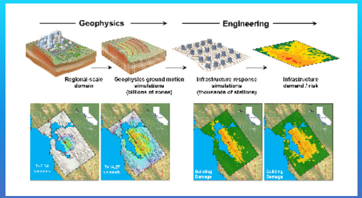

PEER International Pacific Rim Forum
June 16-17, 2021

Seismically-induced Slope Deformations: Pile Supported Wharfs and Bridges

Ahmed Elgamal
Zhijian Qiu, Zhaohui Yang, and Jinchi Lu
University of California, San Diego

June 16, 2021

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering

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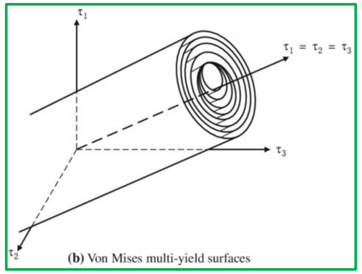
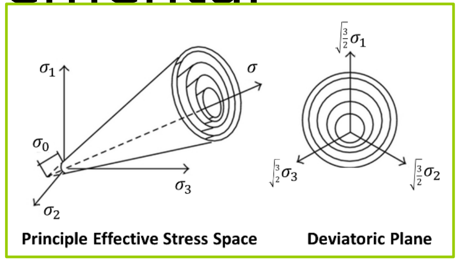
Geotechnical FE Framework and Capabilities

- PEER OpenSees https://opensees.berkeley.edu/

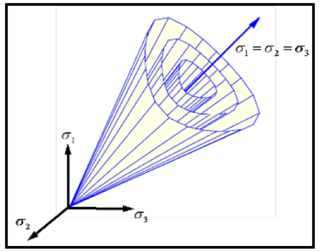


UC San Diego Contributions to OpenSees

-Nonlinear soil response: 2D and 3D multi-yield surface incremental Plasticity model



- For liquefaction analysis
  - Fully coupled (u-p) 2D and 3D Solid-Fluid Formulation liquefaction analyses)
  - Pressure-dependent 2D and 3D multi-yield surface models



Khosravifar, A., Elgamal, A., Lu, J., & Li, J. (2018). A 3D model for earthquake-induced liquefaction triggering and post-liquefaction response. *Soil Dynamics and Earthquake Engineering*, *110*, 43-52. https://www.sciencedirect.com/science/article/pii/S0267726117308722?casa_token=OCUnSo0vjnEAAAAA:0mHhhqfN1lhwjBAQd5RQme5zdIZq0-QV4Zxtr2MkjGyj2GbfnPBKY3qRV1F_RgXJkMgEPPmtog

Emphasis on the following themes …..

- Soil-structure interaction (using the SOA OpenSees structural elements by other researchers)
- **Small** strains (e.g. equivalent linear analysis, .. order of 0.1%)
- **Large** strains (e.g., nonlinear elasto-plastic analysis … order of 1.0 %)
- **Very large** strains (e.g., liquefaction-induced permanent deformation … order of 10.0 %)
- **Very very large** strains (e.g., at ground-foundation interfaces … order 100.0 %)
- **3D ground-structure response** for all of the above

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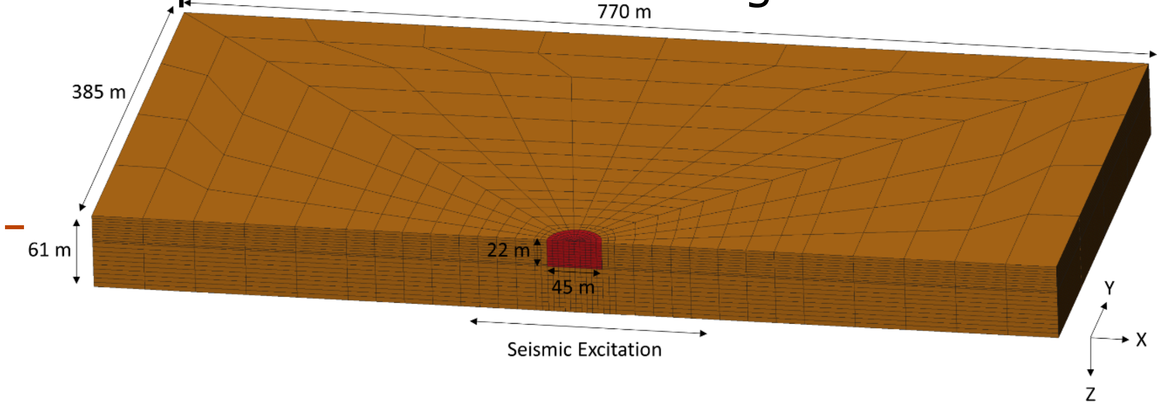
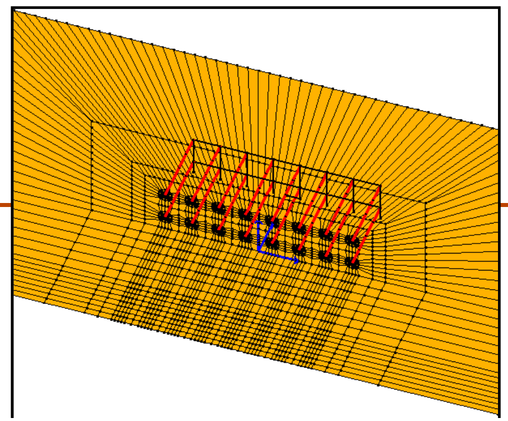
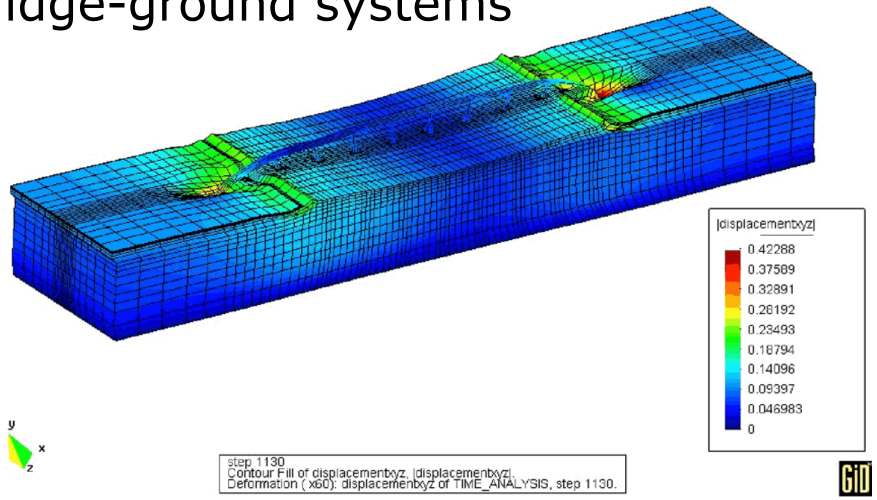
Site response and embedded rigid structures



