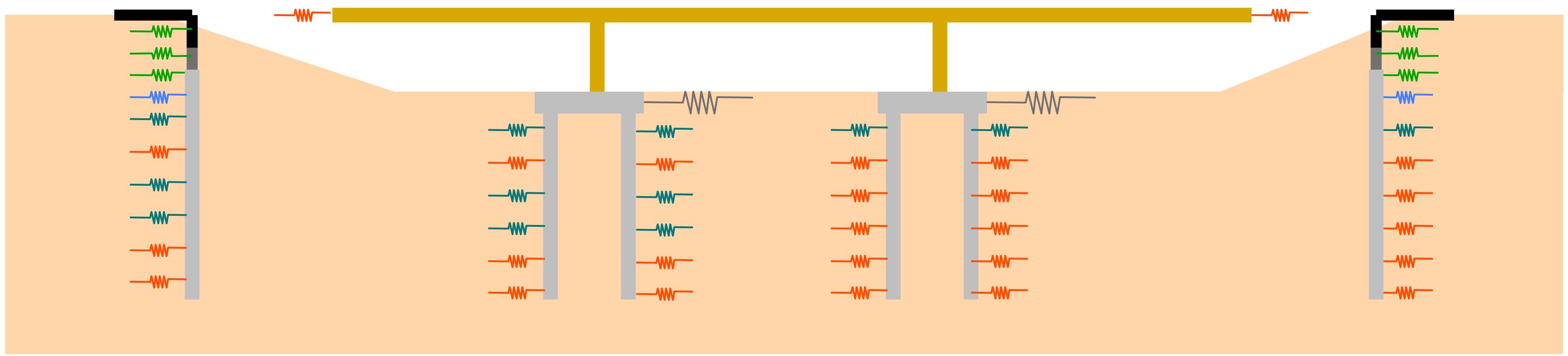


SPSI of a complete bridge system

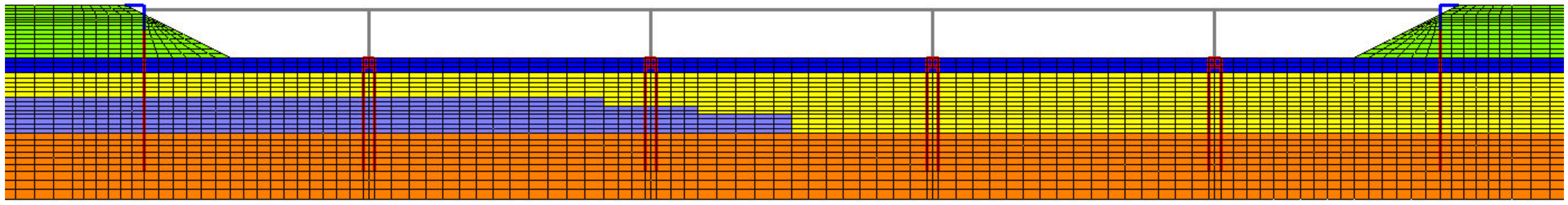


SPSI of a complete bridge system

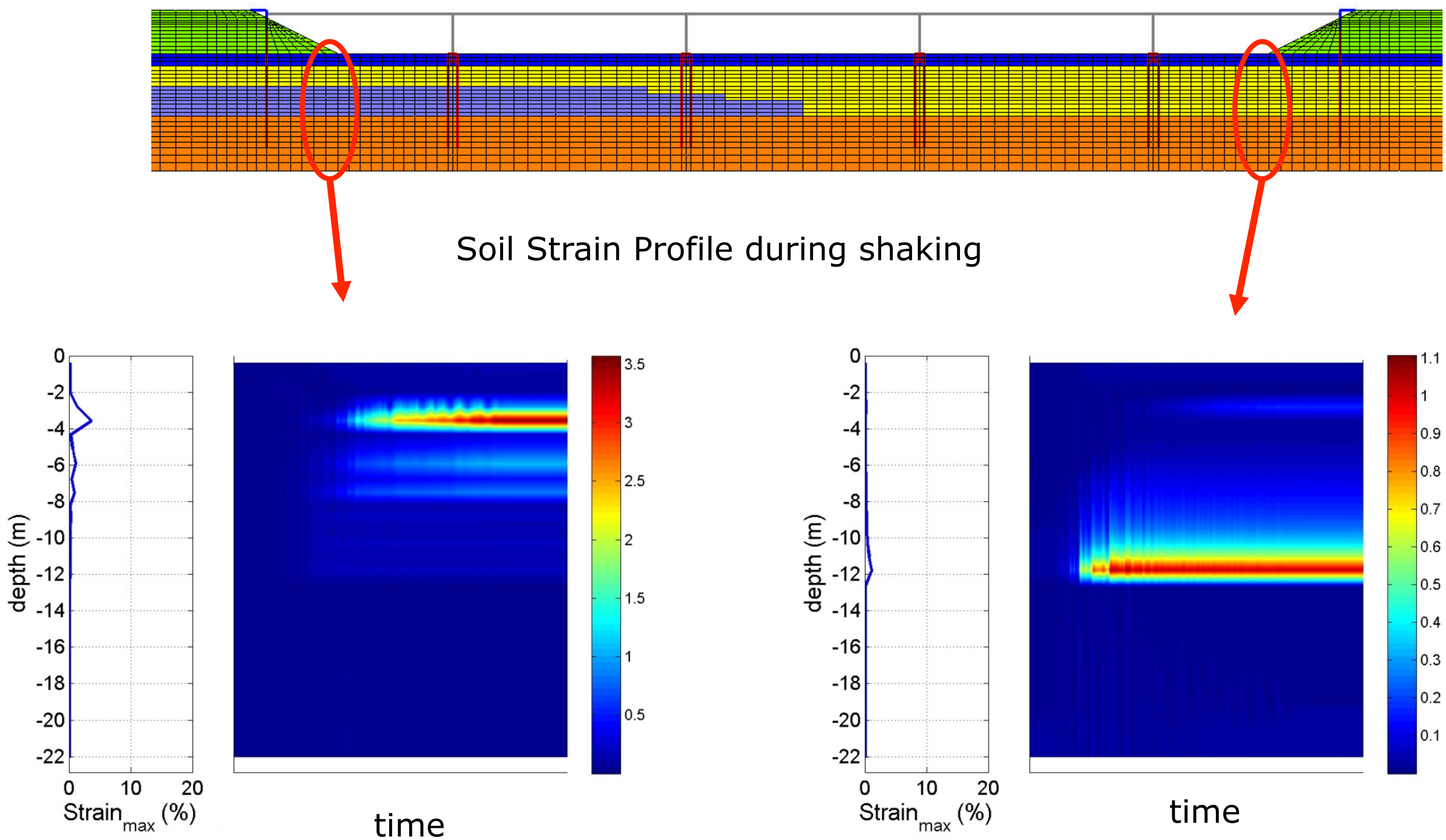
Bridge Idealization



OpenSees model

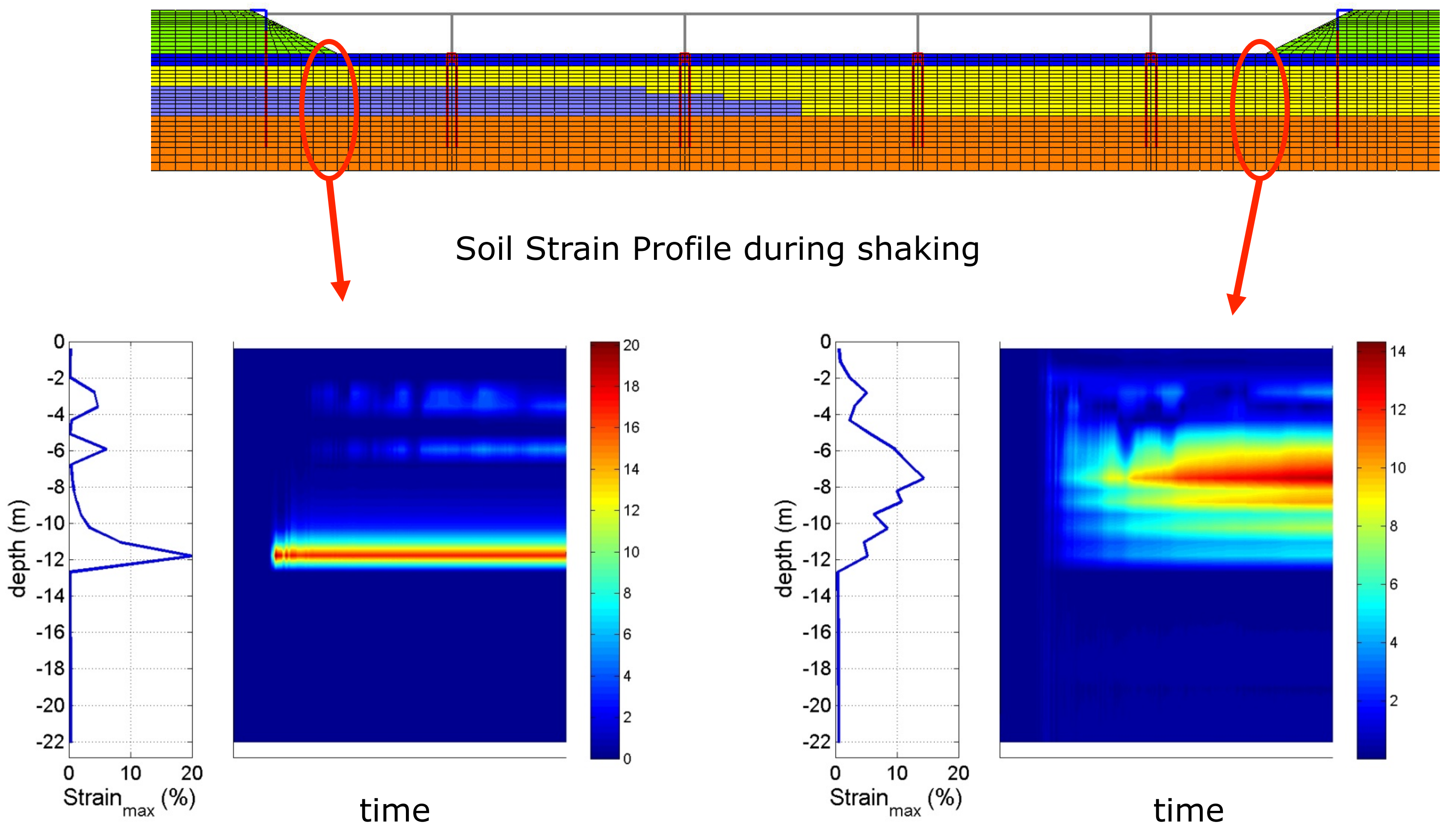


SPSI of a complete bridge system



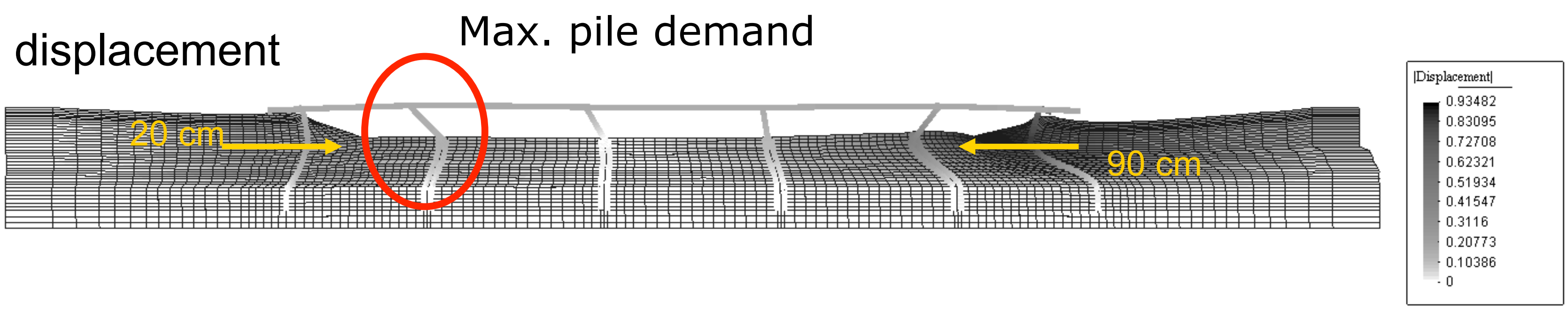
Northridge motion (0.25g)

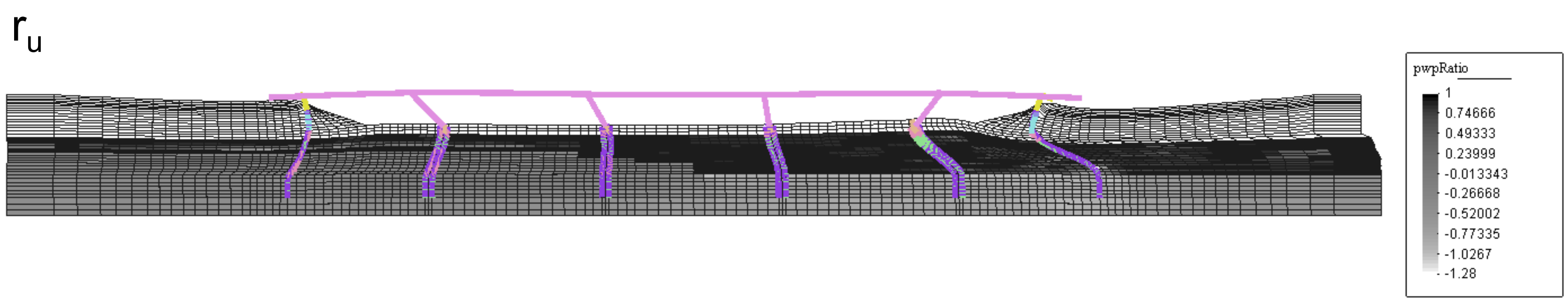
SPSI of a complete bridge system



Loma Prieta (1.19g)

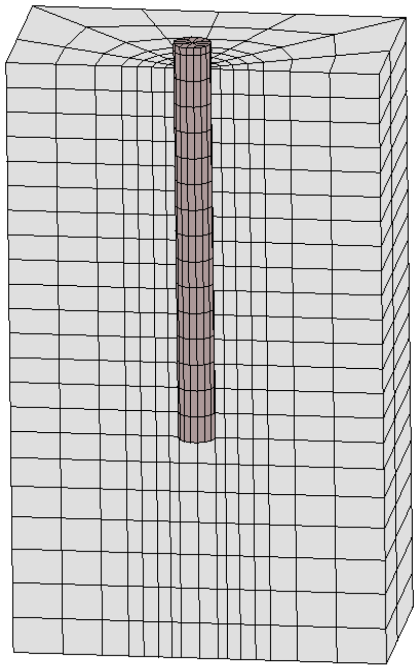
SPSI of a complete bridge system



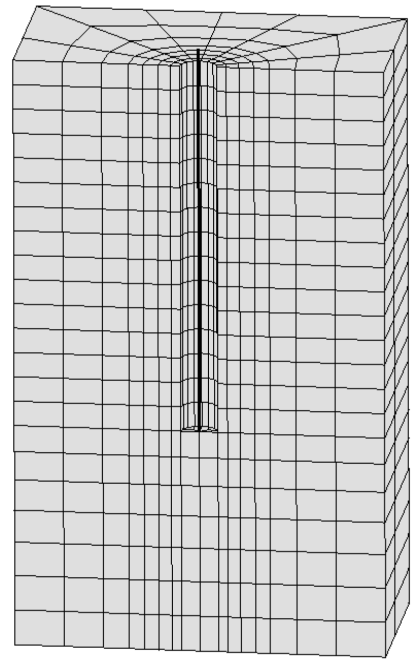


Erzincan, Turkey 1992 (a_{max} = 0.70g)

3D Pile Analysis



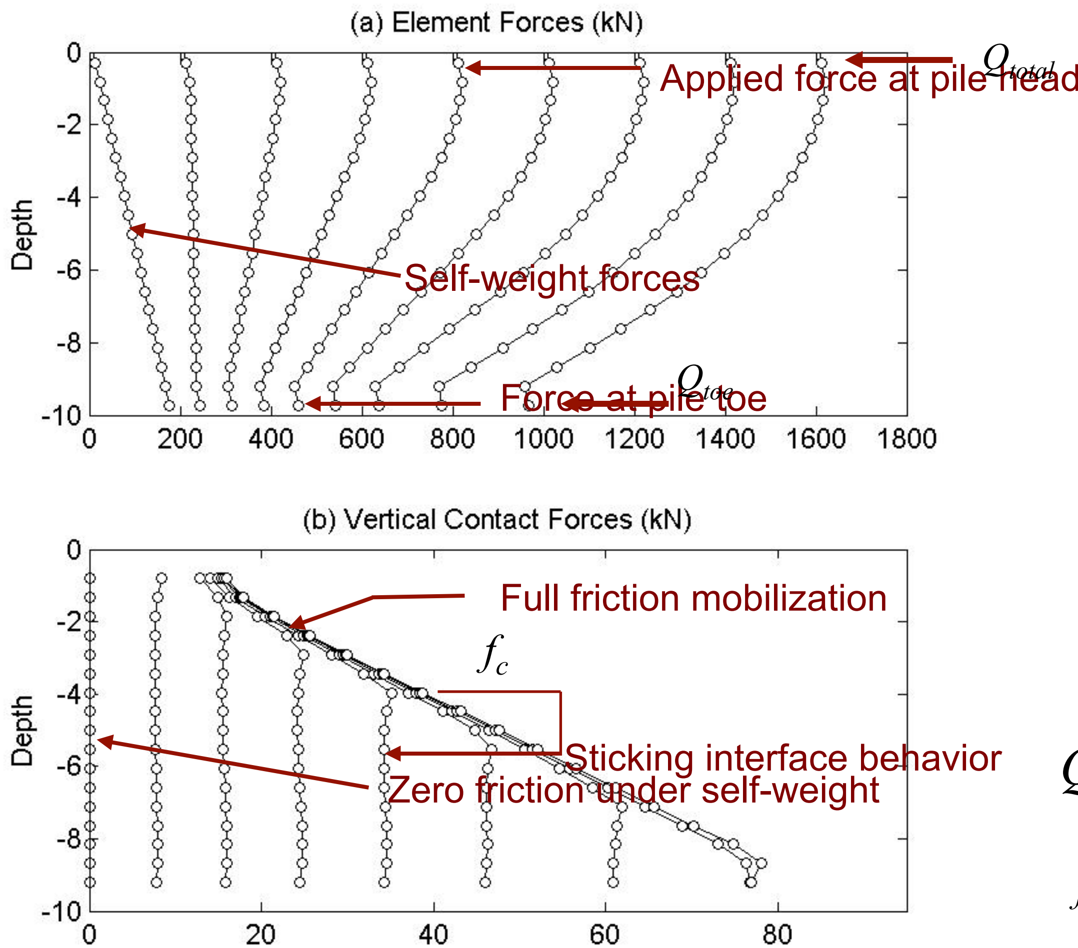
Solid-Solid Model

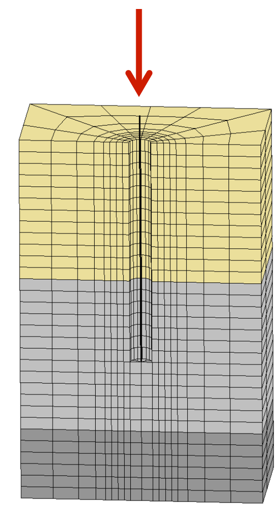


Beam-Solid Model

3D Pile Analysis
Axially Loaded Piles

- Evaluation of pile forces and accumulation of side resistance





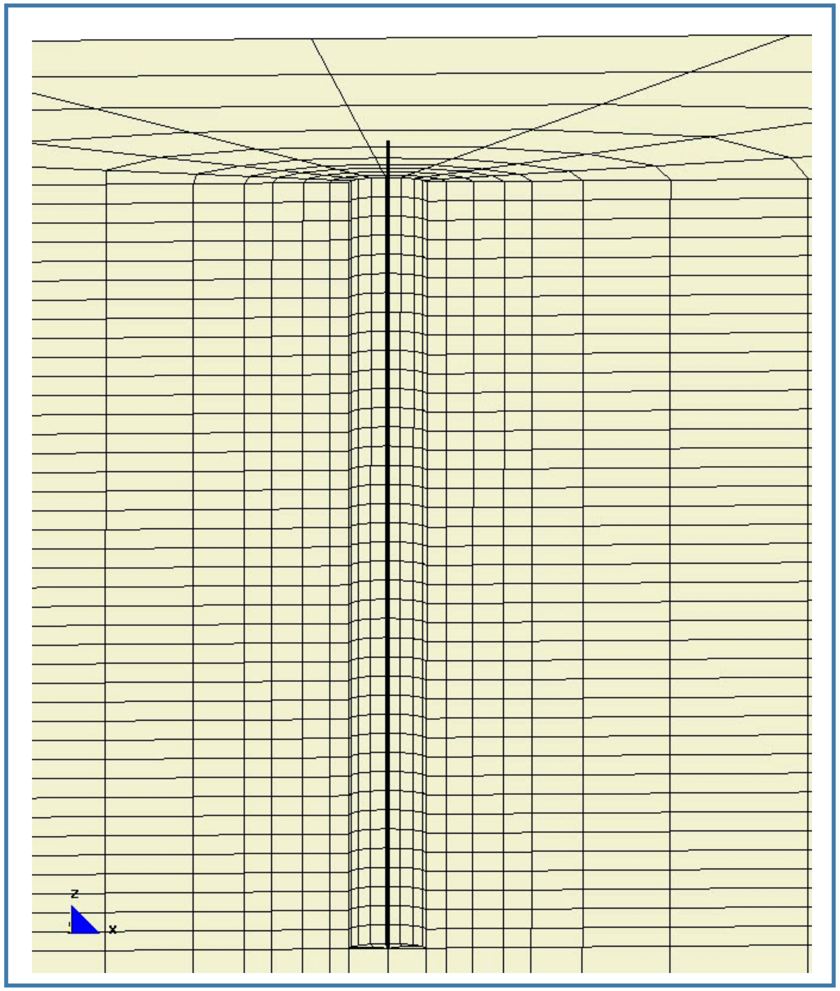
$$Q_{total} = Q_{toe} + Q_{side}$$

$$Q_{side} = \pi B \sum f_c \, dz$$

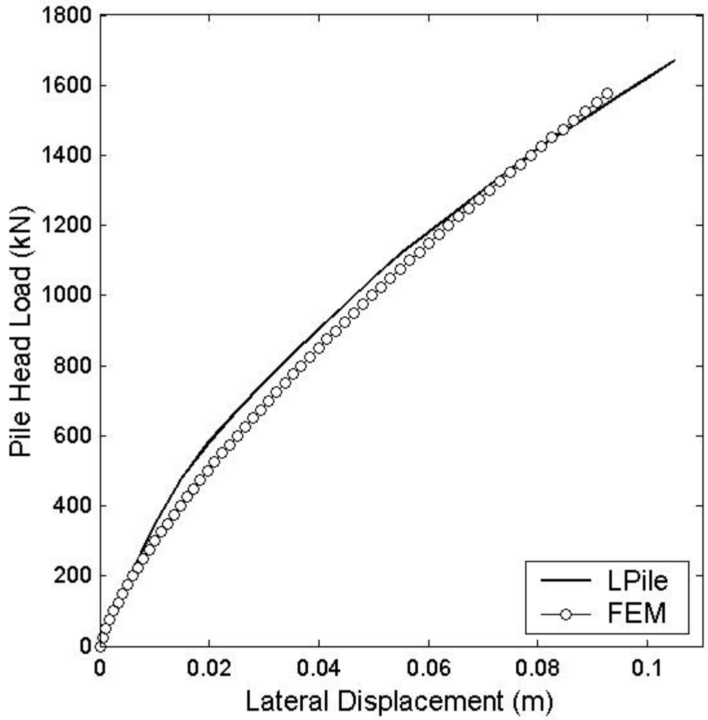
$$f_c = \sigma_h(z) \tan \delta$$

3D Pile Analysis
Laterally Loaded Piles (solid-beam contact element)

- Perform numerical load test



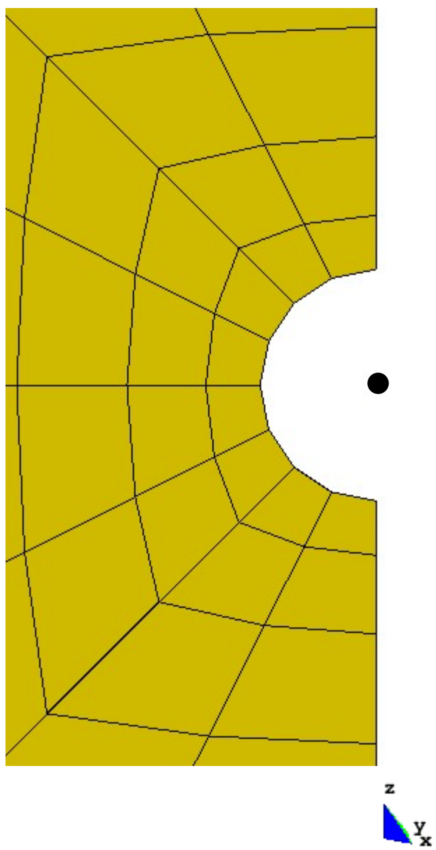
- Compare results

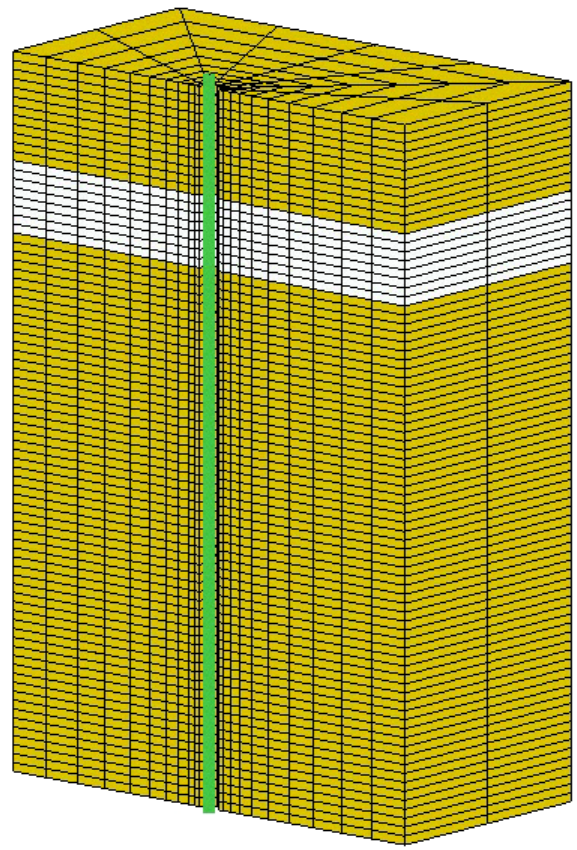


3x Magnification

3D Pile Analysis
Lateral Spreading Effects

Bateralsispmodeled withdbrickaeempnisgandfreleDfuckdisPlacemerfapeofile to the
bounstitutive fnthe motlecapture pressure-dependent strength



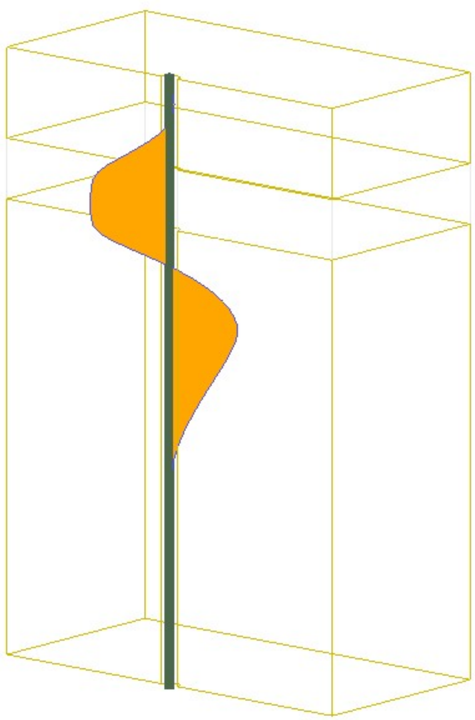


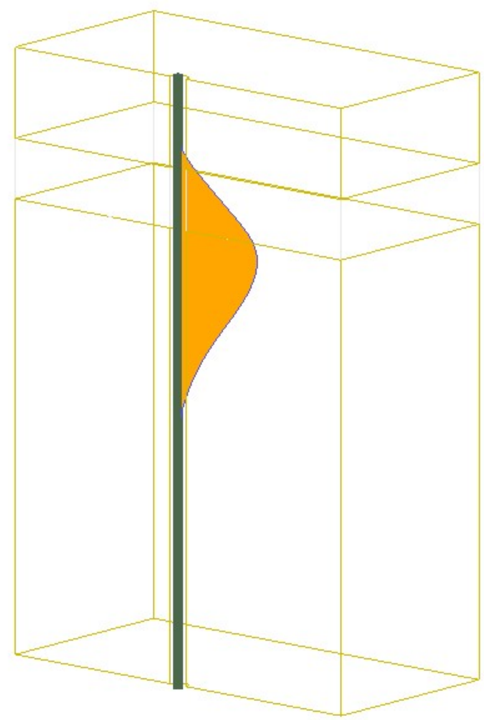
3D Pile Analysis
Lateral Spreading Effects

The beam-solid contact elements enable the use of standard beam-column elements for the pile

This allows for simple recovery of the shear force and bending moment demands placed upon the pile

Additionally, the surface traction acting on the pile-soil interface can be recovered and resolved into the forces applied by the soil to the pile



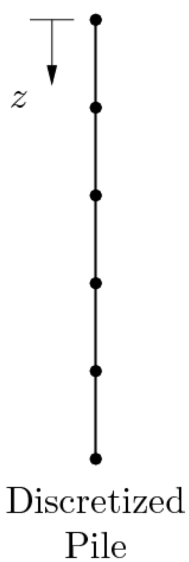


3D Pile Analysis
Lateral Spreading Effects

Work with 3D FE models has shown that use of a general pile deformation creates *p-y* curves which are influenced by the selected pile kinematics

A rigid pile kinematic is used to evenly activate the soil response with depth and to obtain *p-y* curves which are free from the influence of pile kinematics, reflecting only the response of the soil.

Computational process

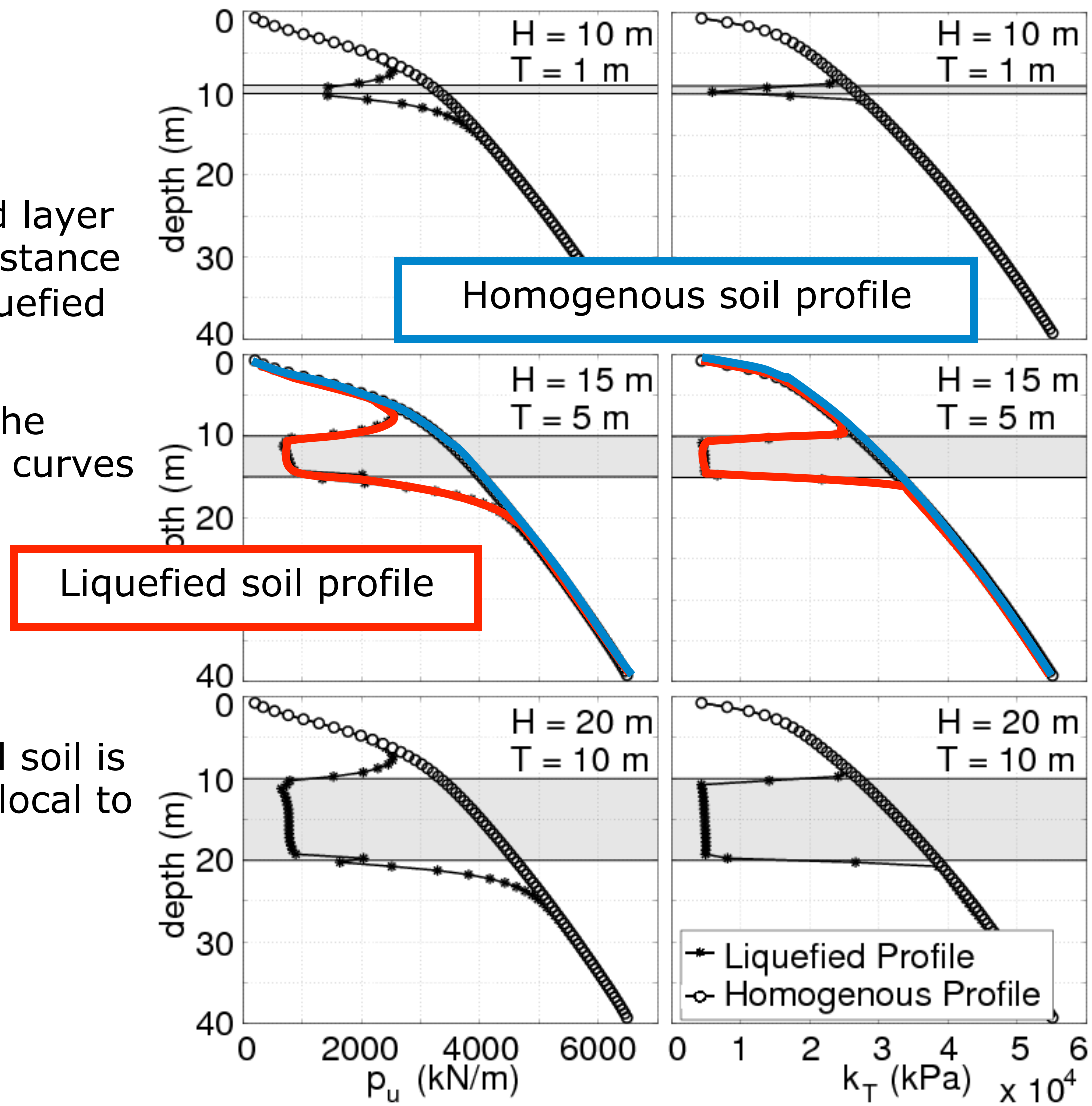


3D Pile Analysis
Lateral Spreading Effects

The presence of the weaker liquefied layer effectively reduces the available resistance of the adjacent portions of the unliquefied soil

This is manifested in a reduction in the ultimate lateral resistance of the p-y curves near the liquefied layer