Large pile groups

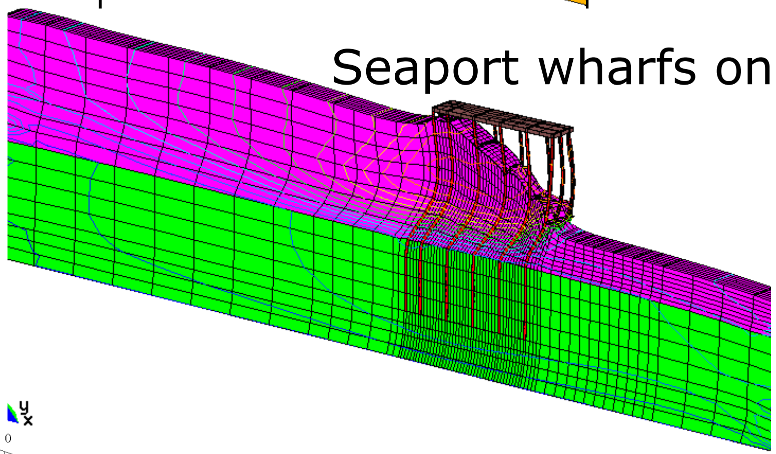


3D bridge-ground systems

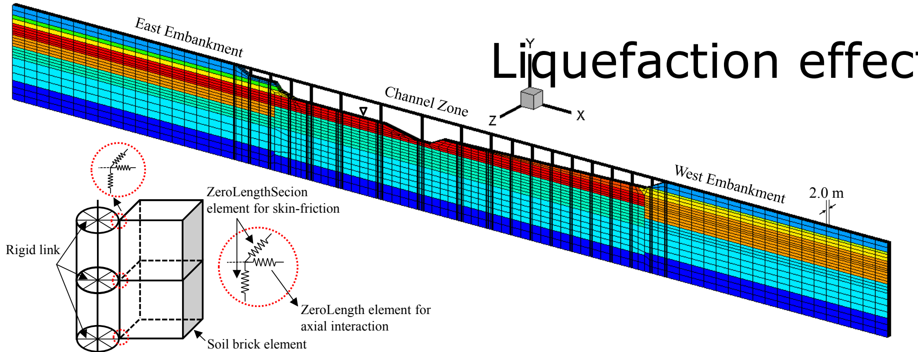


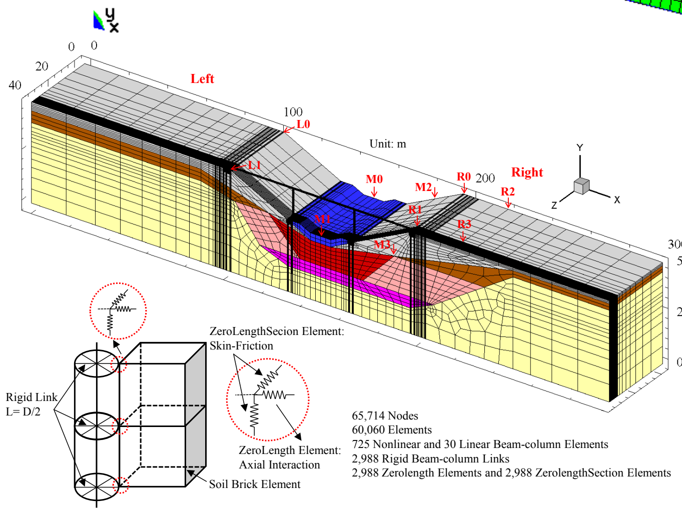
3D

Seaport wharfs on piles



Liquefaction effects on bridges





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3-Dimensional Simulation

Site Response

NPP Containment Structures

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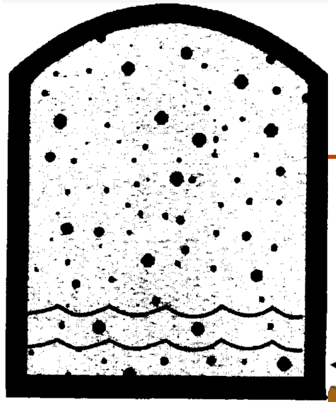
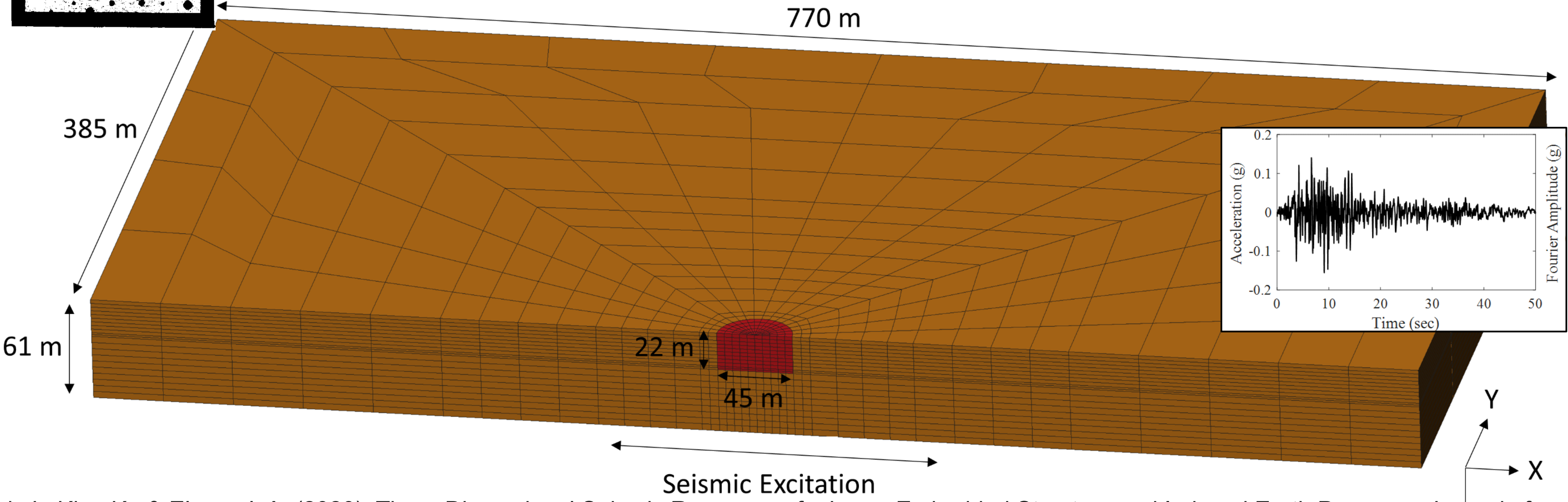
Ground Response and Embedded Rigid Structure

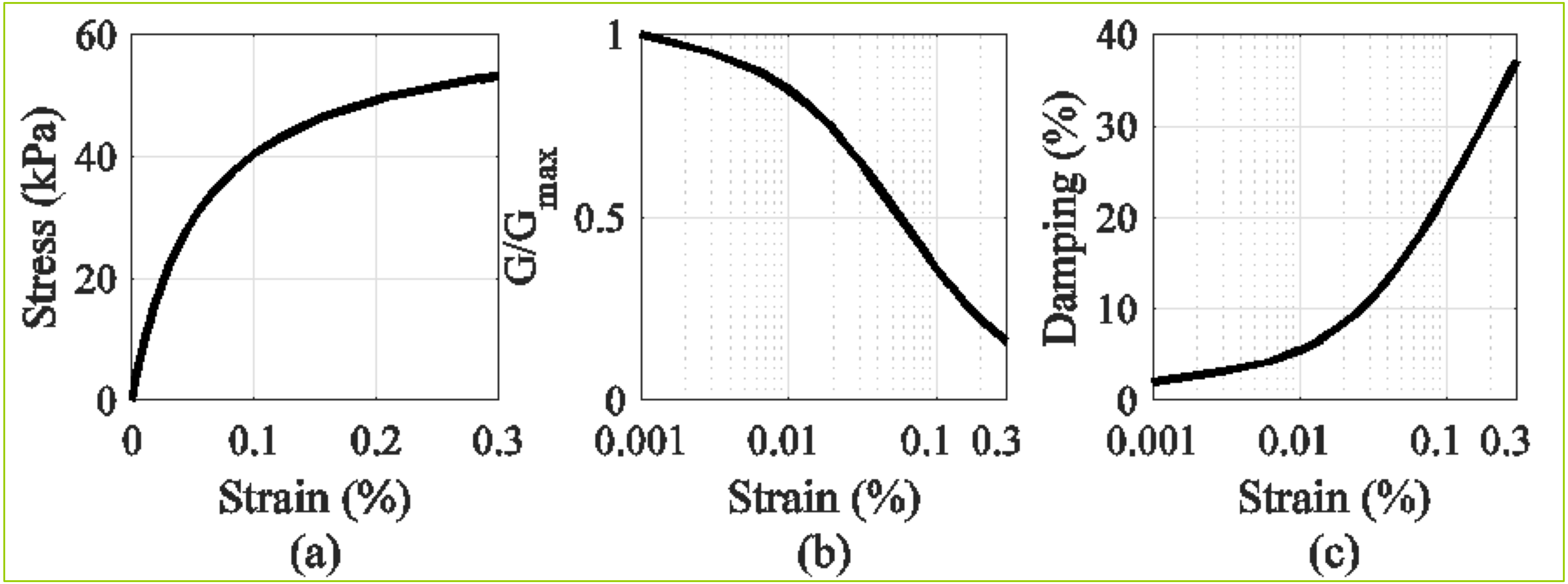


- FE mesh is comprised primarily of 3D 8 node brick elements
- Dimensions of mesh chosen to minimize effect of boundary on structure
- Structure is cylindrical with a height and radius of 22.68 m and 22 m
- Capitalized on symmetry plane
- Transmitting boundary at base of model with material properties based on soft rock



Li, J., Kim, K., & Elgamal, A. (2020). Three-Dimensional Seismic Response of a Large Embedded Structure and Induced Earth Pressure. *Journal of Geotechnical and Geoenvironmental Engineering*, *146*(5), 04020025. https://ascelibrary.org/doi/full/10.1061/%28ASCE%29GT.1943-5606.0002238?casa_token=41qhcQB3x1AAAAAA%3AniyWABfYy56IbmrWfIHhf1LmtFgVRg6617xE1hjTYOUC7X3baIE5k0Si4ELn6erhR4_UHfUZo9Q

Nonlinear Soil Response
Schematic shear stress-strain behavior



Nonlinear

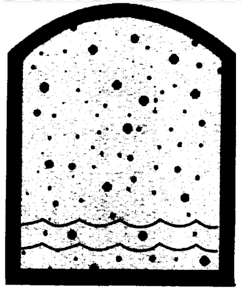
Equivalent Linear

Spectral Response

Free-Field Response

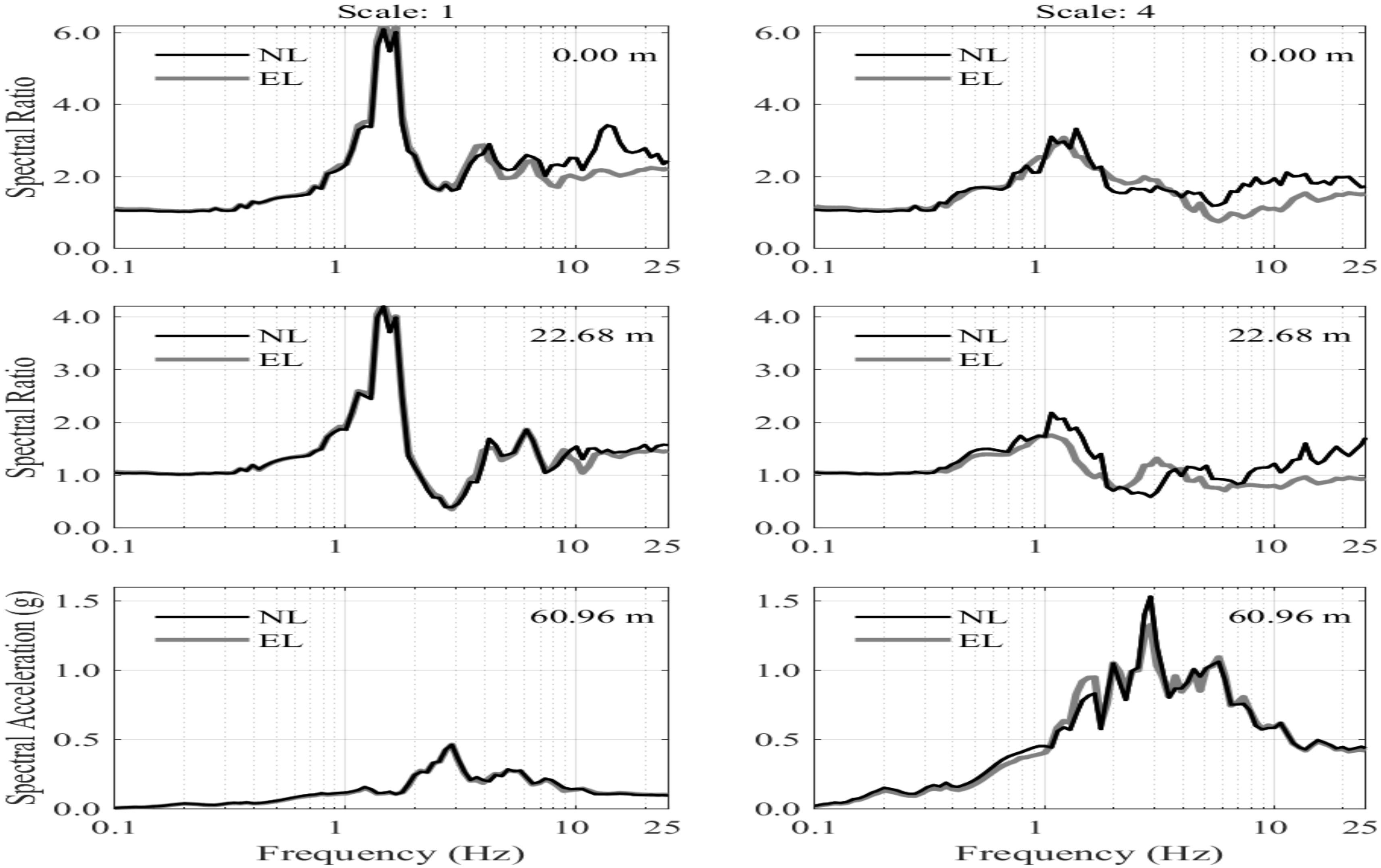
◦ **(Equivalent linear ok for peak , .. but underestimates the high frequency response)**