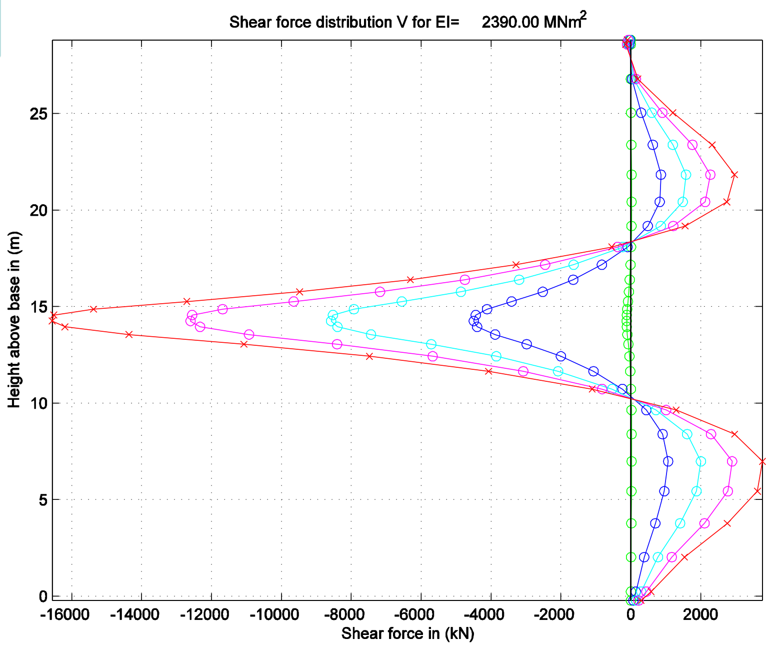
The initial stiffness of the unliquefied soil is also reduced, but the effect is more local to the liquefied interface

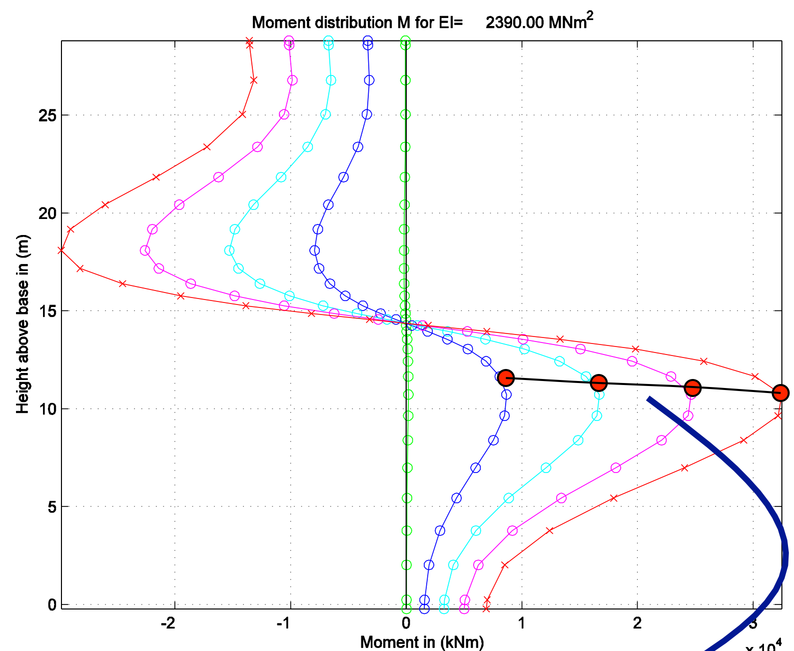


3D Pile Analysis
Lateral Spreading Effects

Shear diagrams

Bending Moment diagrams





Location and value of maxV and maxM changes with soil displacement

Recent Improvements at UW

Efficient solid element formulations would greatly benefit the performance of any simulation

How can we obtain more efficient finite element formulations?

- Reduced integration

  The integration of a typical 4-node quadrilateral element involves 4 integrations points. If this could be reduced to only a single integration point, that's 4 times less work. In 3D, it would be 8 times less work.

Can this be done?

- There are issues which must be overcome in order to use single point integration. The stiffness matrix becomes rank deficient, leading to spurious modes

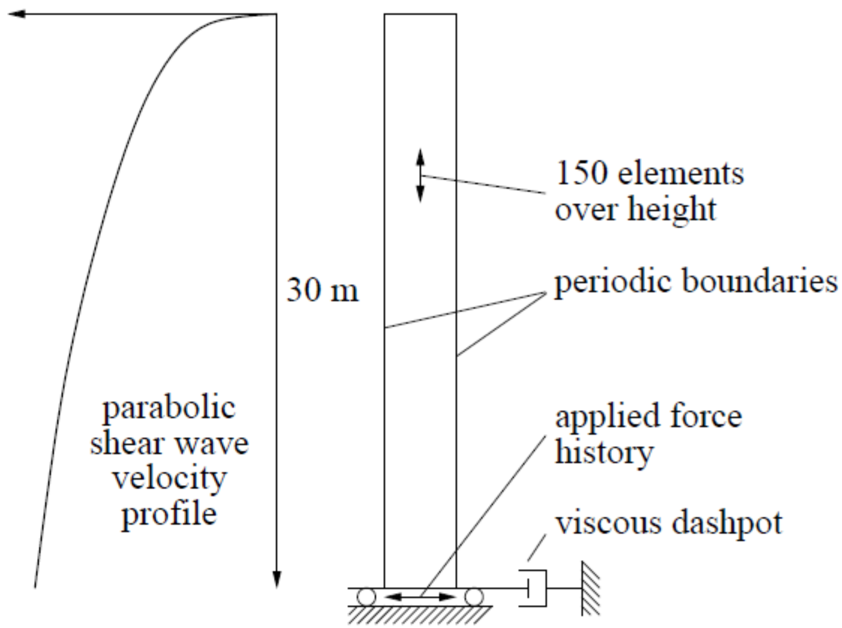
- Stabilization techniques can be used to overcome the rank deficiency

- A single-point integration element with assumed strain hourglass stabilization has been implemented in OpenSees → *SSPquad*

Stabilized Single-Point Quad Element

The single-point element is less computationally demanding than the corresponding full integration element.

Site response analysis test problem



Execution time: Quad element **= 330 sec** SSPquad element = **146 sec**

Modeling Tools and Improvements

Liquefaction and lateral spreading involve saturated soil. When saturated, soil behavior can be described as a two-phase medium.

Finite element formulations have been developed to consider this aspect of soil behavior (Zienkiewicz and Shiomi 1984, Prevost)

The **SSPquad** element has been extended for use in the analysis of fluid saturated porous media. This new element has also been implemented in OpenSees → ***SSPquadUP***

The ***SSPquadUP*** element uses a mixed pressure-displacement formulation commonly known as the u-p approach.

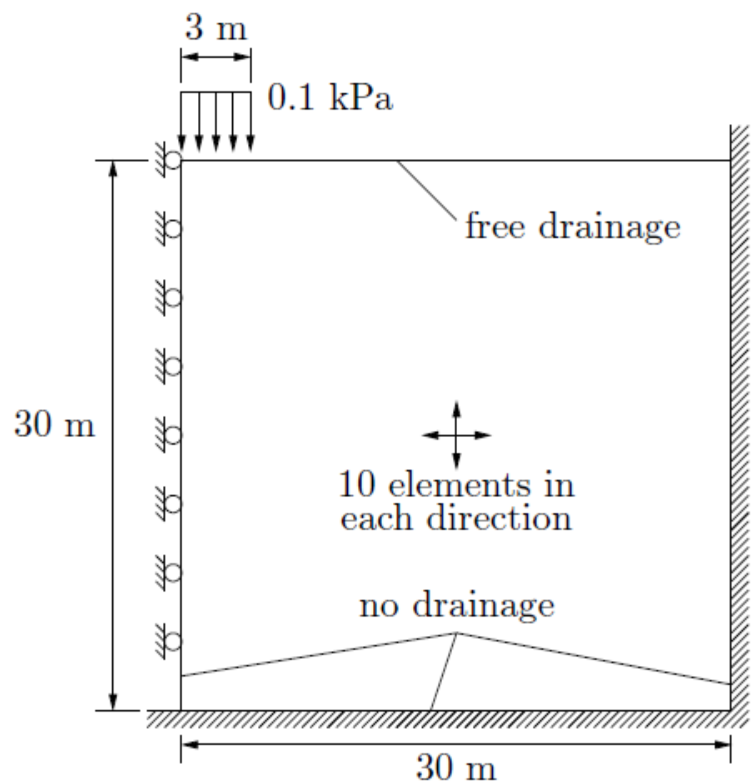
A staggered time integration scheme is used to introduce unconditional stability in the temporal solution and to symmetrize the coupled system.

Near the incompressible-impermeable limit, this element does not satisfy the inf-sup condition, and stability of the pressure field solution cannot be guaranteed. A consistent stabilizing term is added to the system.

Recent Improvement
Stabilized u-p Quad Element

The SSPquadUP element is evaluated using several test problems. The results are compared to a nine-node quad element with a u-p formulation.

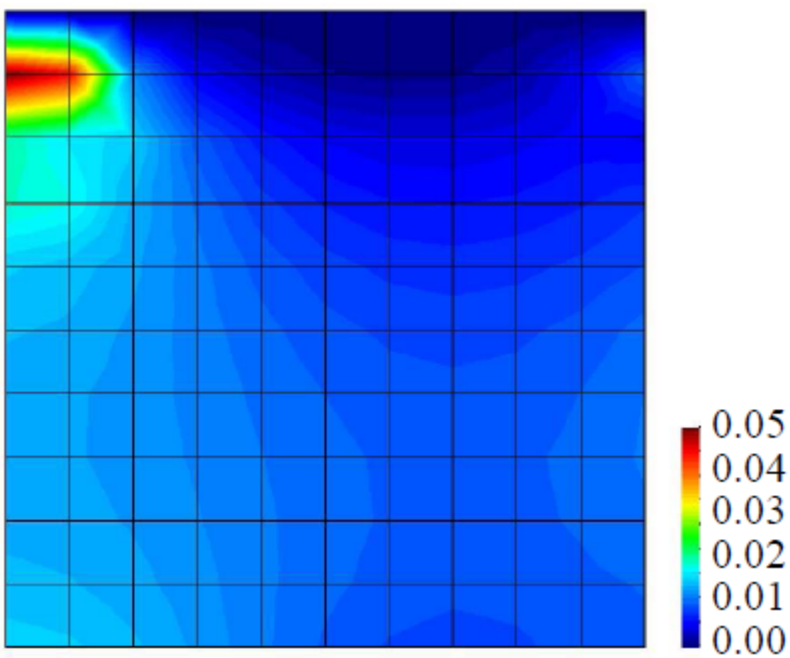
Flexible footing load test problem



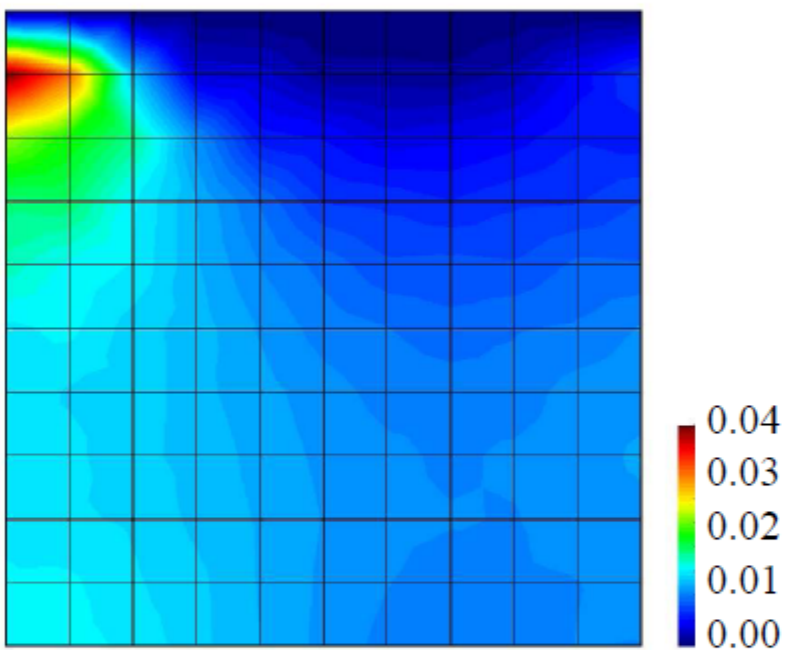
Recent Improvements
Stabilized u-p Quad Element

The effectiveness of the pressure field stabilization near the incompressible limit can be demonstrated by comparing the pore pressure distribution for stabilized and unstabilized cases.

9 node quad element



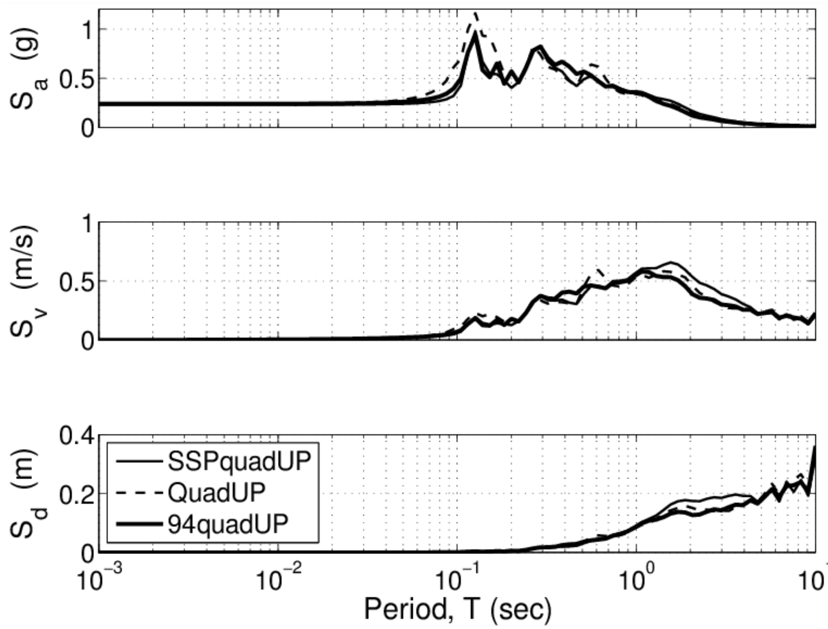
stabilized SSPquadUP



Recent Improvements
Stabilized u-p Quad Element

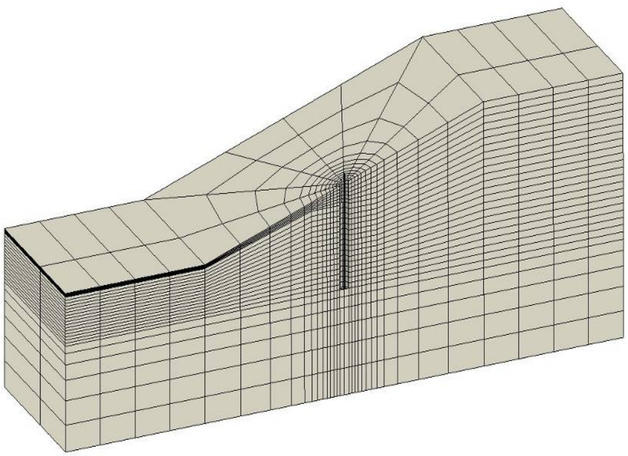
A site response analysis is conducted to gauge the robustness and efficiency of the SSPquadUP element.

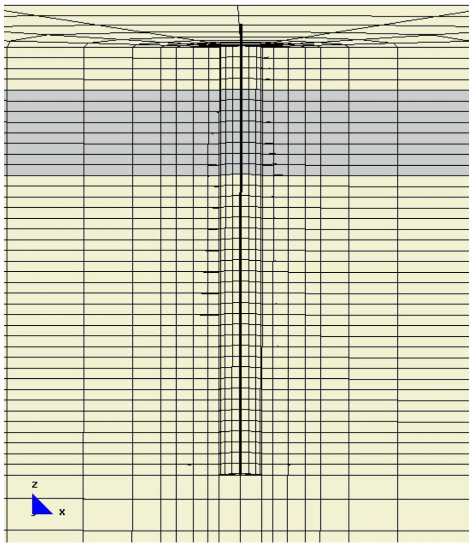
Surface response spectra

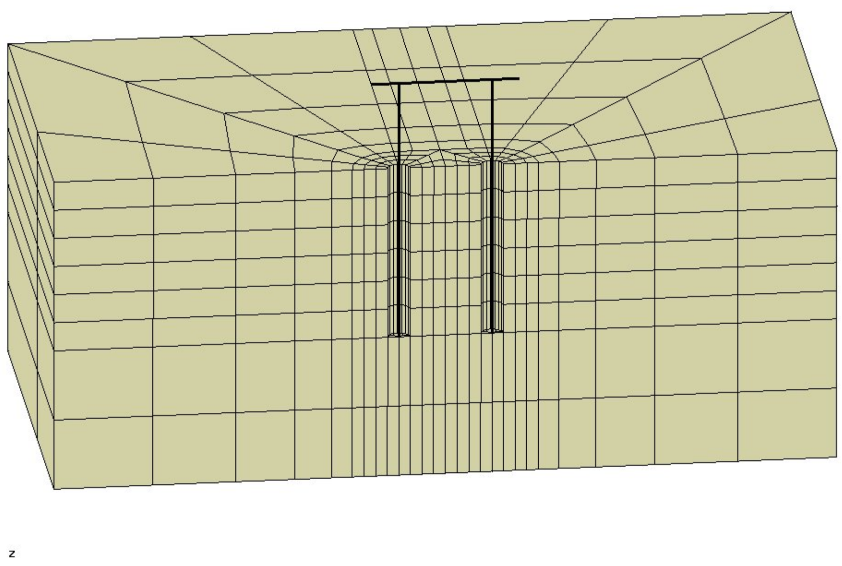


Element	SSPquadUP	QuadUP	94quadUP
Execution time	4 min 12 sec	17 min 41 sec	15 min 20 sec