Ground Surface



Base of structure

Base of Model



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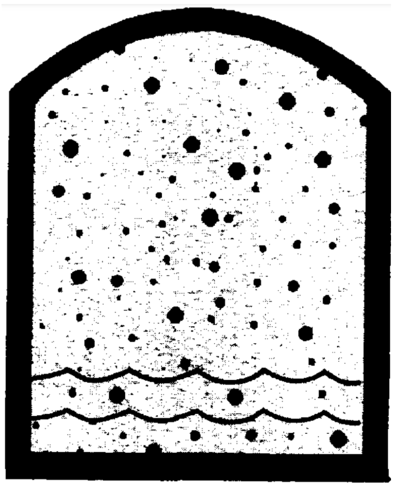
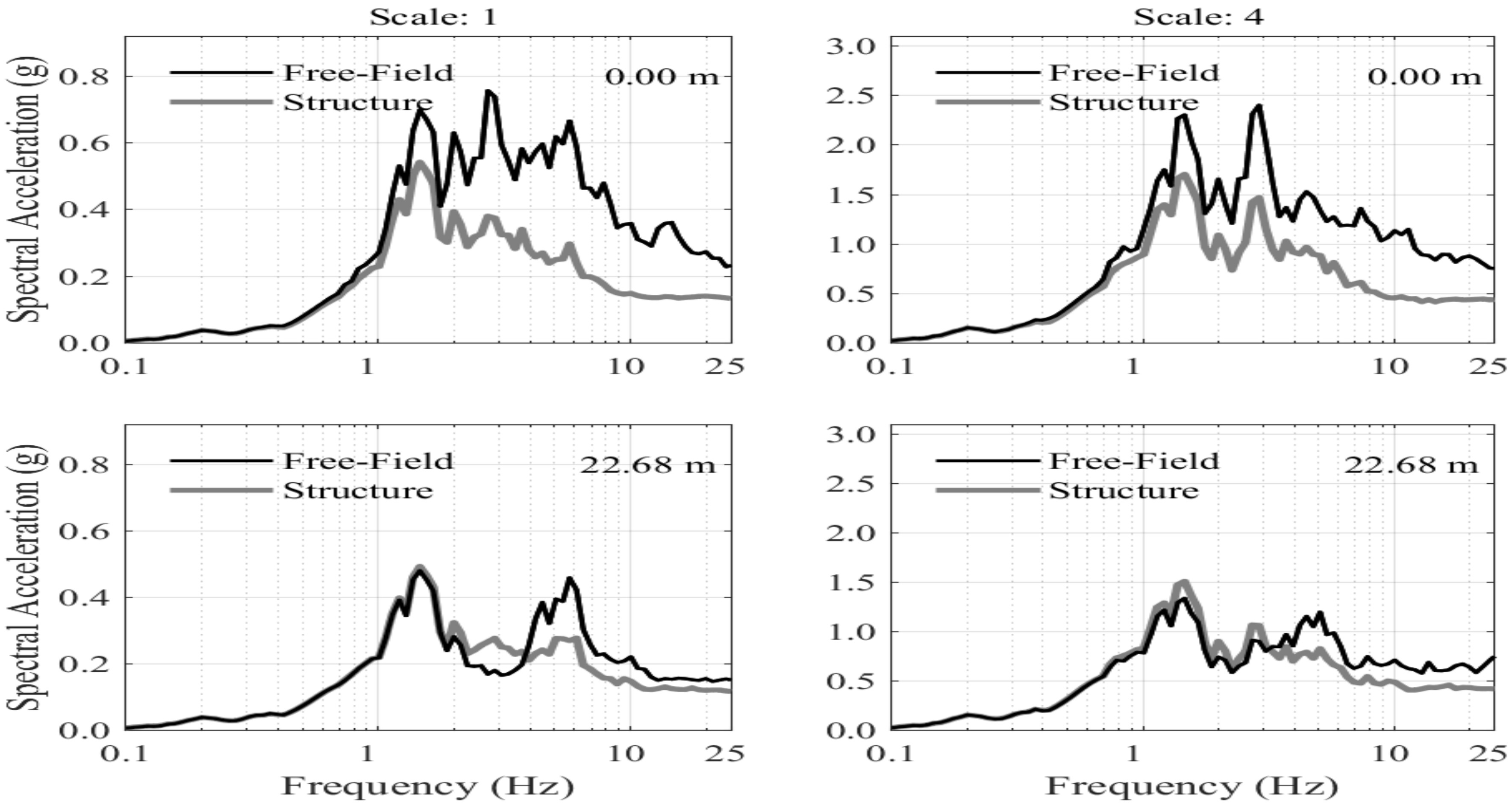
Spectral Acceleration

Structure

- Acceleration at the top of the structure is very similar to the base
- High frequency response was much reduced when compared to free-field

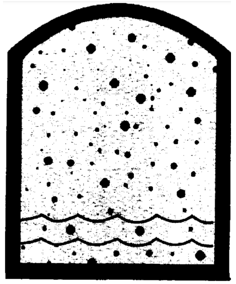




Spectral Response

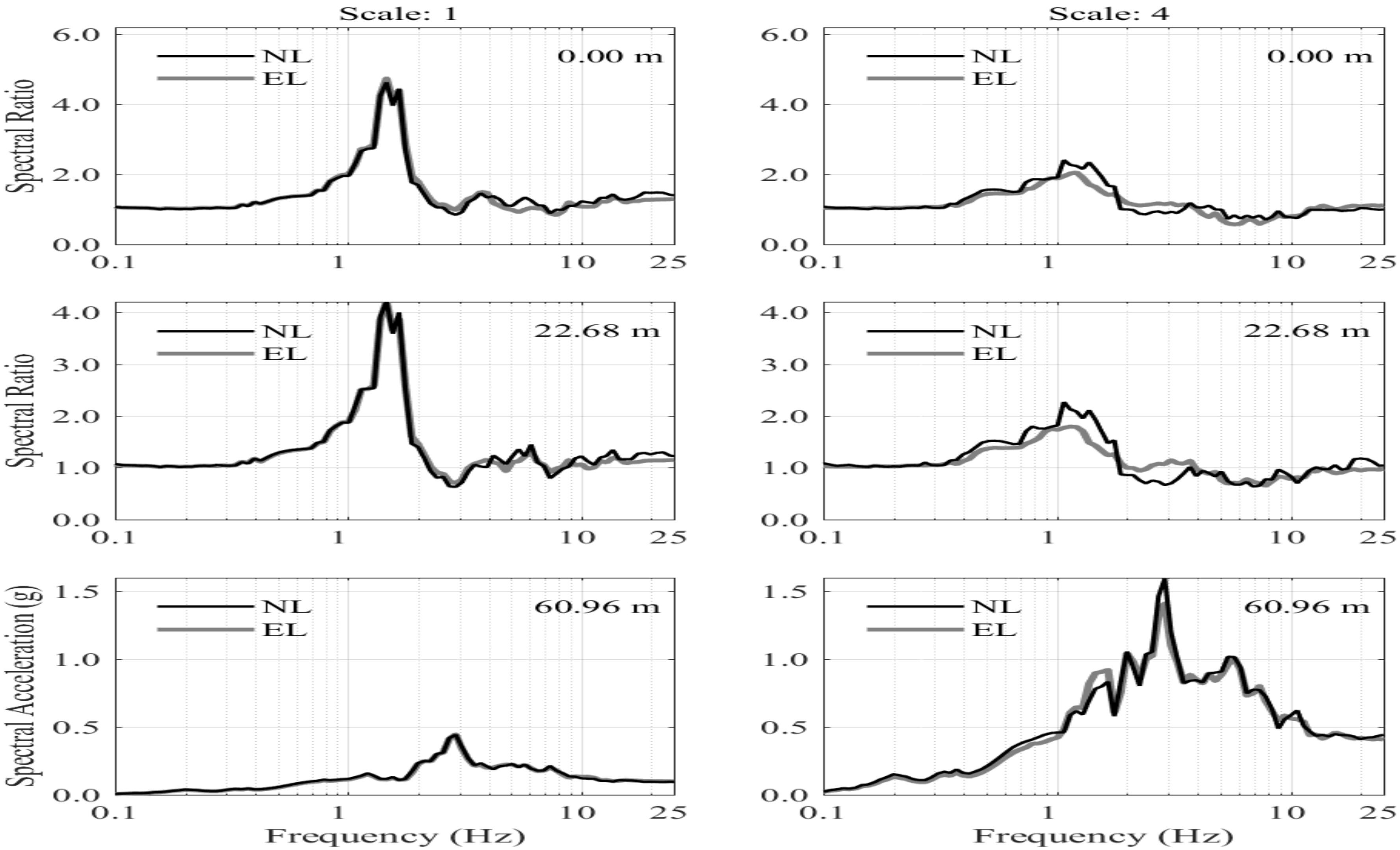
Structure

Ground Surface



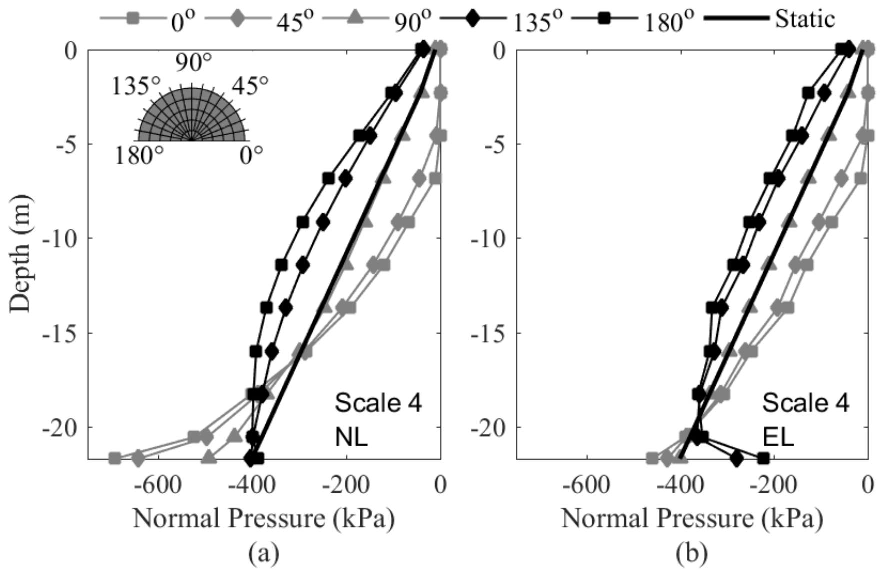
Base of structure

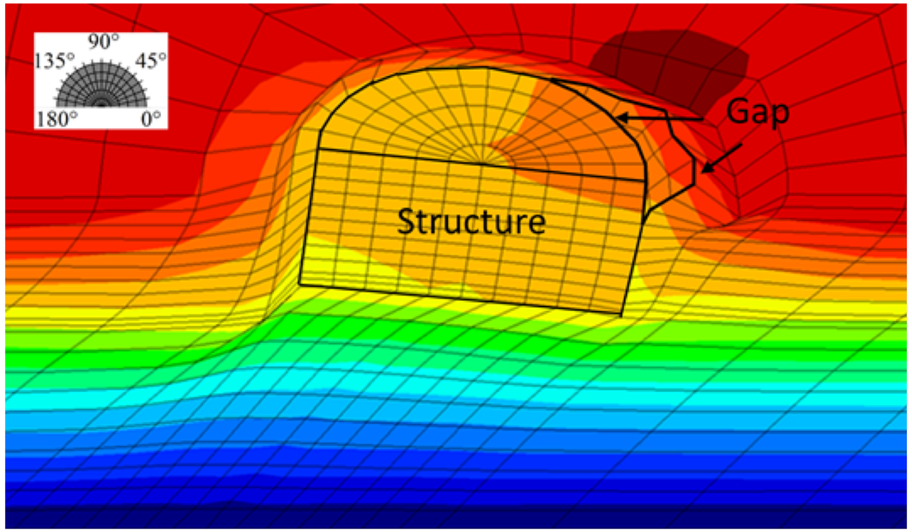
Base of Model

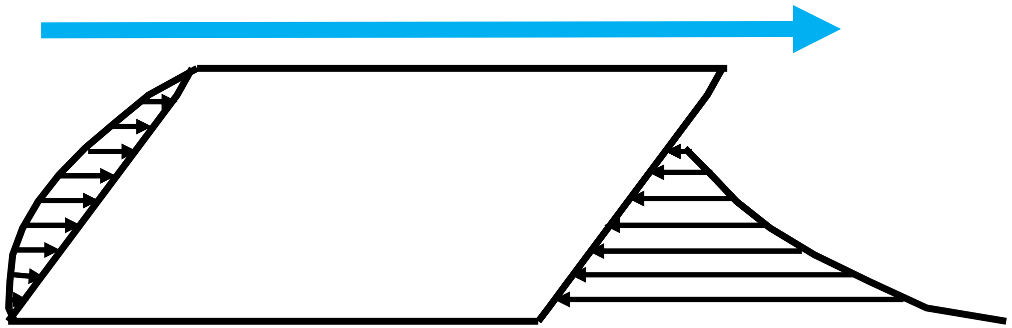


Lateral Earth Pressure on wall

- The main change in lateral pressure occurs within a 45-degree zone measured from the 0° to the 180° degree.
- Within the 45° degree to 135° zone, the pressure barely changed compared to the static state.
- The overall force was largest when the soil is pushing on the structure. (180°)
- On the opposing side, the force increases considerably at the base. (0°)







3-Dimensional Simulation

Large Pile Groups

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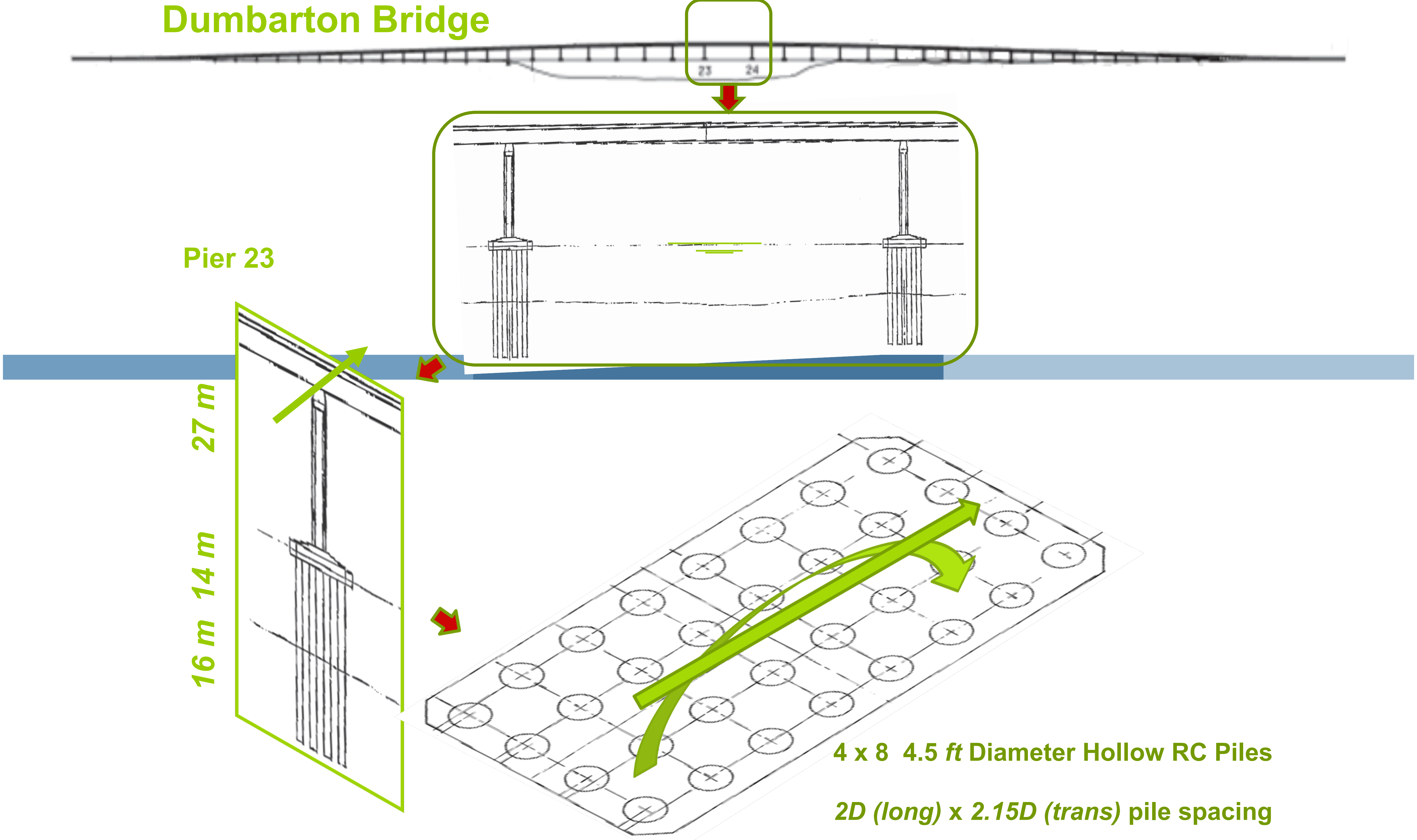
http://en.wikipedia.org/wiki/File:DumbartonBridgeCA_and_Towers.jpg

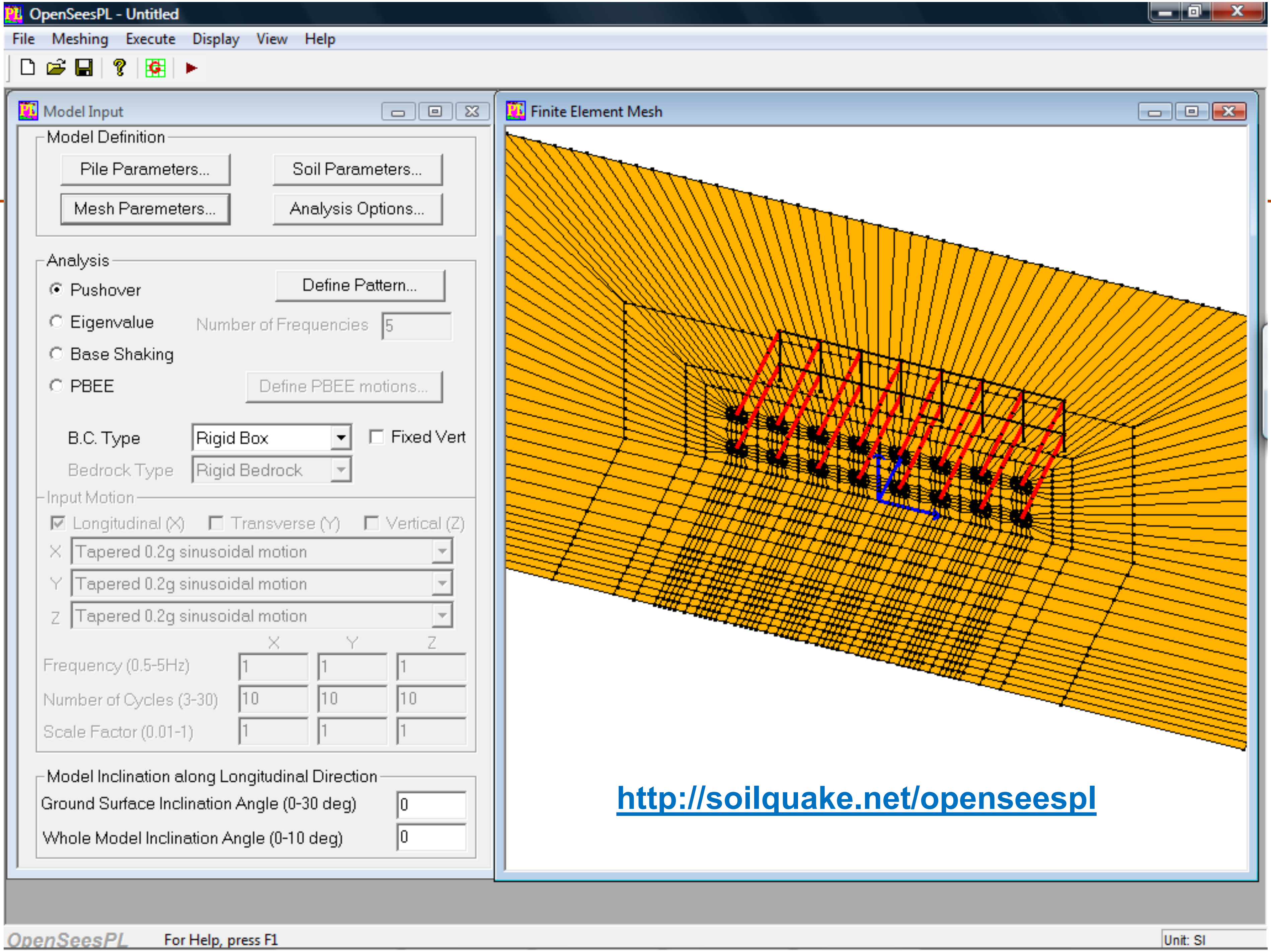
Sunset Under The Dumbarton by Vincent® /