Other Applications: Piles in Sloping Ground, Bridge bent analysis

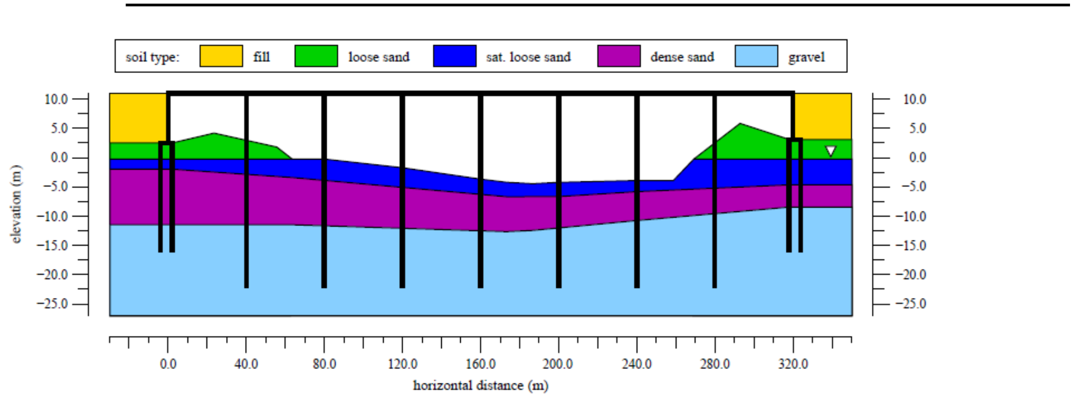




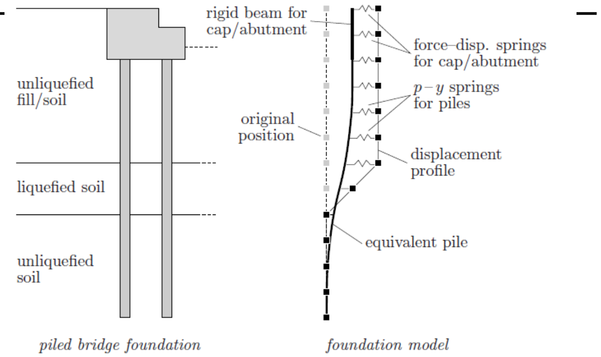


Application

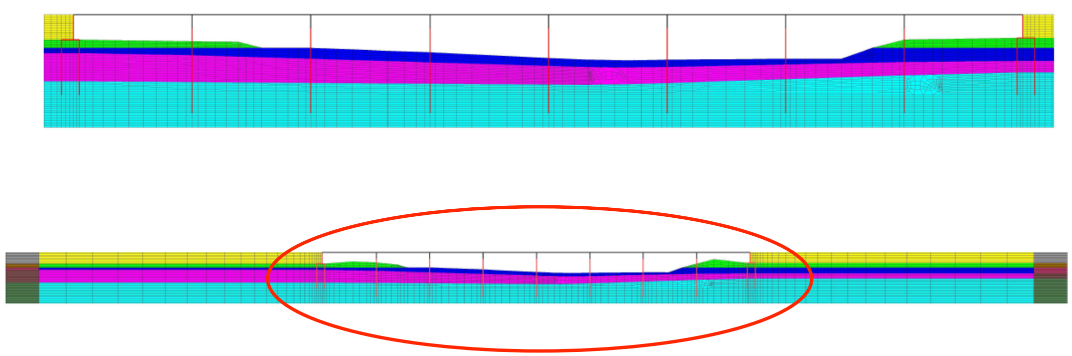
Numerical Analysis of Mataquito River bridge



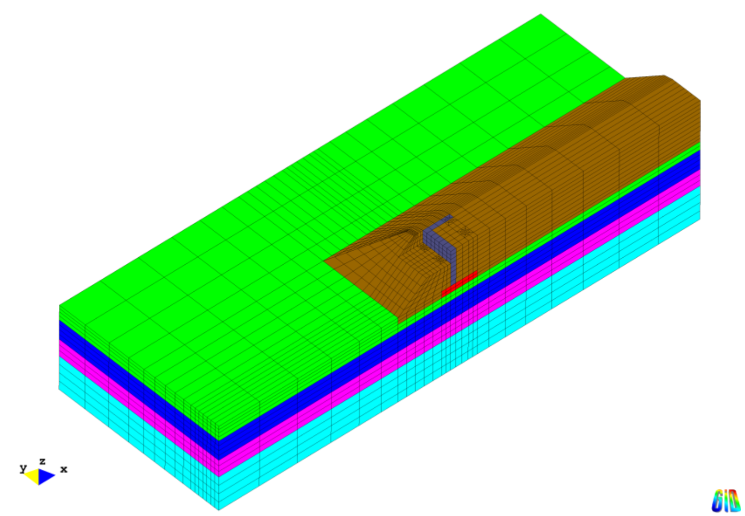
Prototype



1D Modeling Approach



2D Modeling Approach

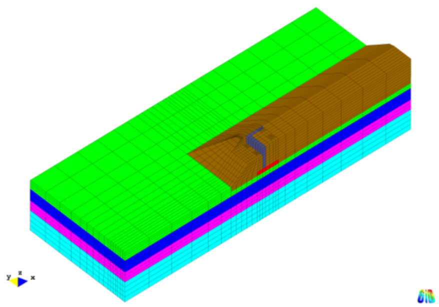


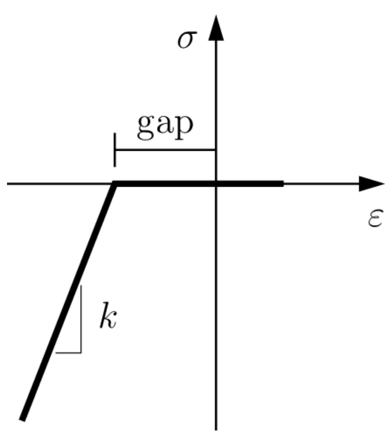
3D Modeling Approach

Application

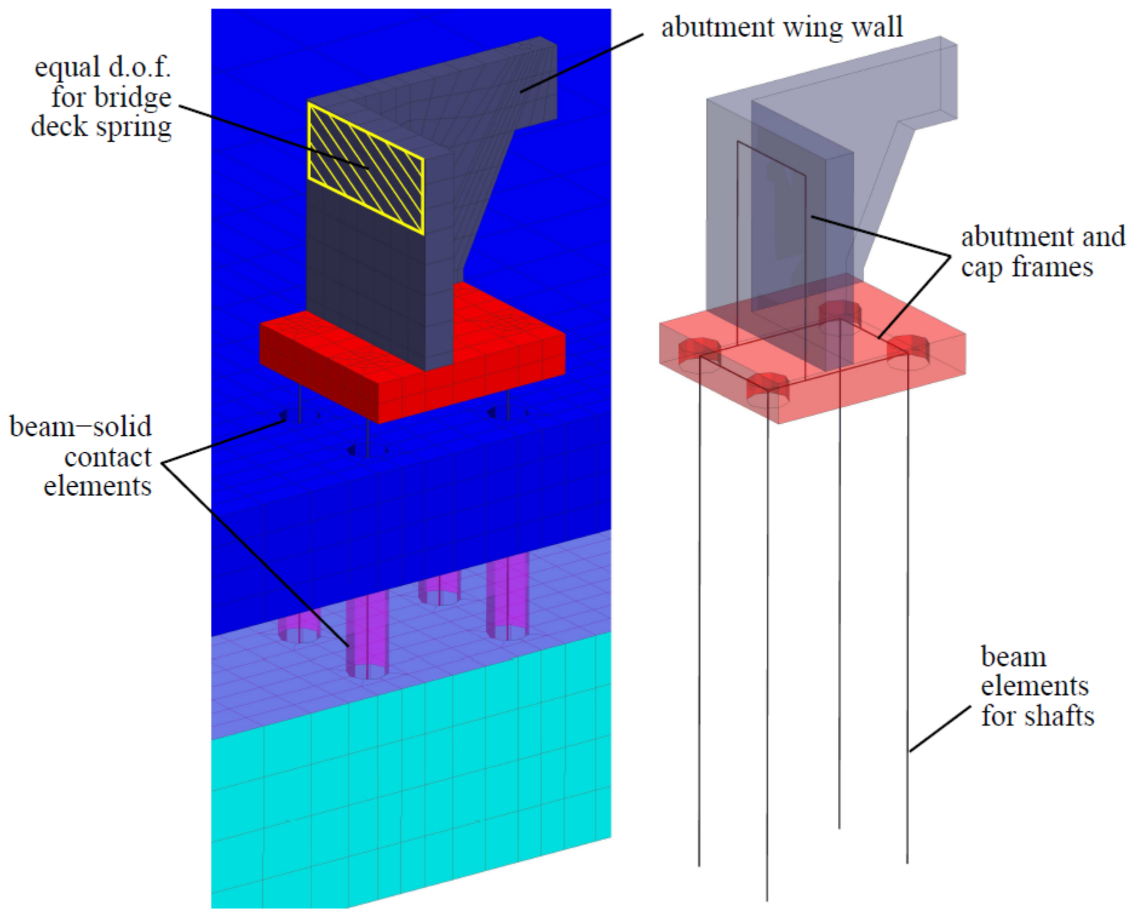
Numerical Analysis of Mataquito River bridge

Modeling the abutment and grouped shaft foundation





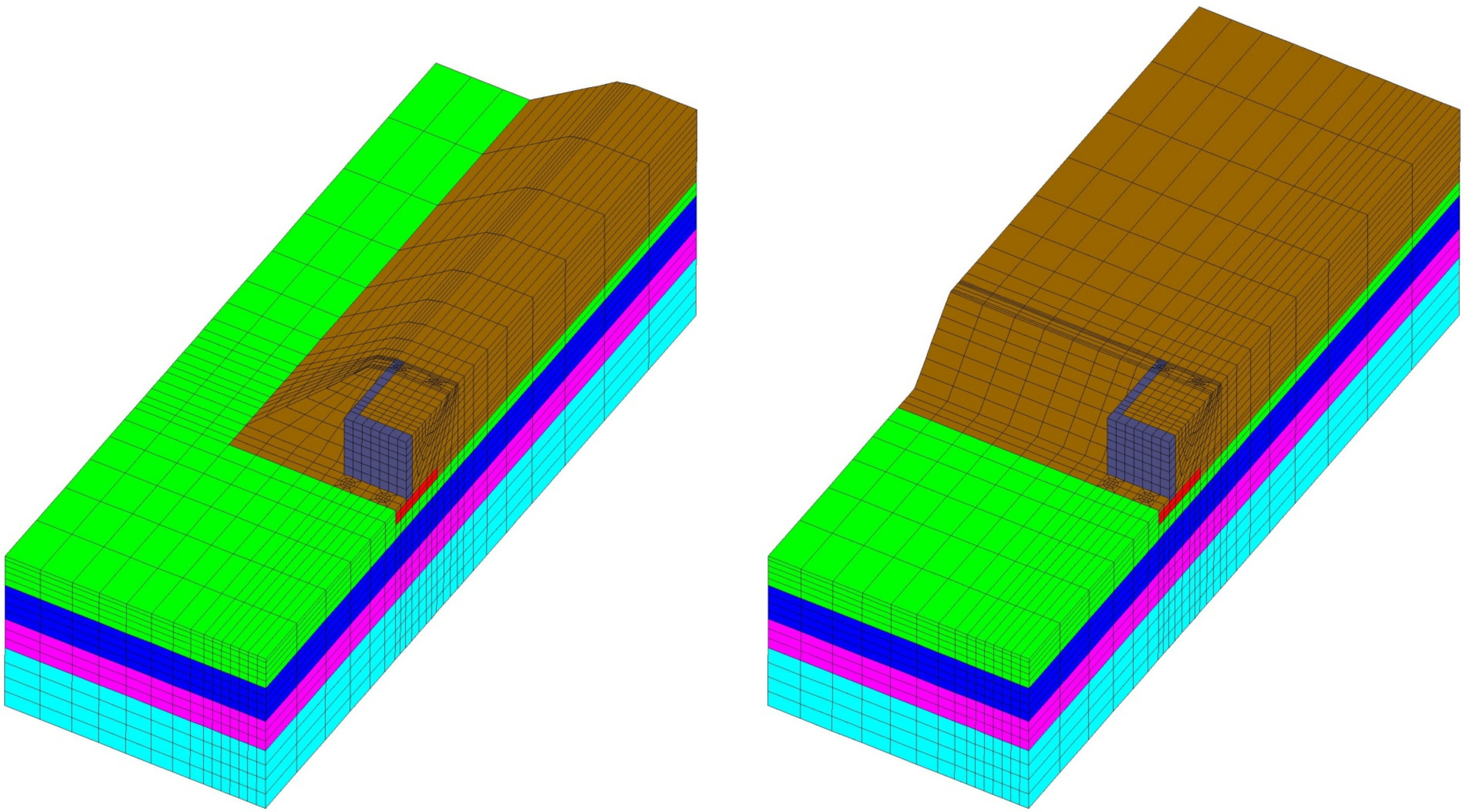
Bridge deck spring



Application

Numerical Analysis of Mataquito River bridge

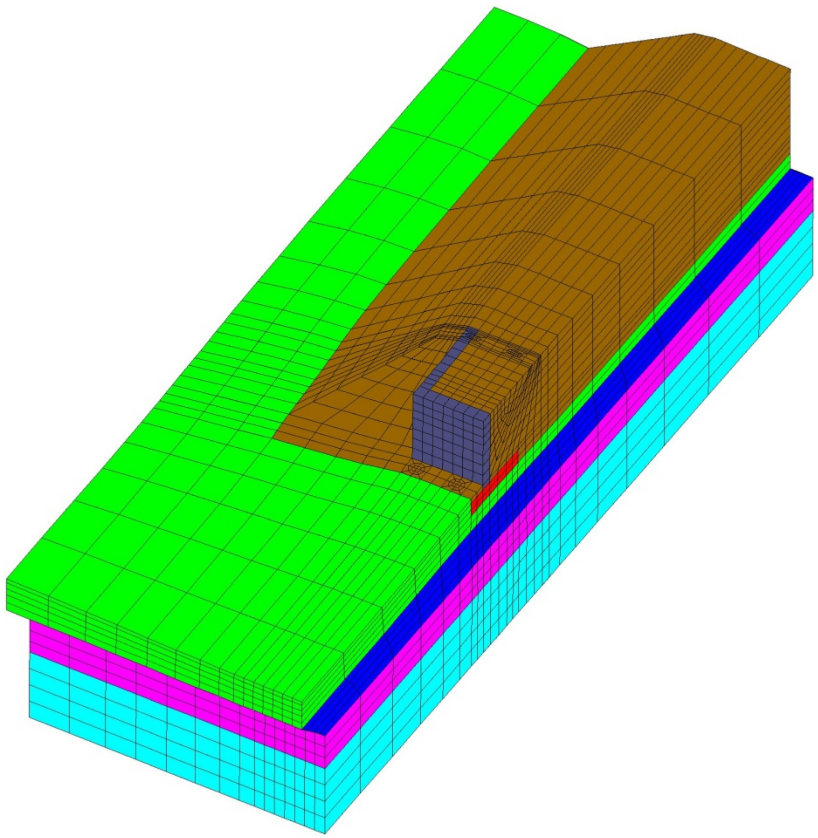
3D Applied Kinematic Model

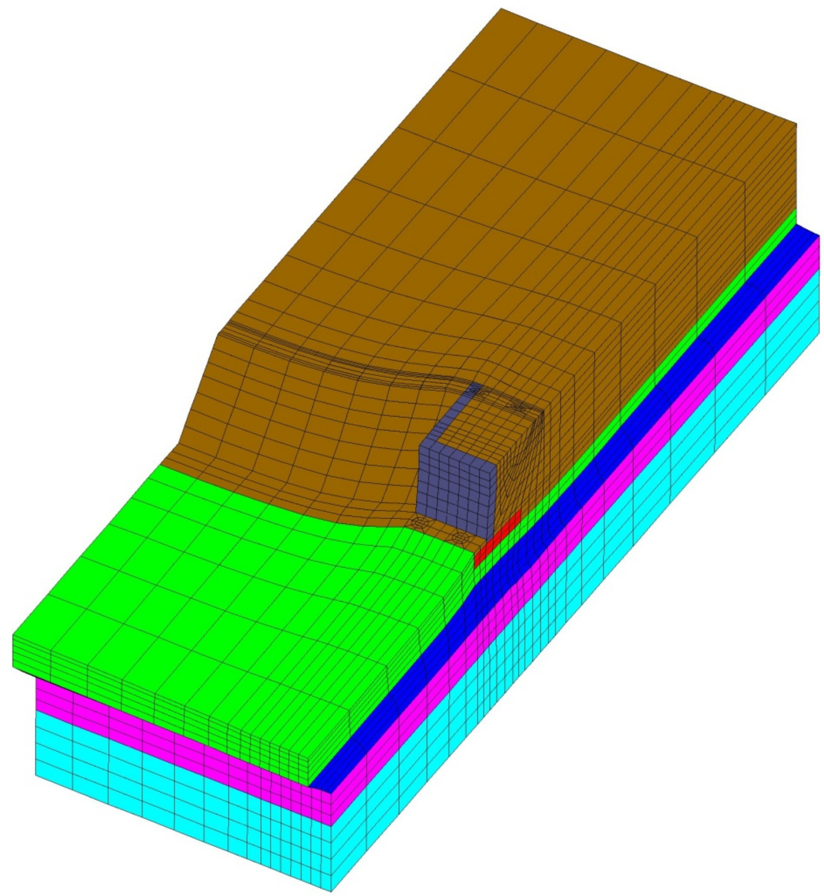


Application

Numerical Analysis of Mataquito River bridge

3D Applied Kinematic Model

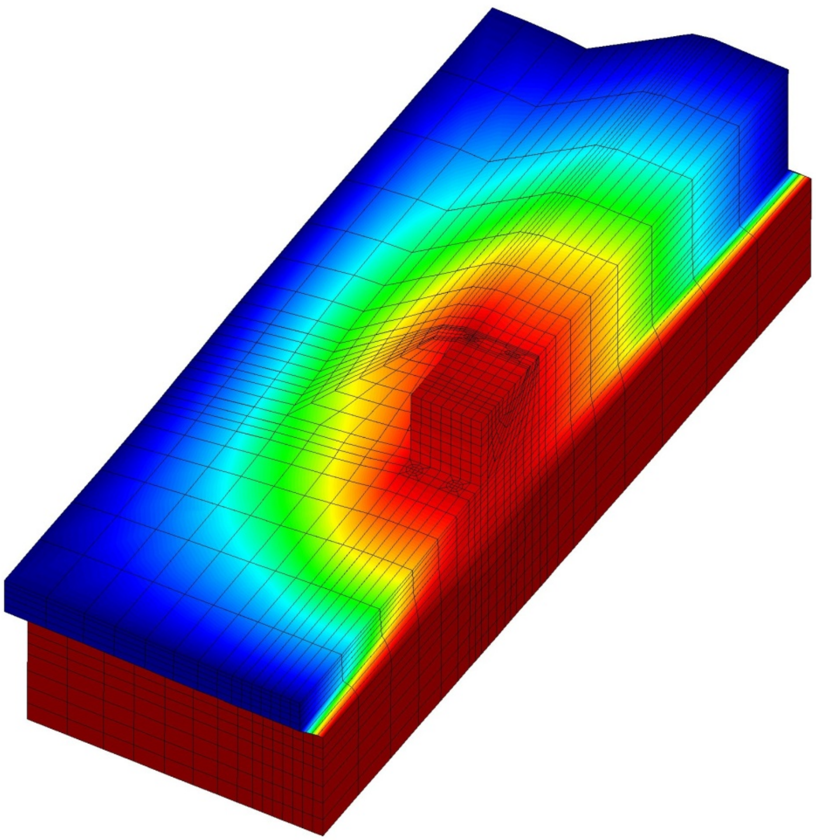


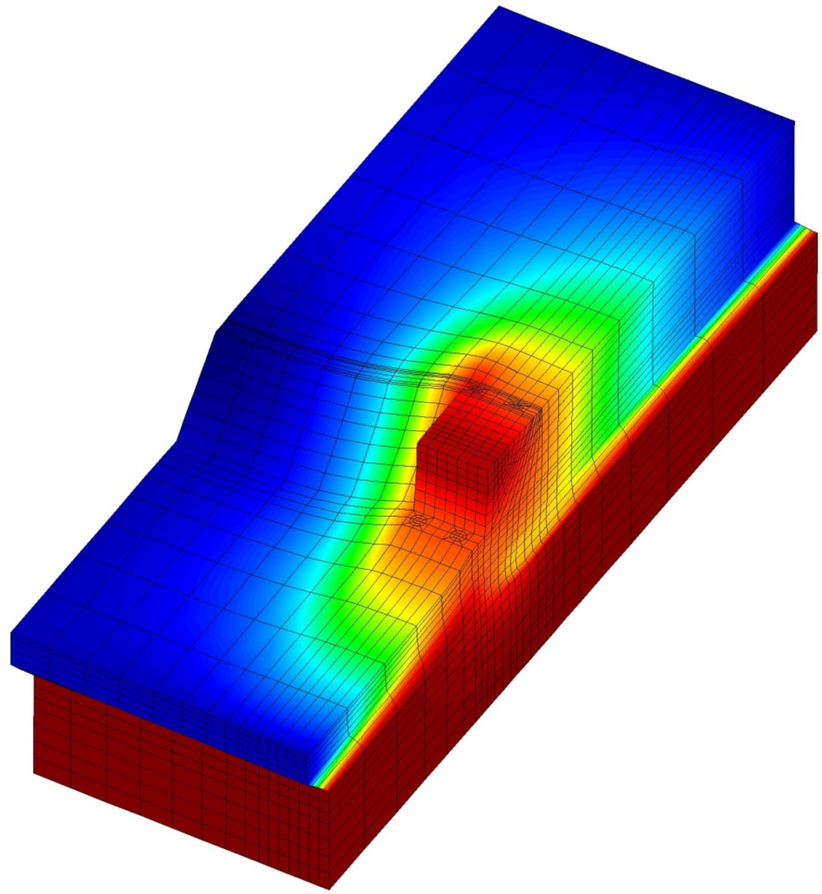


Application

Numerical Analysis of Mataquito River bridge

3D Applied Kinematic Model

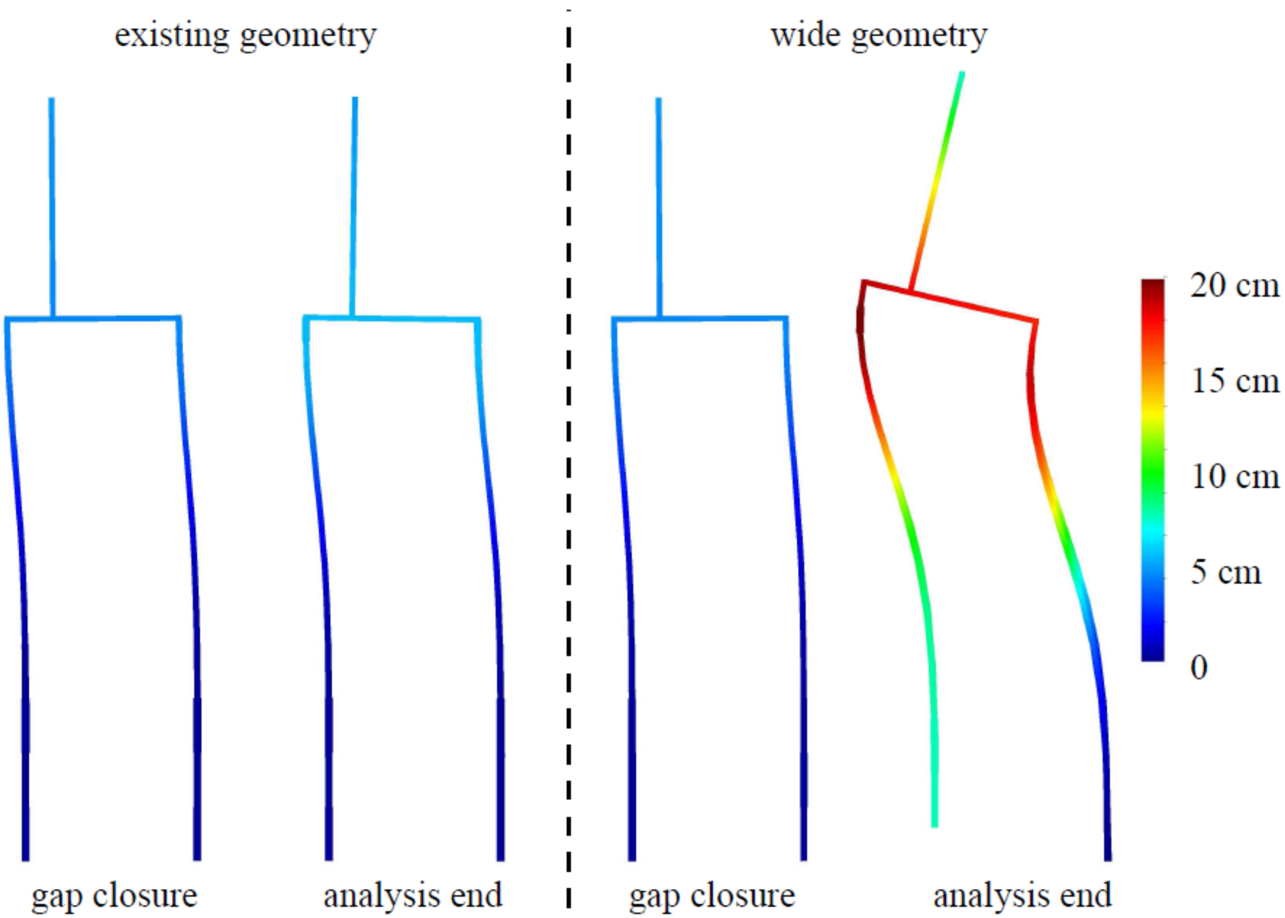




Application

Numerical Analysis of Mataquito River bridge

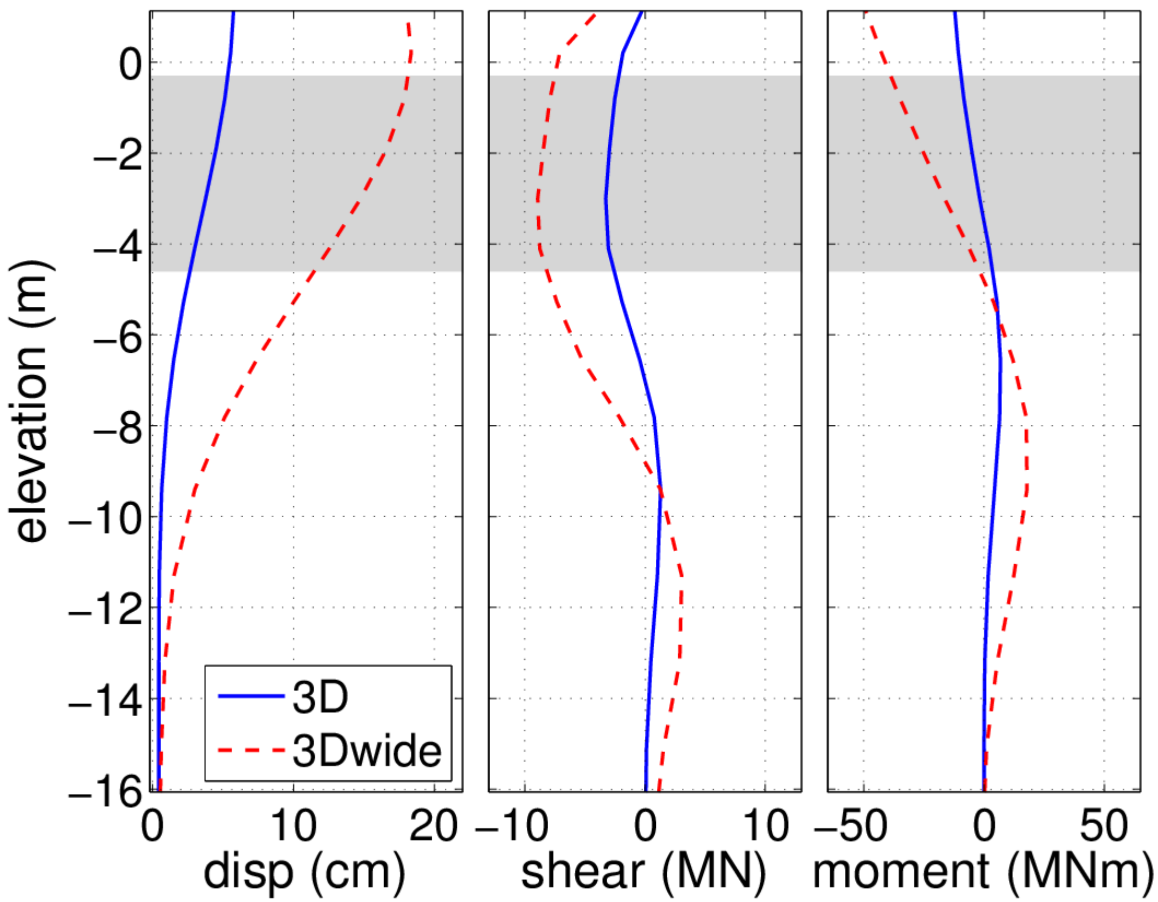
3D Applied Kinematic Model



Application

Numerical Analysis of Mataquito River bridge

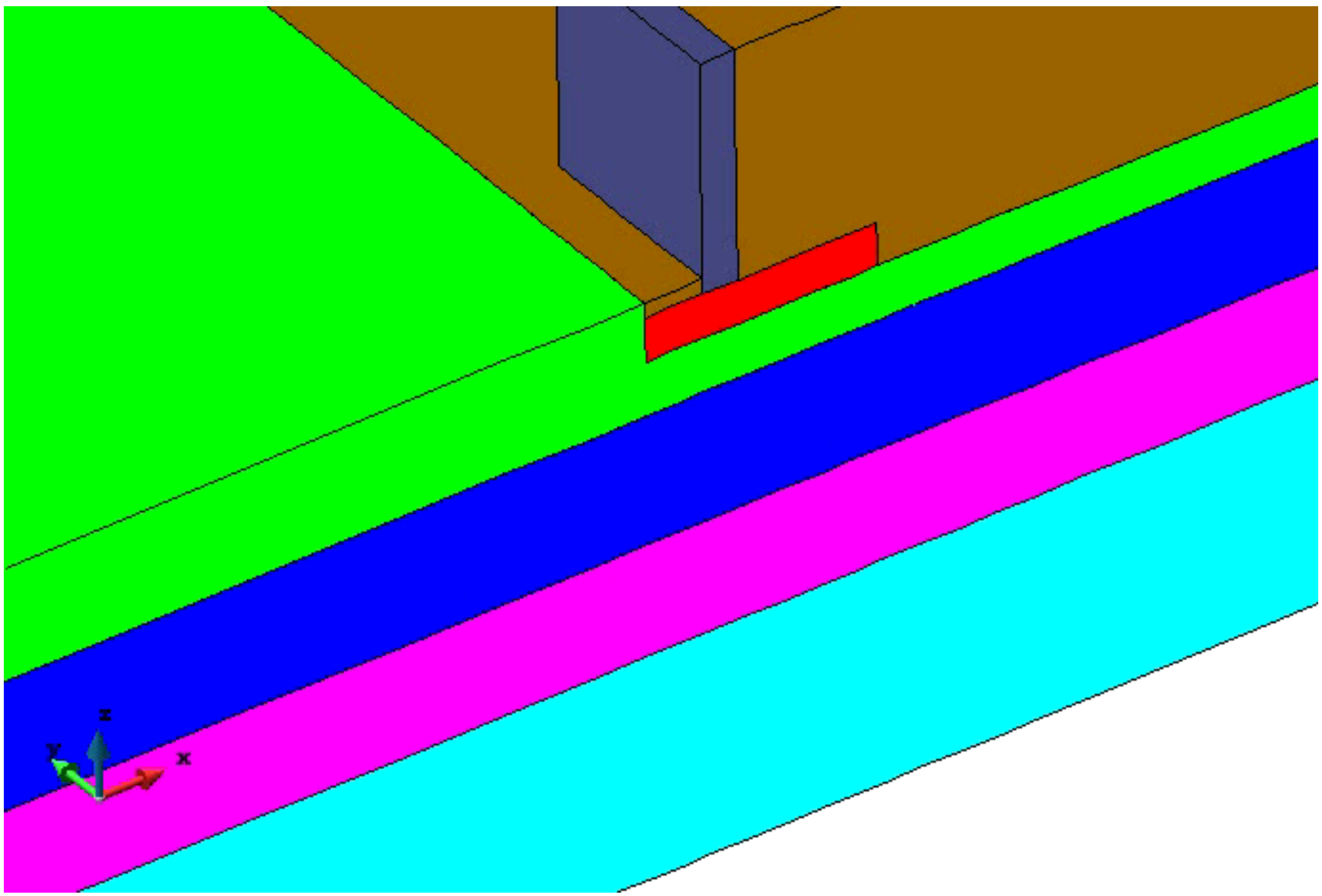
3D Applied Kinematic Model



Application

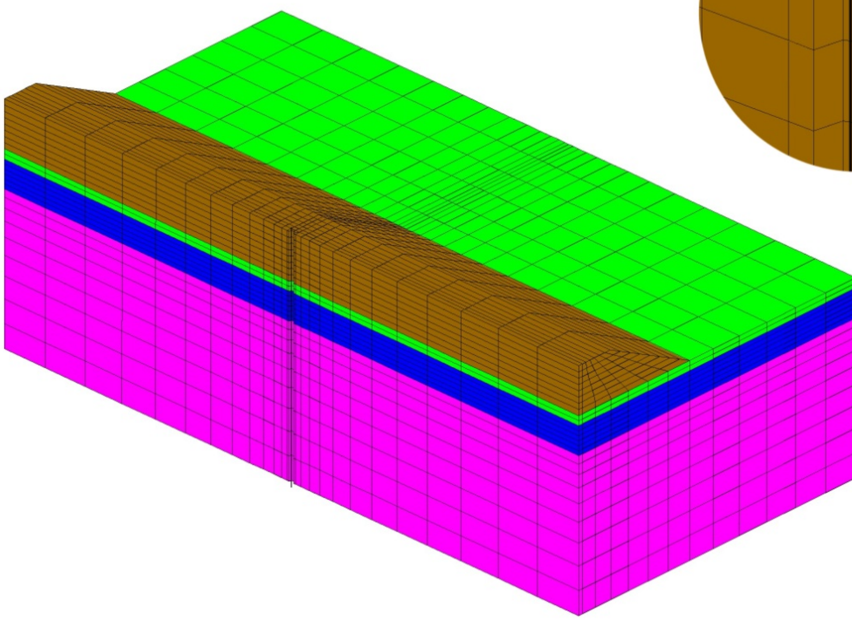
Numerical Analysis of Mataquito River bridge

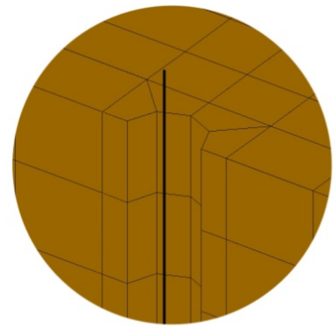
Deformation of shafts with contact forces acting on their surfaces