Dumbarton Bridge



4 x 8 4.5 *ft* Diameter Hollow RC Piles

***2D (long)* x *2.15D (trans)* pile spacing**



http://soilquake.net/openseespl

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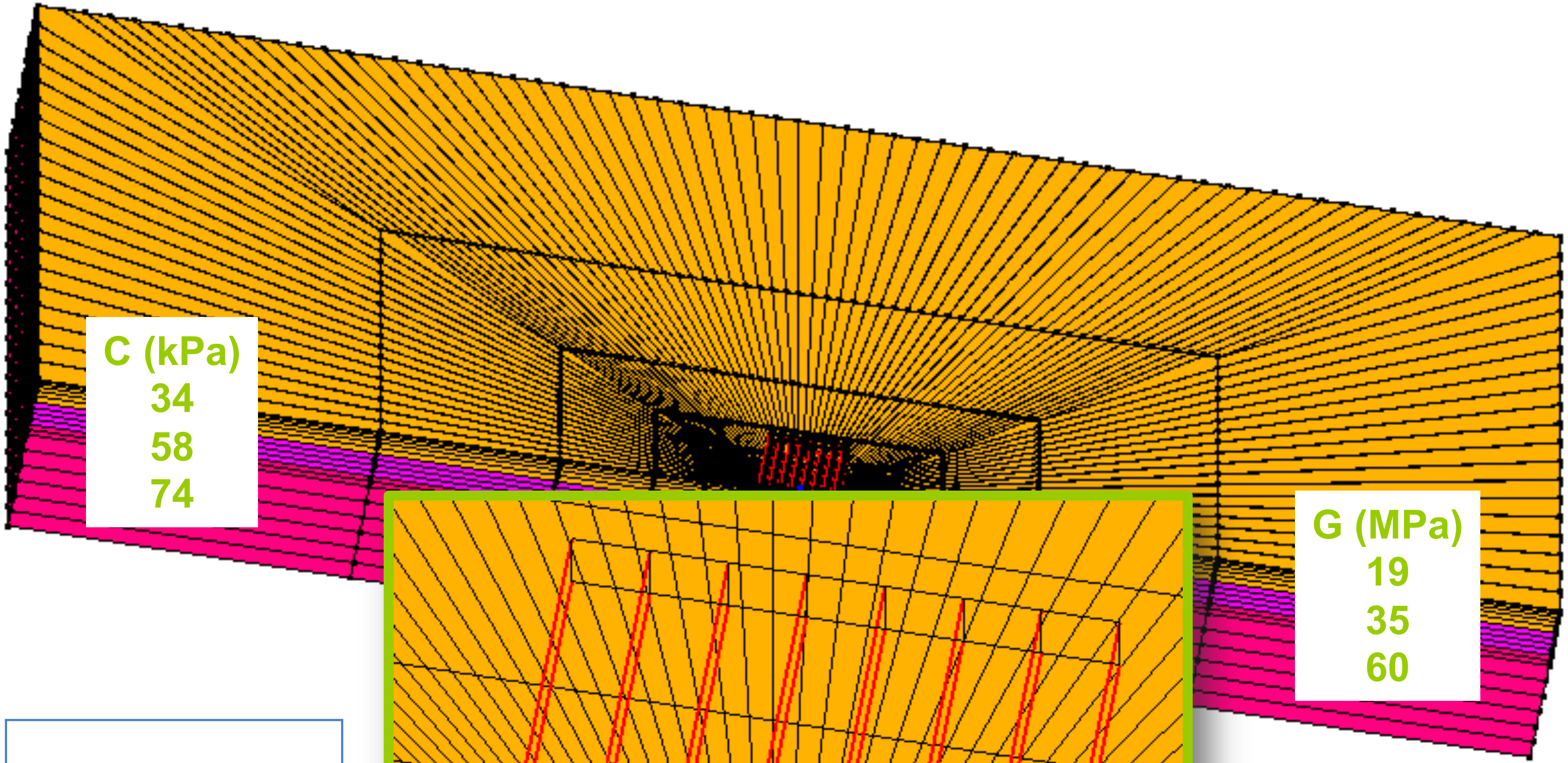
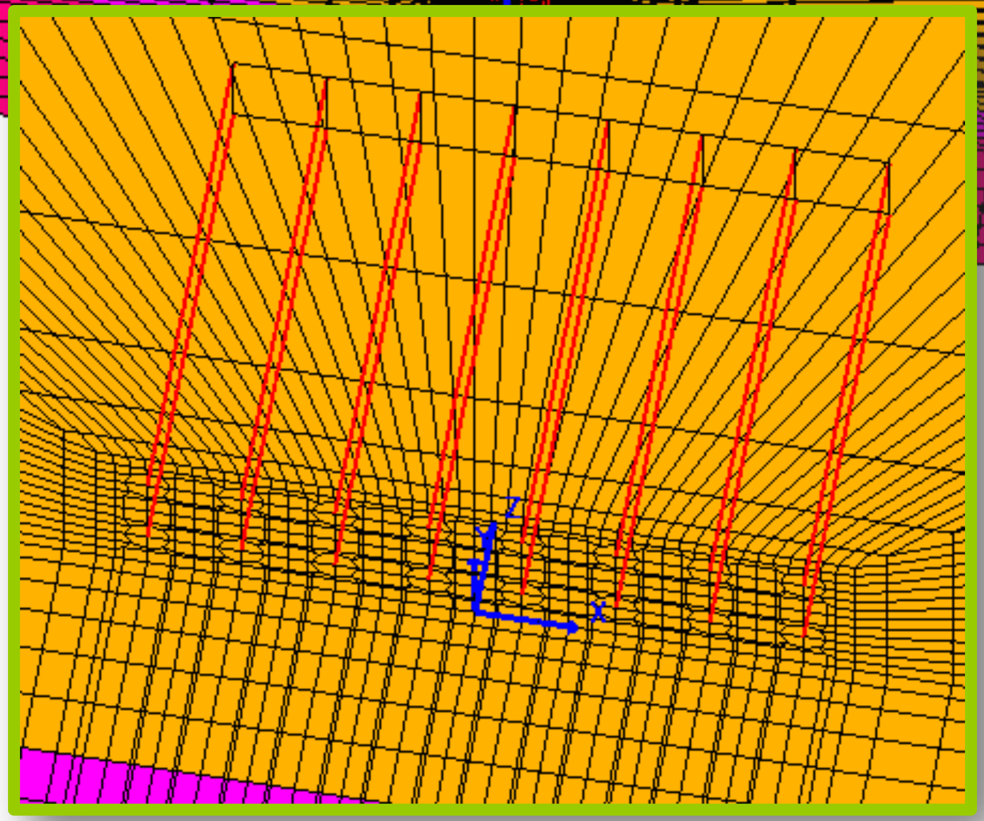
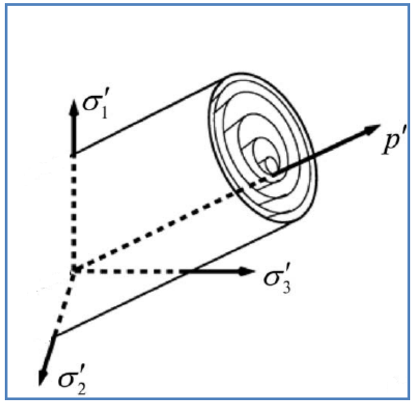

C (kPa)
34
58
74
G (MPa)
19
35
60

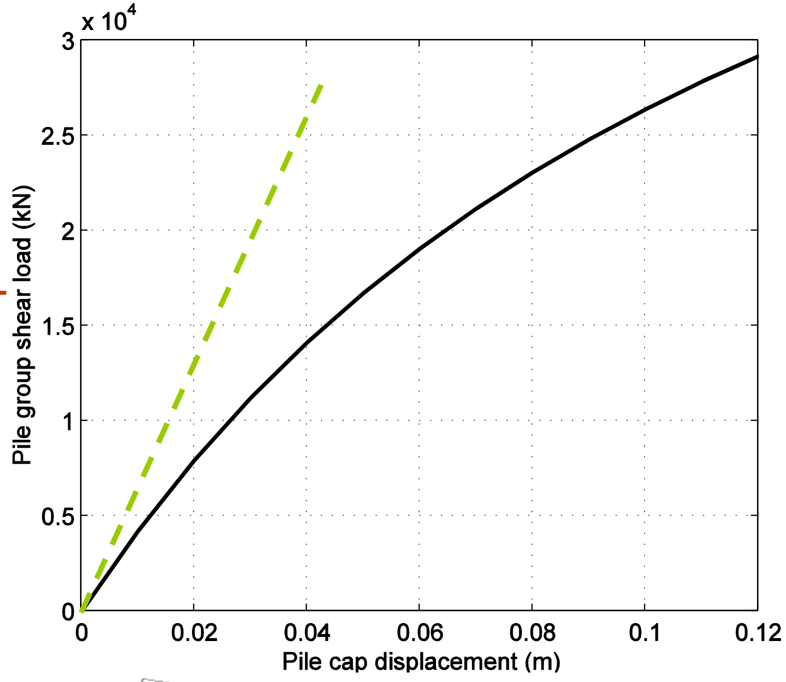


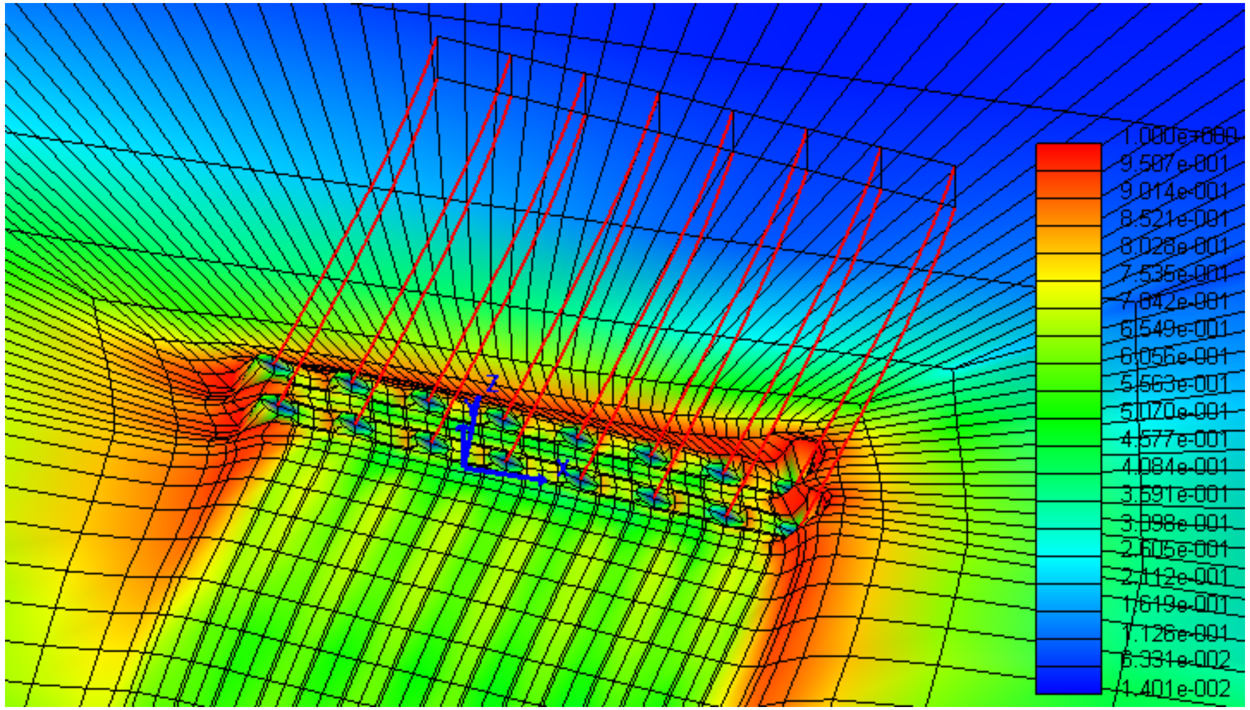

σ'_1
p'
σ'_3
σ'_2

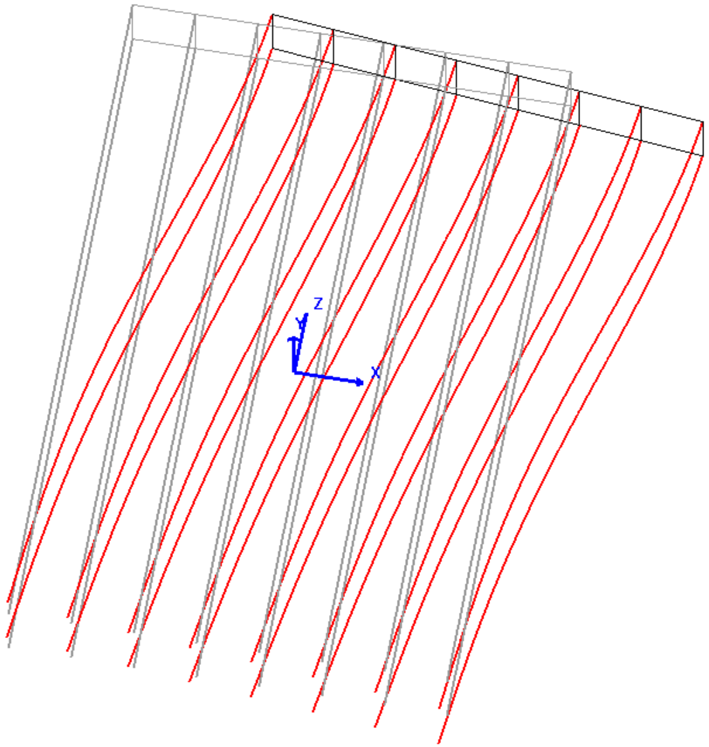
Applied Loads

1. Bridge Own weight

2. Pushover analysis (1 g)







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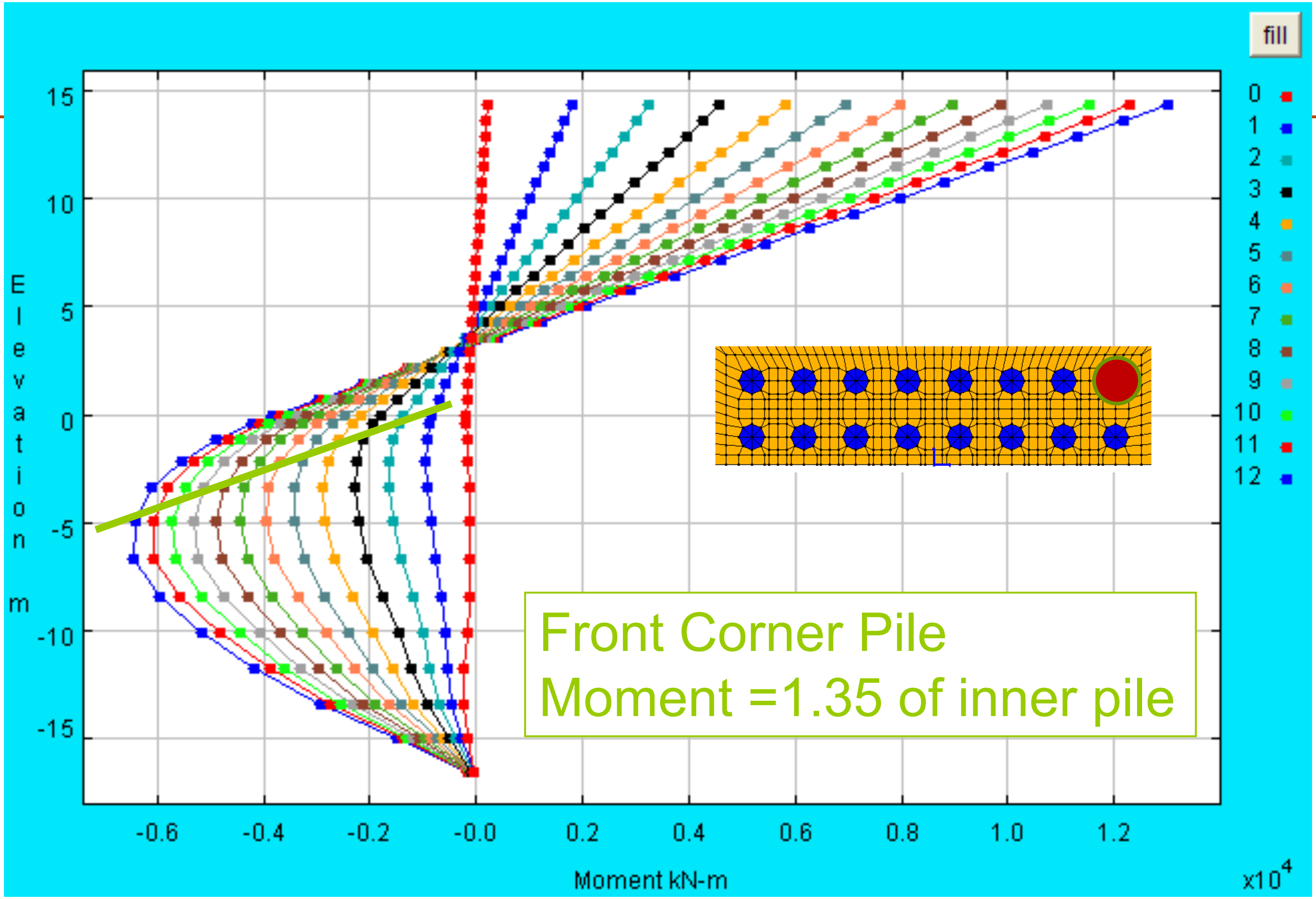