Application

3D Parametric Study





Application

3D Parametric Study

Liquefiable Layer Thickness

Liquefiable Layer Depth

1 m

3 m

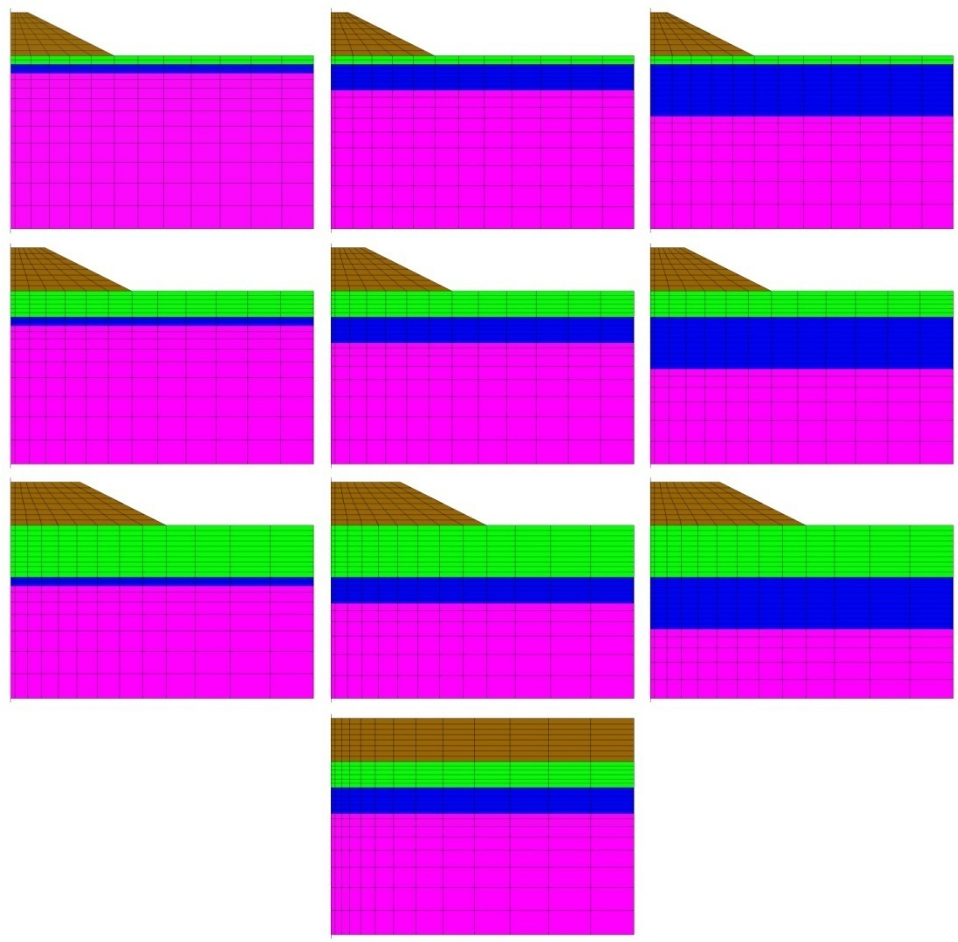
6 m

Embankment Width

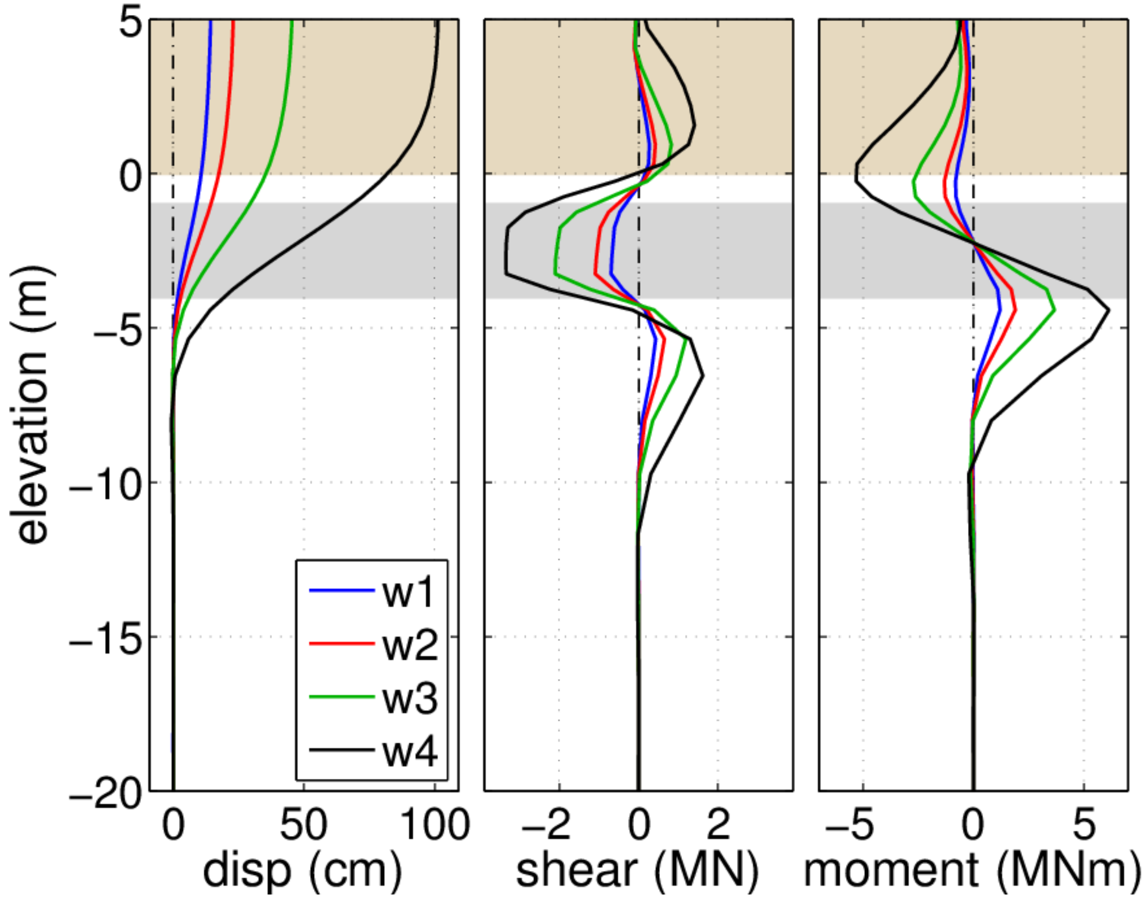
4 m

8 m

16 m

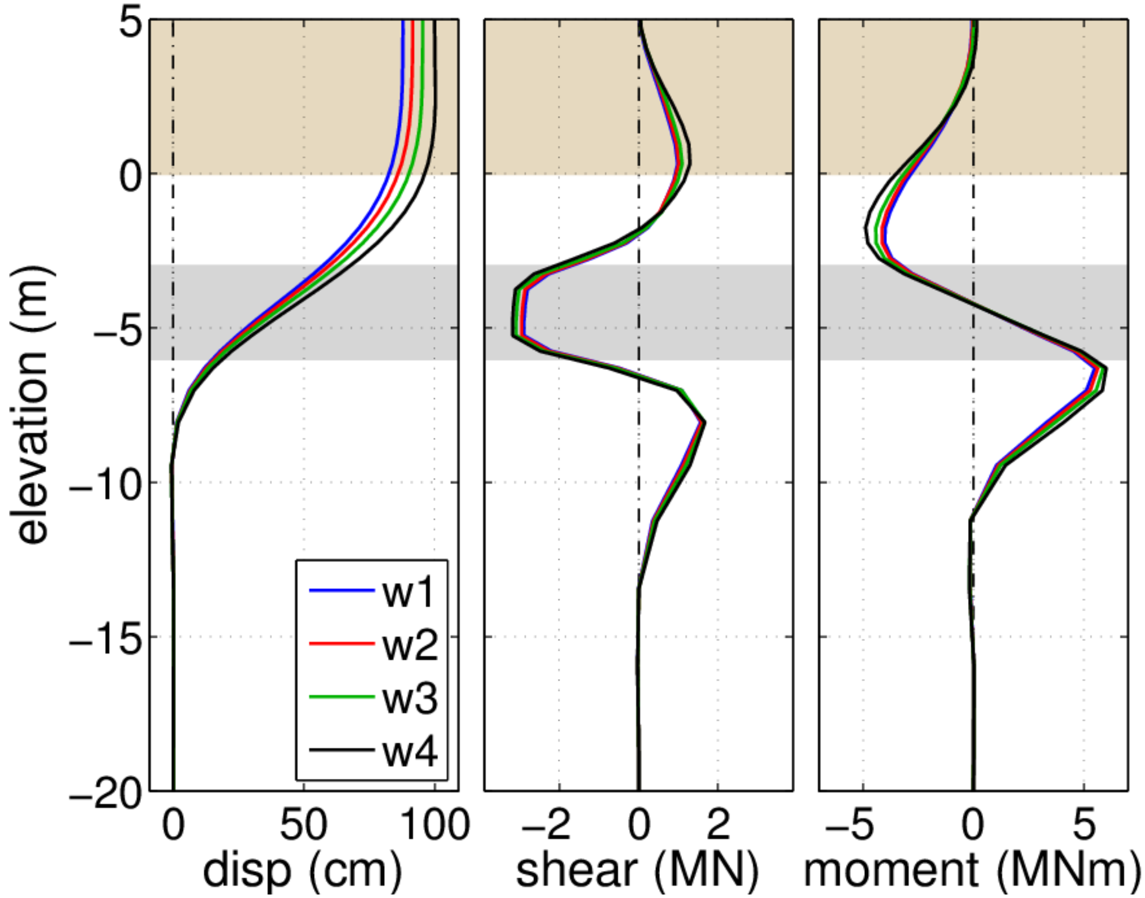


Application
3D Parametric Study

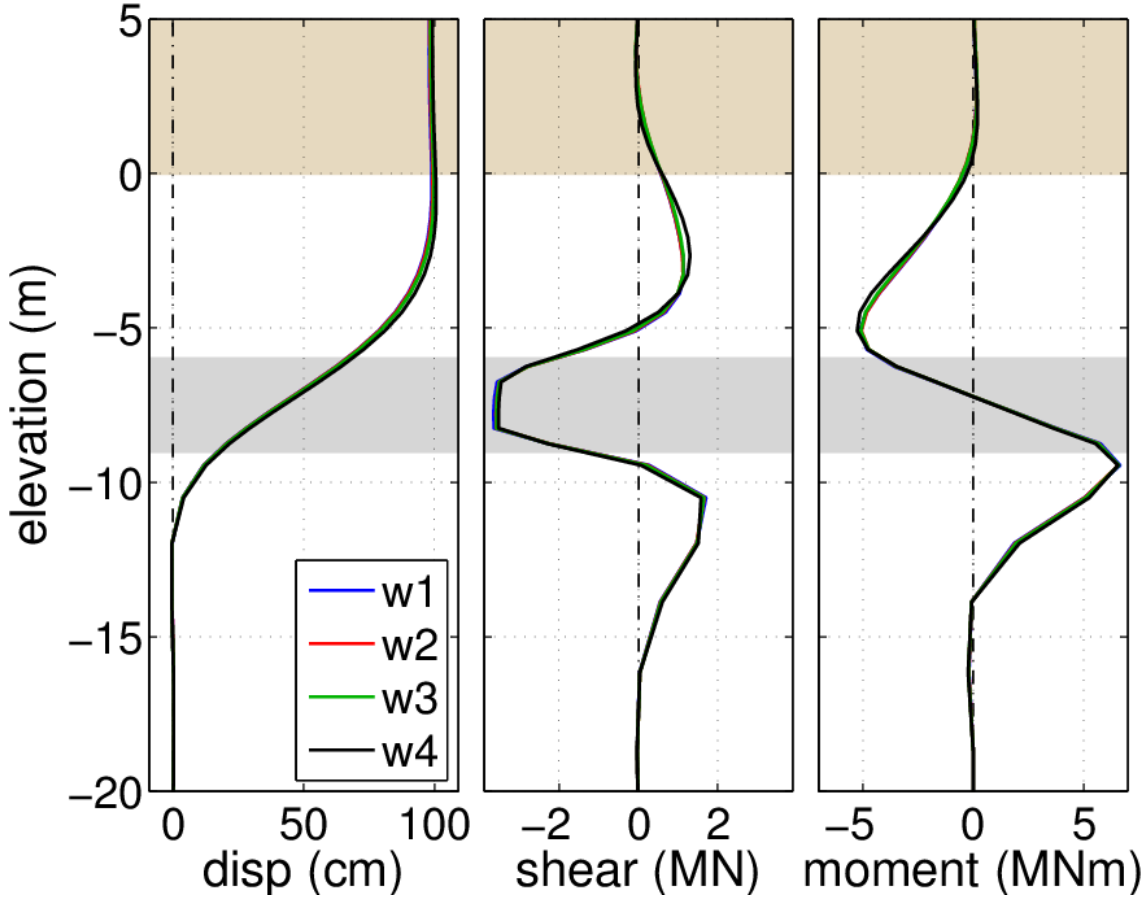


Application

3D Parametric Study



Application
3D Parametric Study



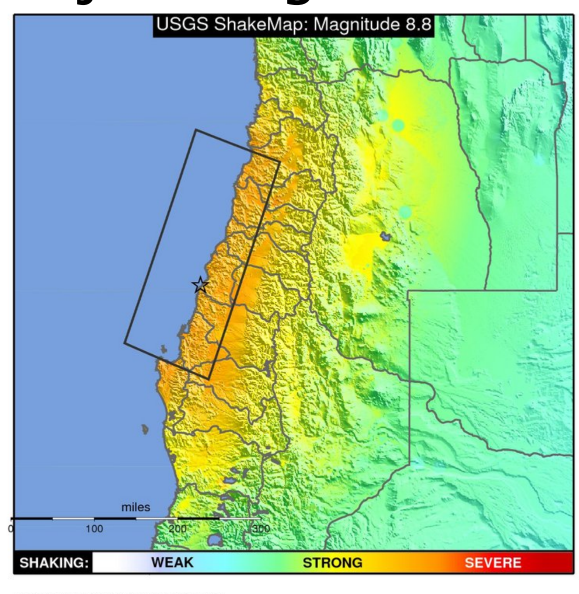
Representative Case History

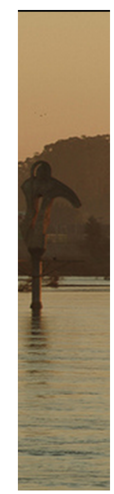
Llacolén Bridge – Concepción – Chile

- Across Bío-Bío river - Length : 2160 m
- Completed in 2000
- Simply supported precast pre-stressed concrete girder
- Column bent with inverted-T cap beam
- Two seismic bars between each adjacent girder

February 27, 2010 Maule earthq

- Moment Magnitude 8.8
- Duration more than 2 minutes
- Depth 35 Km
- 105 Km North-East of Concepc





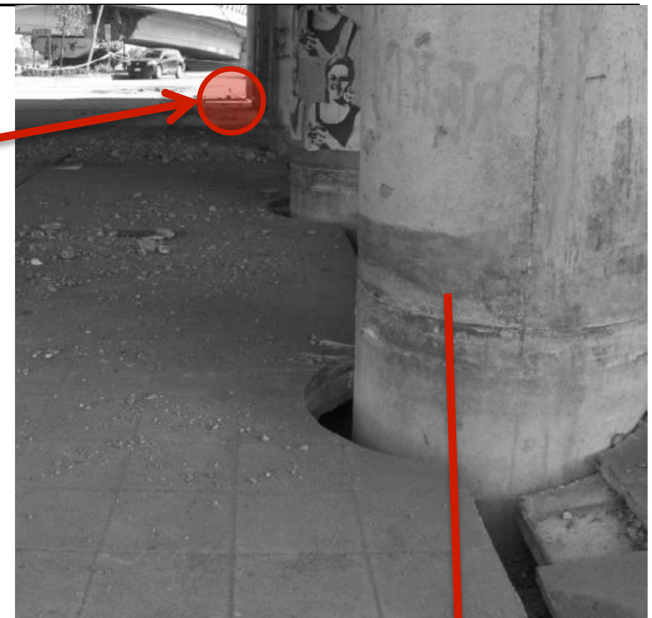
Bridge Damage – Lateral Spreading

- Unseated span due to lateral

Bridge Damage – Lateral Spreading

Source: Mitchell, Denis et al (2012)

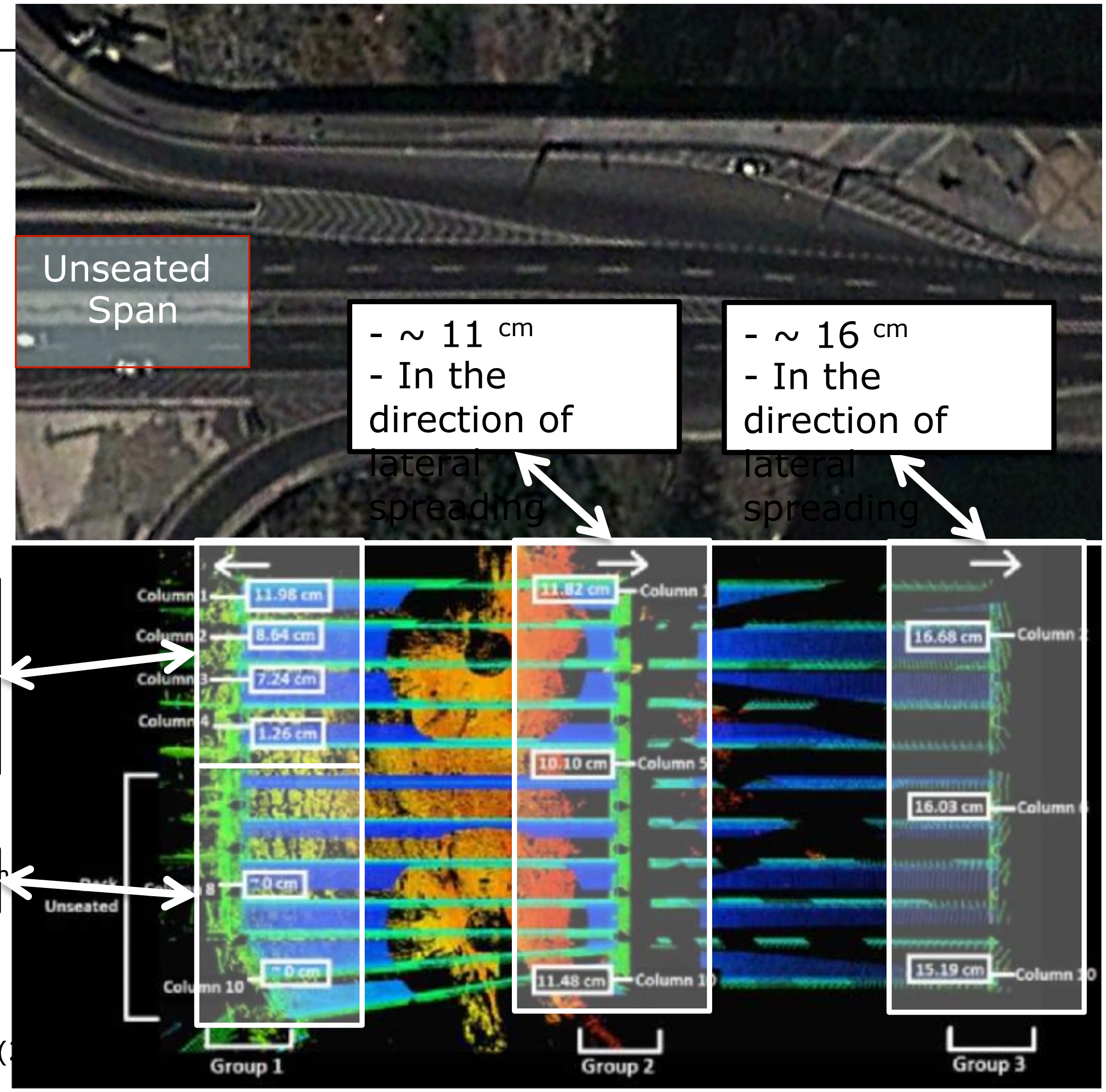
Source: Olsen, Michael J. et al (2012)