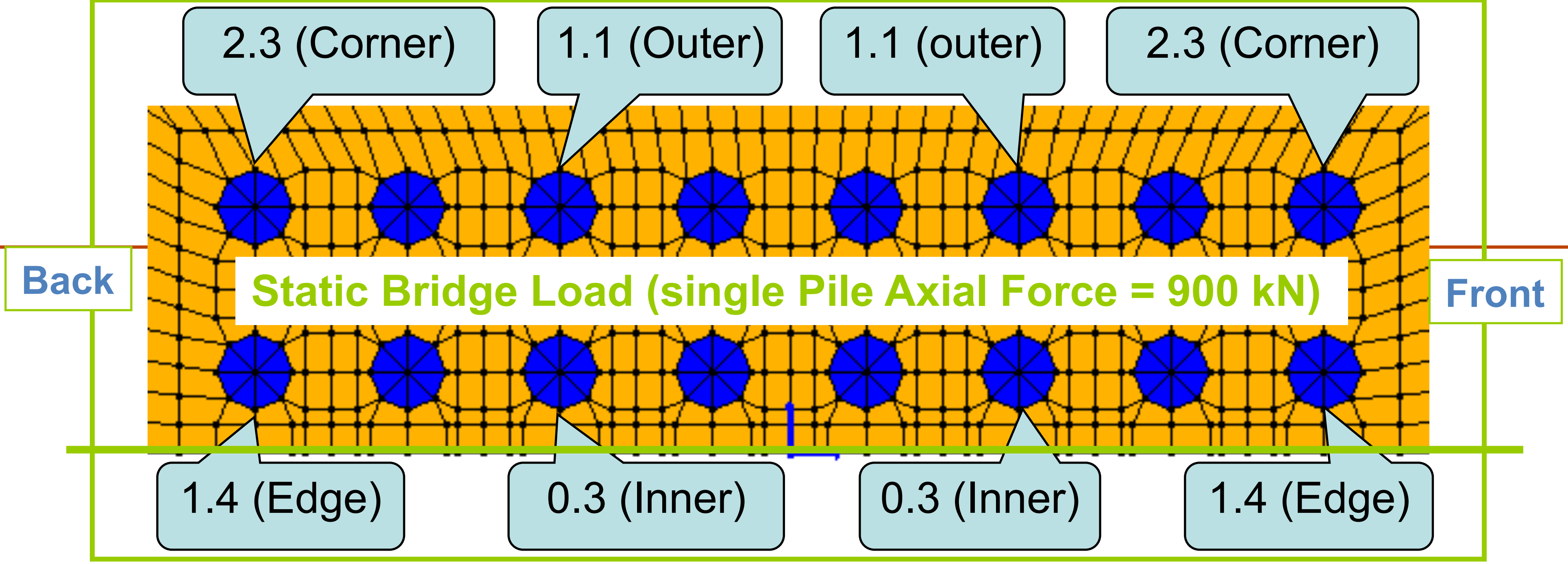
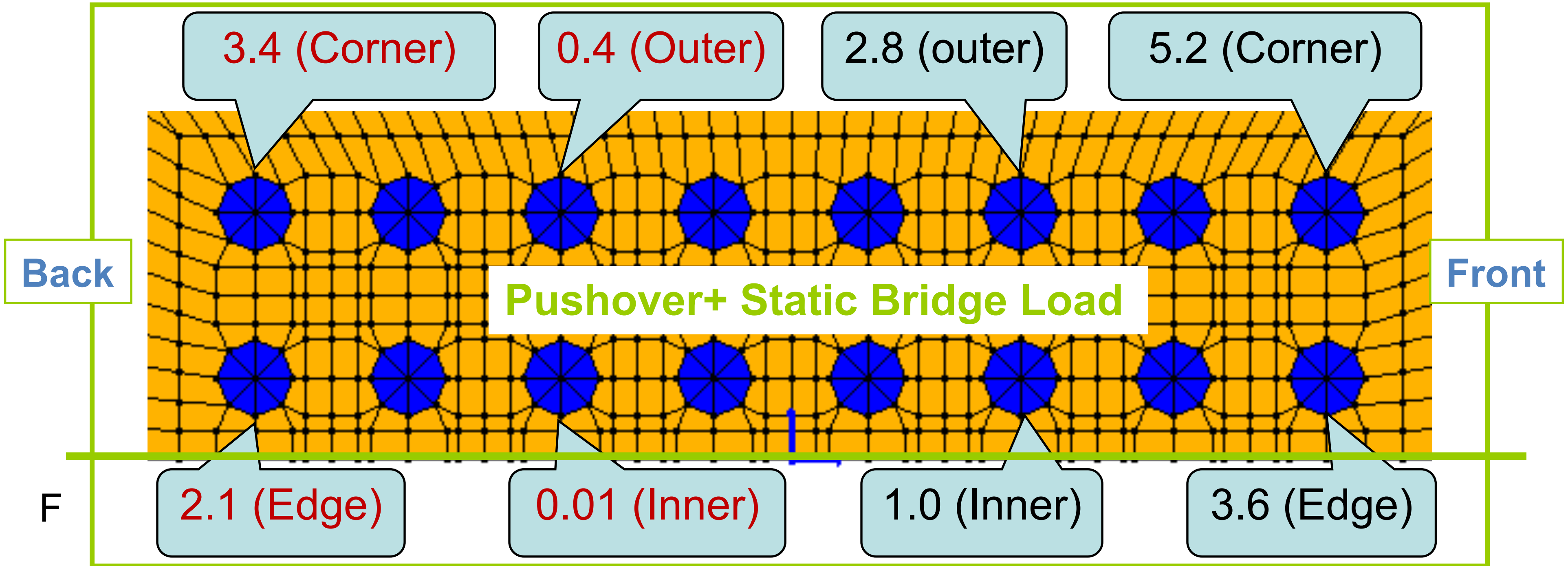
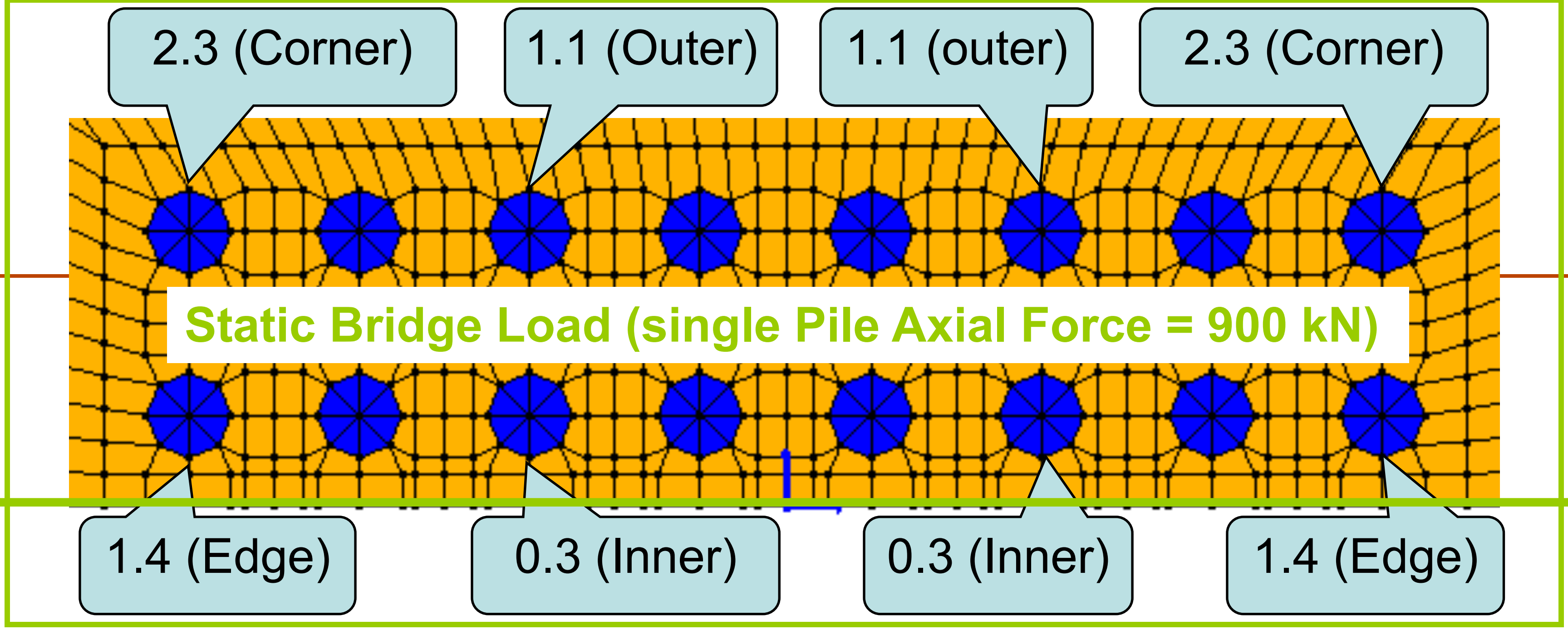
Moment

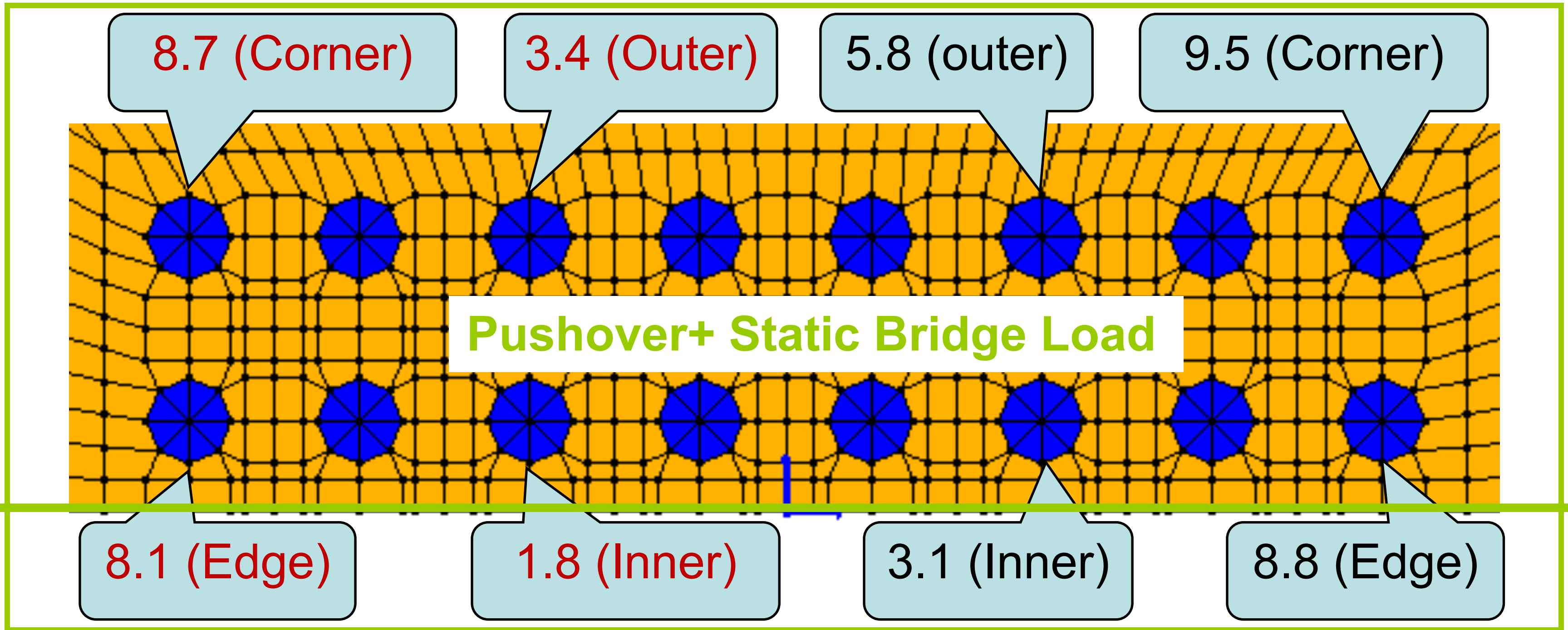


Case of force only


2.3 (Corner)
1.1 (Outer)
1.1 (outer)
2.3 (Corner)
Back
Static Bridge Load (single Pile Axial Force = 900 kN)
Front
1.4 (Edge)
0.3 (Inner)
0.3 (Inner)
1.4 (Edge)