Source: FHWA-HRT-11-030

Bridge Damage – Lateral Spreading

- Relative movement of columns with respect to their bases

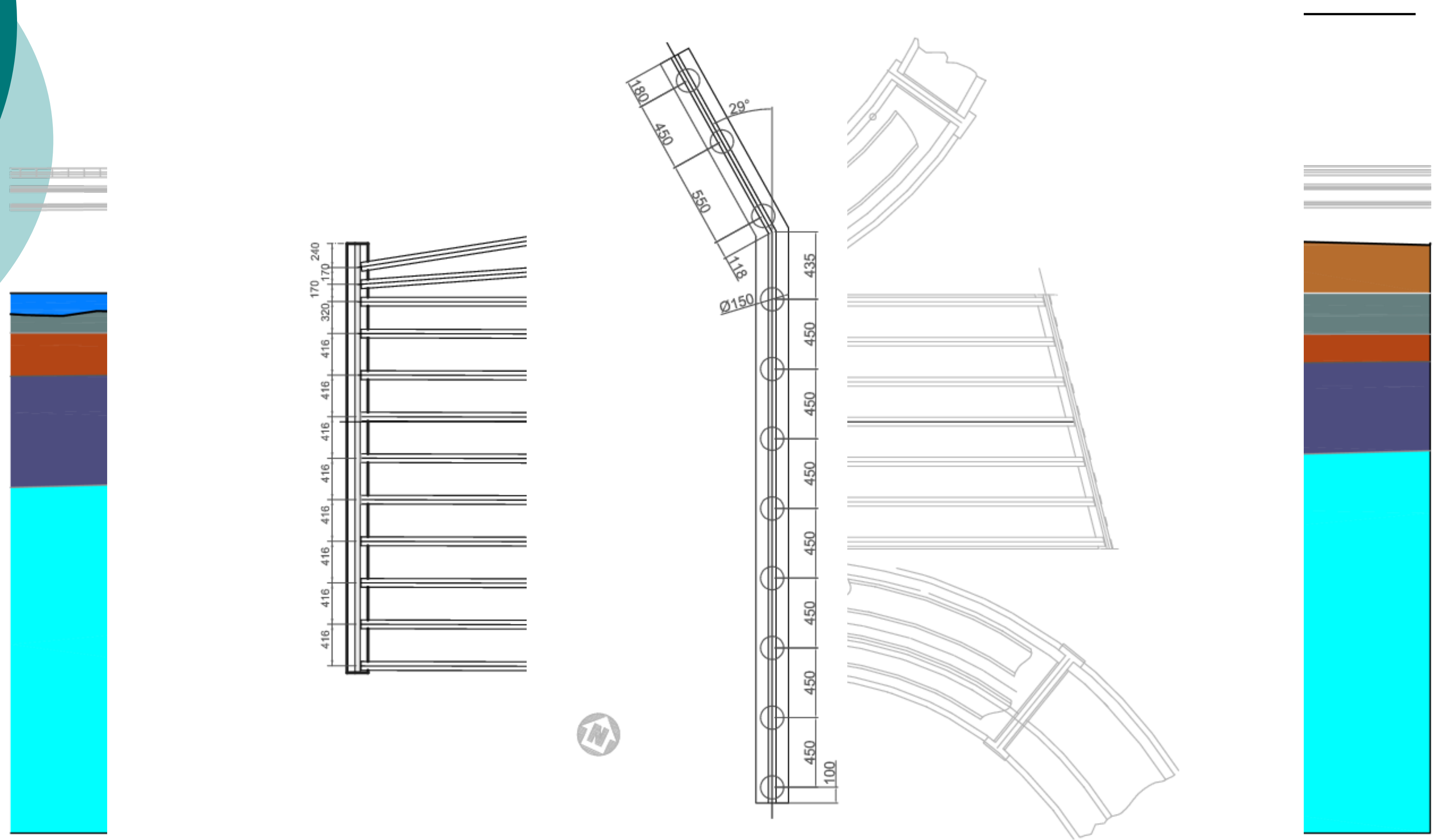


- Increasing from 1.26 cm to 11.96 cm
- Opposite to lateral spreading direction

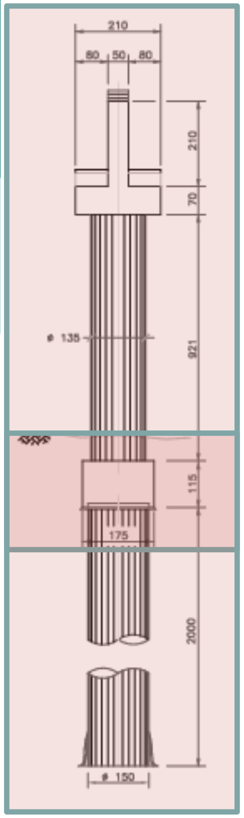
~ 0 cm

Source: Olsen, Michael J. et al (

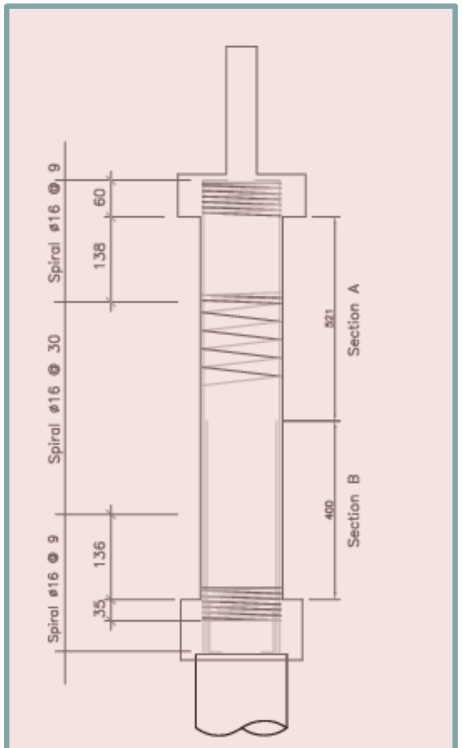
3-D Finite Element Model



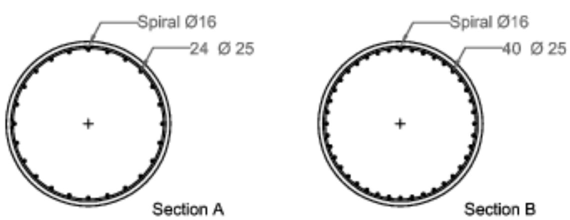
Llacolén Bridge – Structural Details



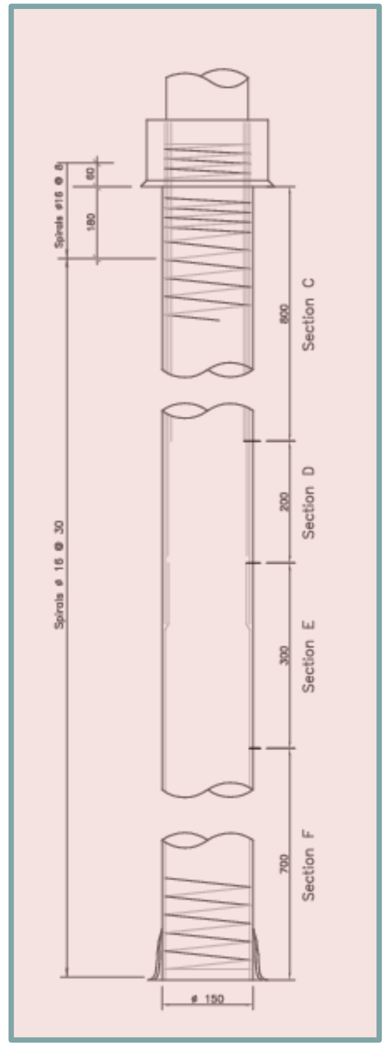
Lateral View



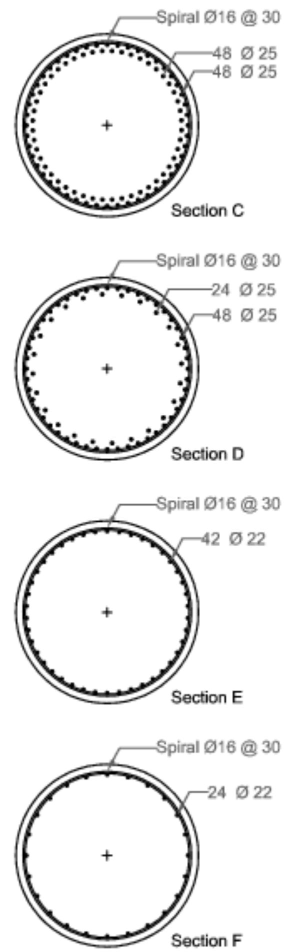
Columns Reinforcement



Columns Cross Sections
Cover = 3.8 cm

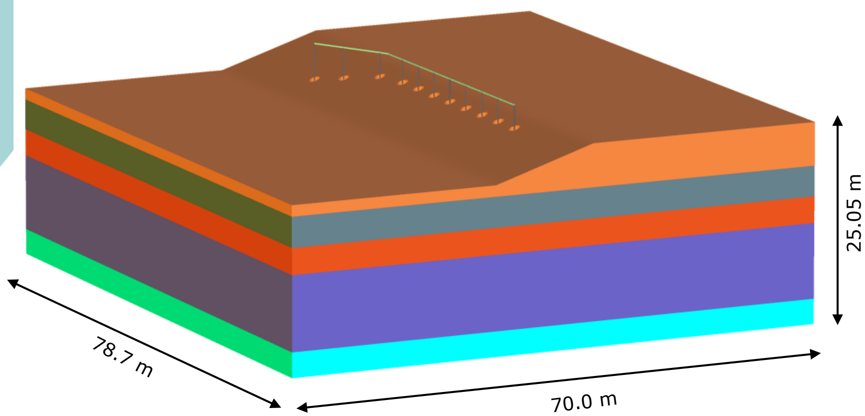


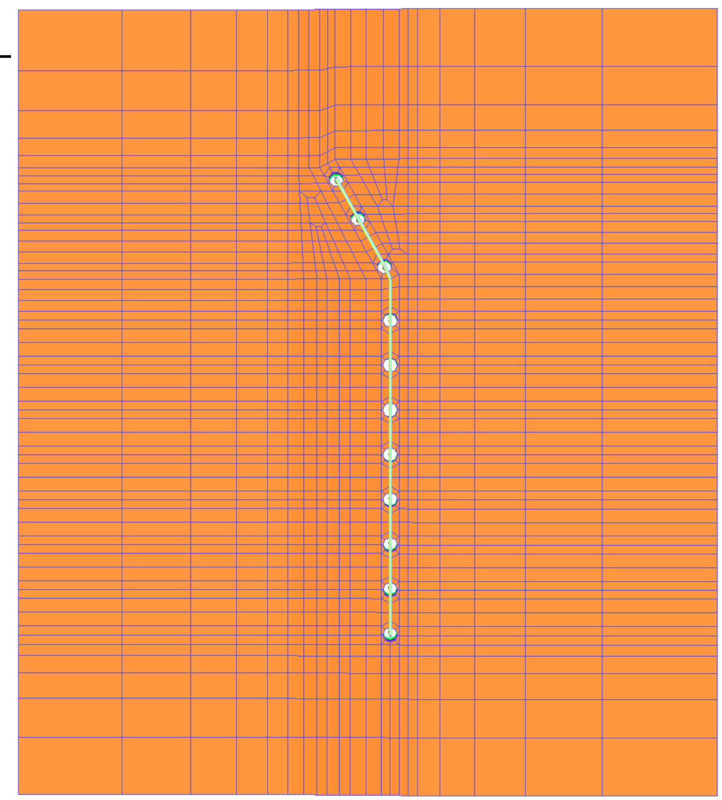
Pile Reinforcement

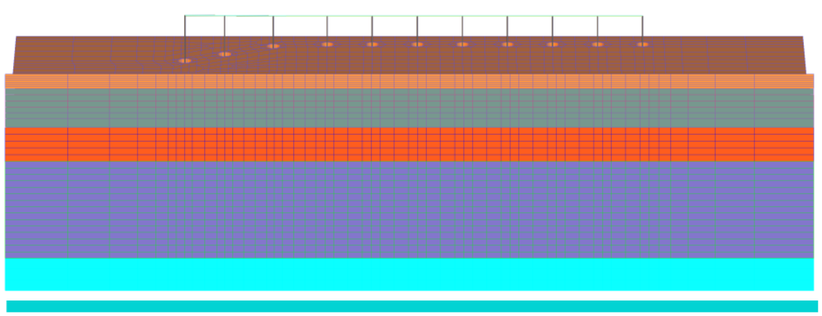


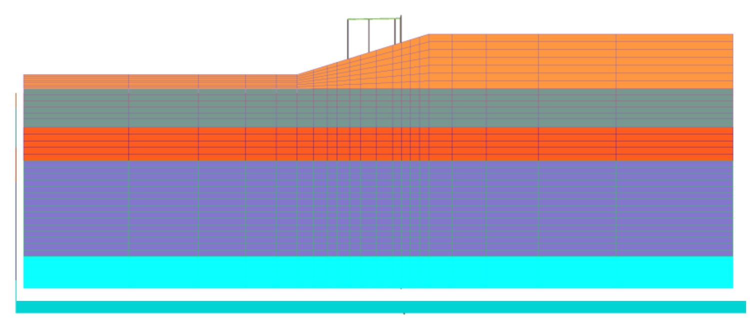
Pile Cross Sections
Cover = 7.5 cm

3-D Finite Element Model

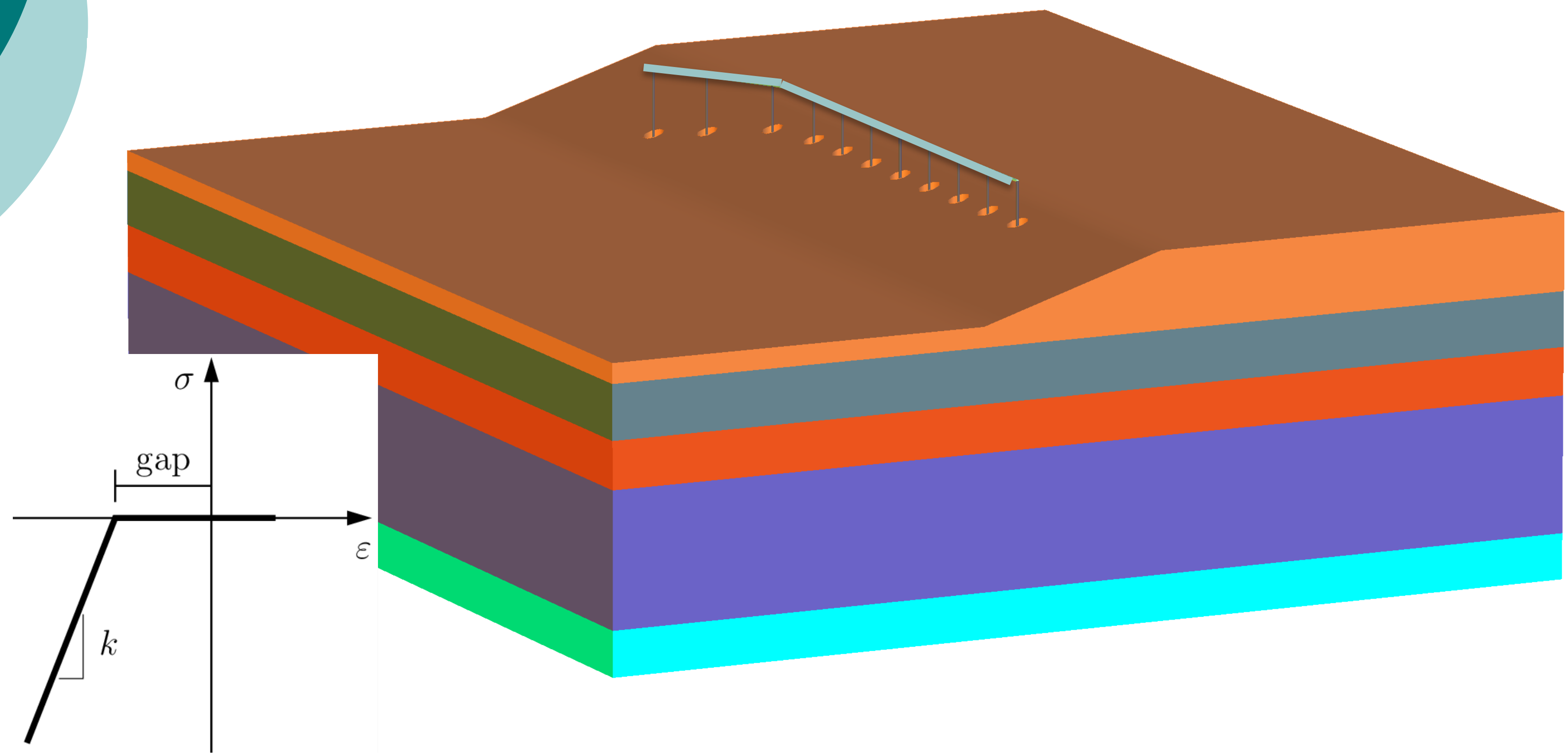






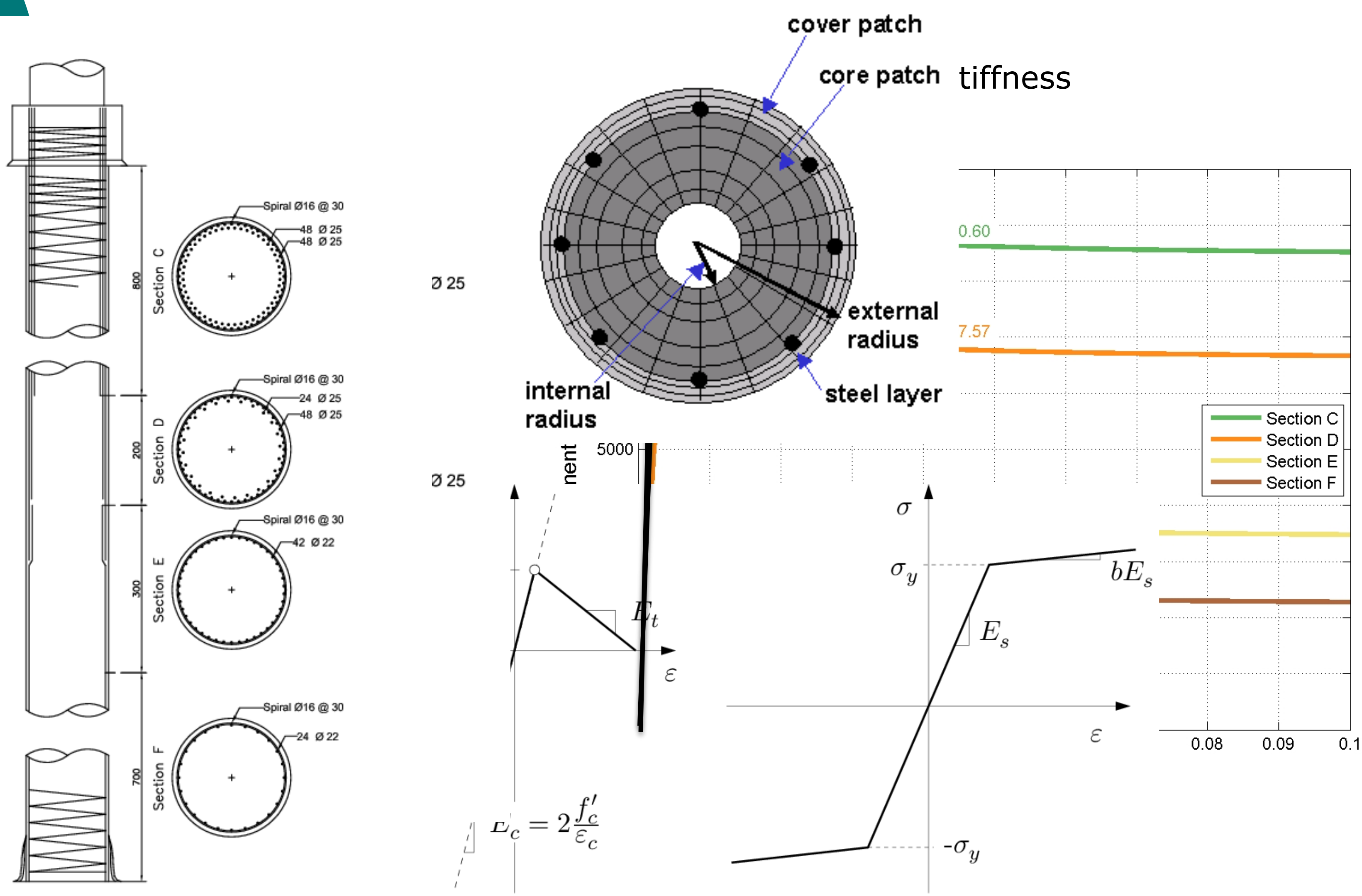


3-D Finite Element Model



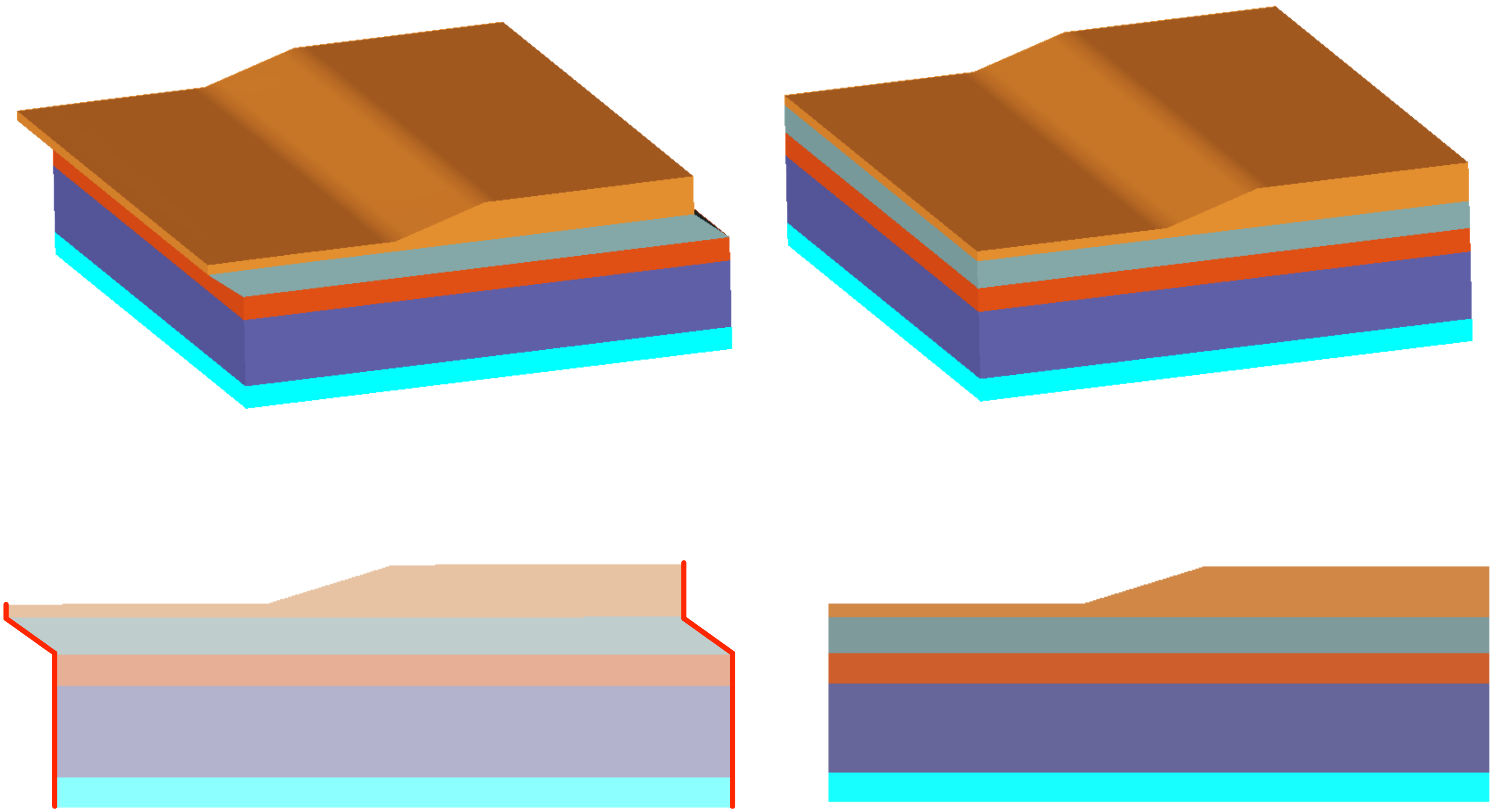
Bridge deck spring

Columns’ and Piles’ Sections

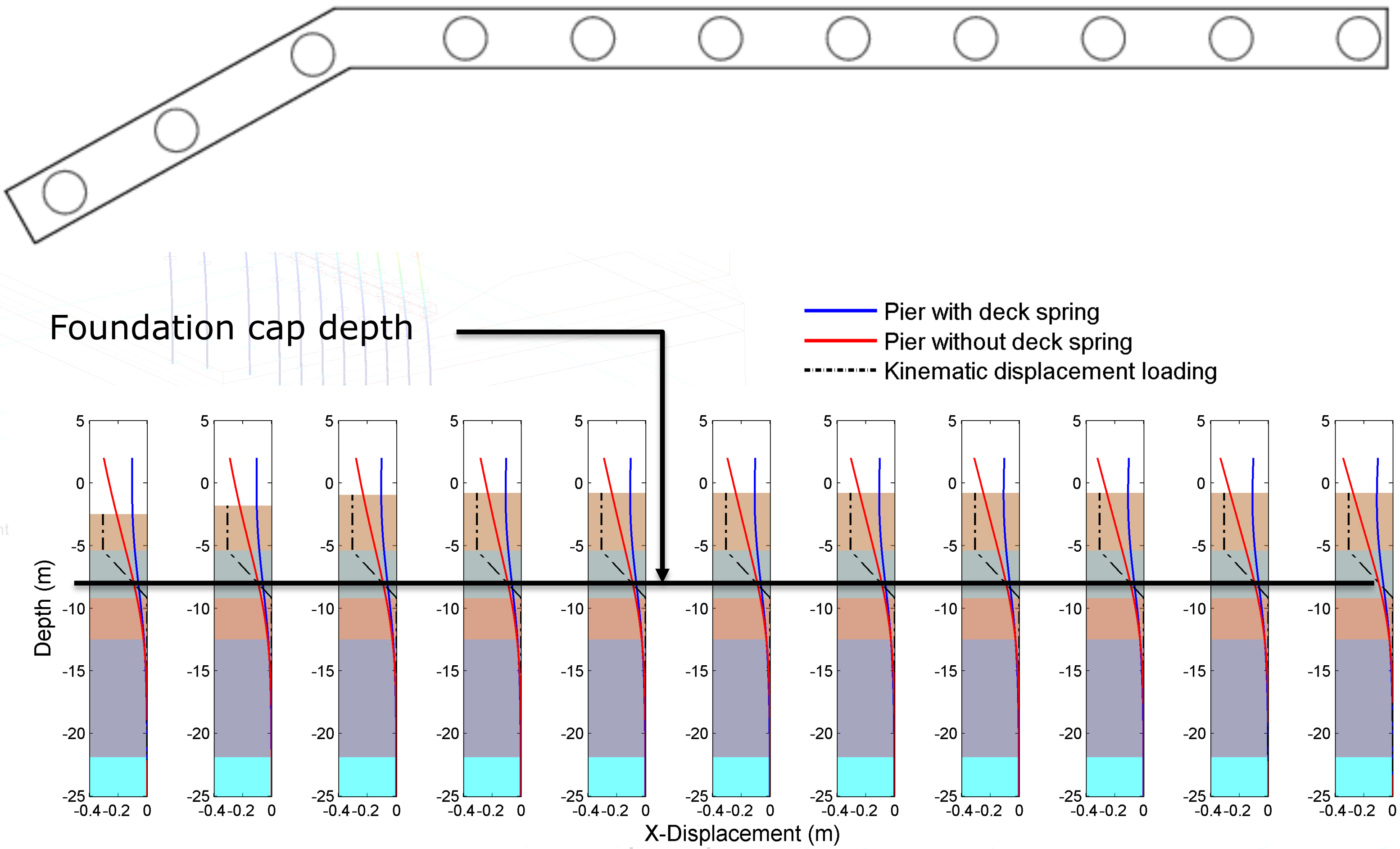


Concrete and Steel Uniaxial Material Constitutive Models

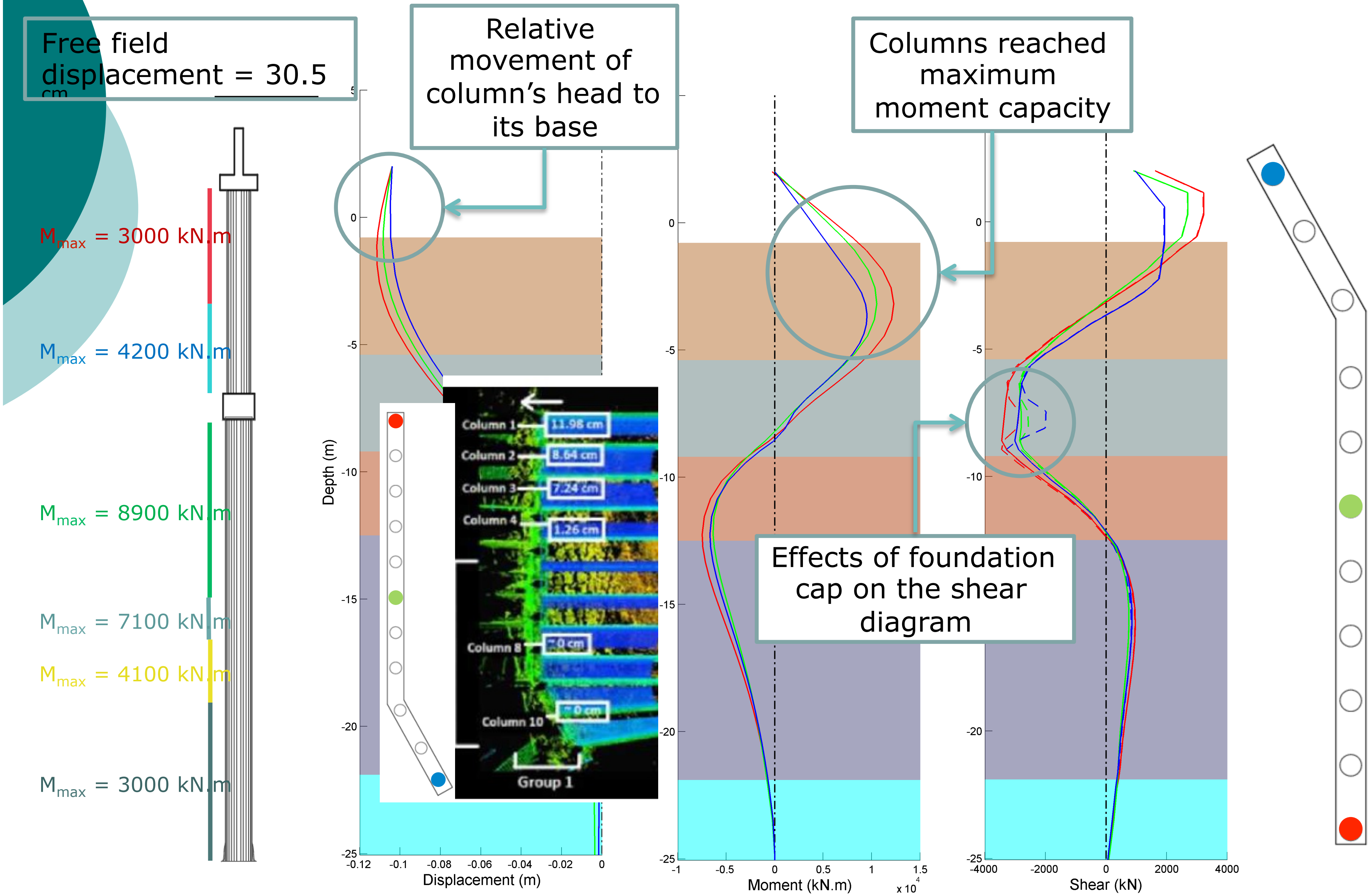
Kinematic Loading



Results – Pile Pinning and 3-D Geometrical Effects



Results – Structural Demands



Thank You!   Questions?