3.4 (Corner)
0.4 (Outer)
2.8 (outer)
5.2 (Corner)
Back
Pushover+ Static Bridge Load
Front
F
2.1 (Edge)
0.01 (Inner)
1.0 (Inner)
3.6 (Edge)


2.3 (Corner)
1.1 (Outer)
1.1 (outer)
2.3 (Corner)
Static Bridge Load (single Pile Axial Force = 900 kN)
1.4 (Edge)
0.3 (Inner)
0.3 (Inner)
1.4 (Edge)


8.7 (Corner)
3.4 (Outer)
5.8 (outer)
9.5 (Corner)
Pushover+ Static Bridge Load
8.1 (Edge)
1.8 (Inner)
3.1 (Inner)
8.8 (Edge)

F + M

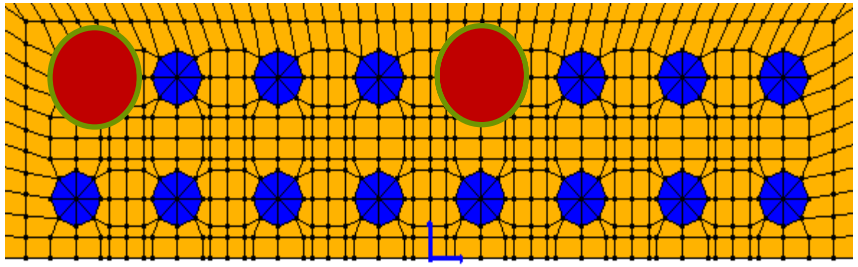
For the employed *cohesive soil* scenario:

- Corner piles are most vulnerable

- Edge piles carry much more axial load than inner piles

- Axial response and skin friction (t-z springs) may play a critical role

- Pile **tensile** forces may be quite significant and affect RC response (connection to pile-cap, reduction in confinement)



3-Dimensional Simulation

Seaport Wharf on Pile Foundations

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Gray Buildings © 2009 CyberCity
Data CSUMB SFML, CA OPC
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
©2009 Google

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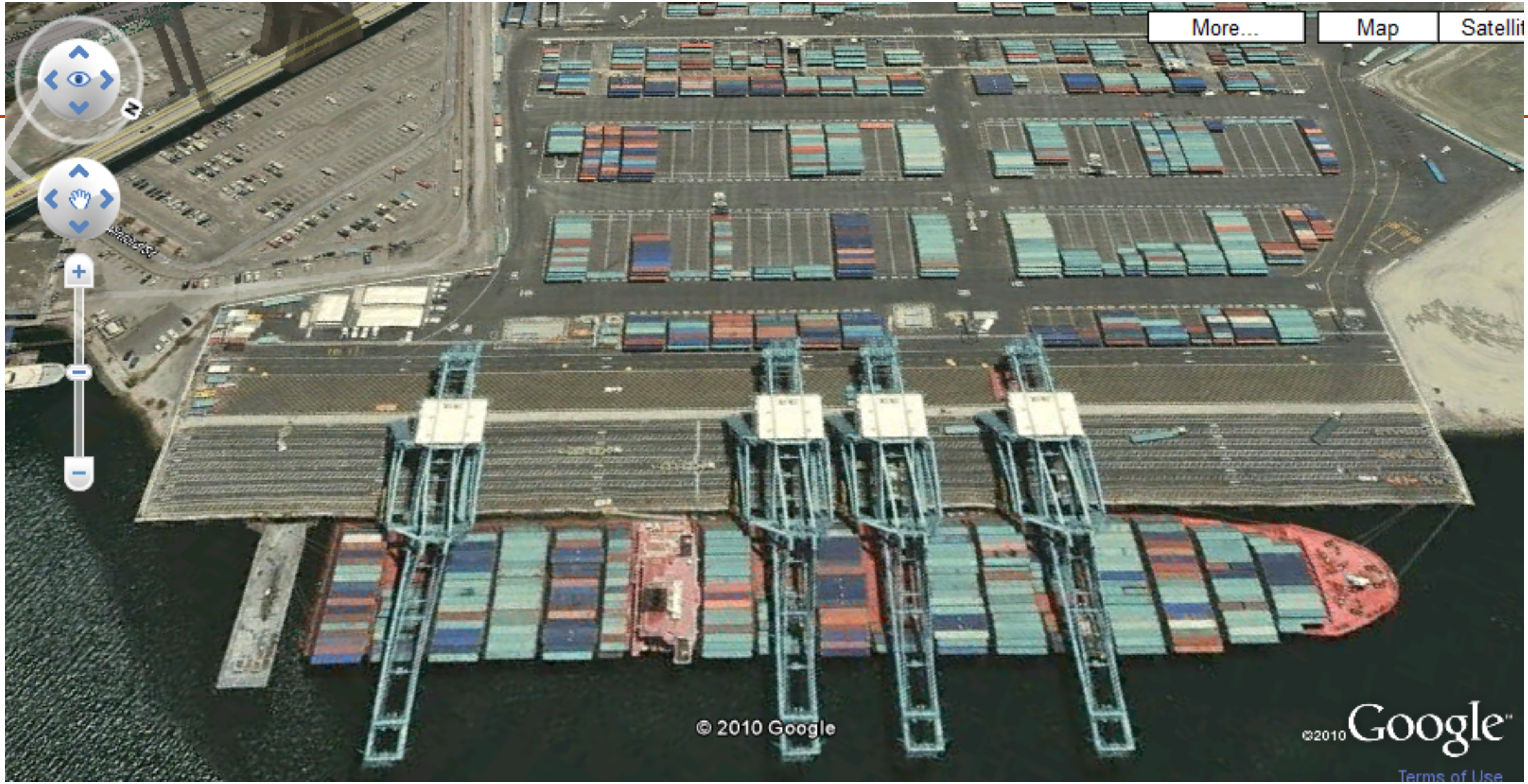
More...
Map
Satelli
© 2010 Google
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Container Wharf supported on Piles

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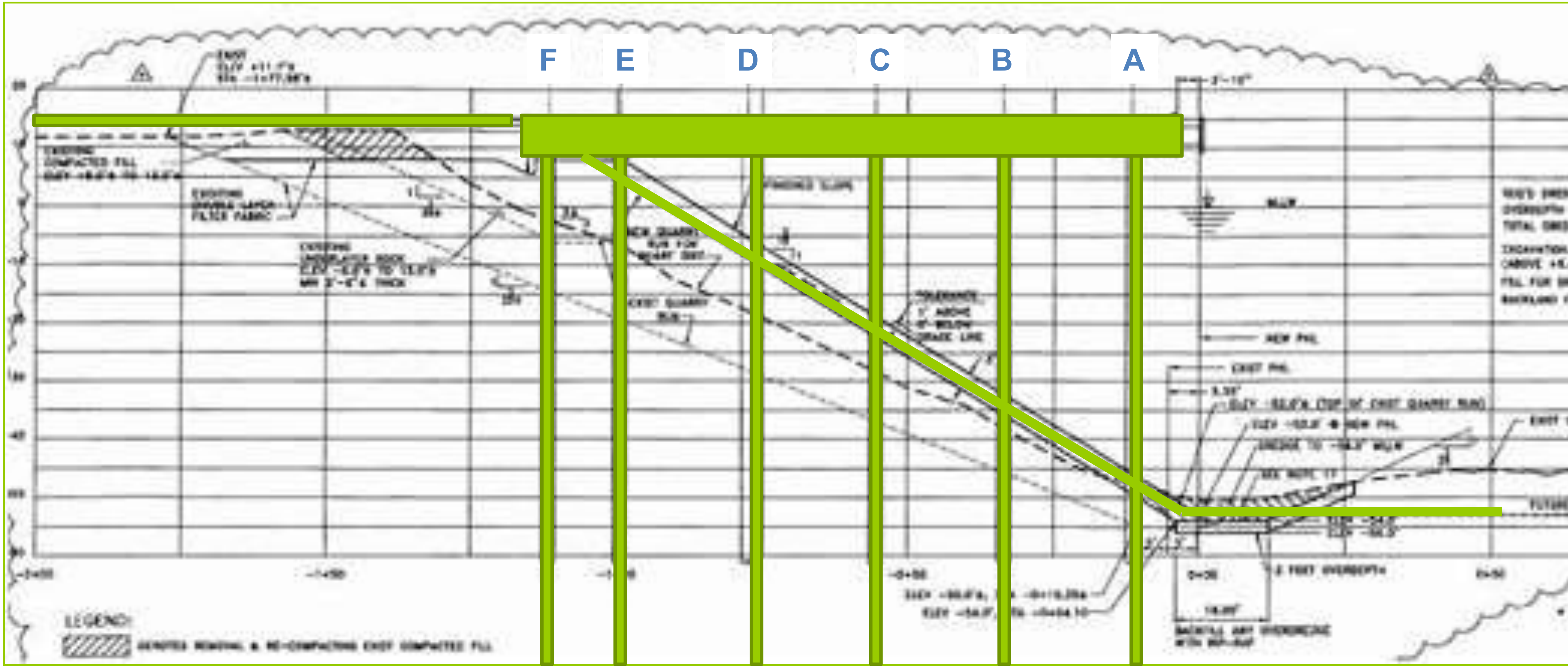
Berth 100 Container Wharf at Port of LA

(Dr. Arul Arulmoli, Earth Mechanics)



Cross-section

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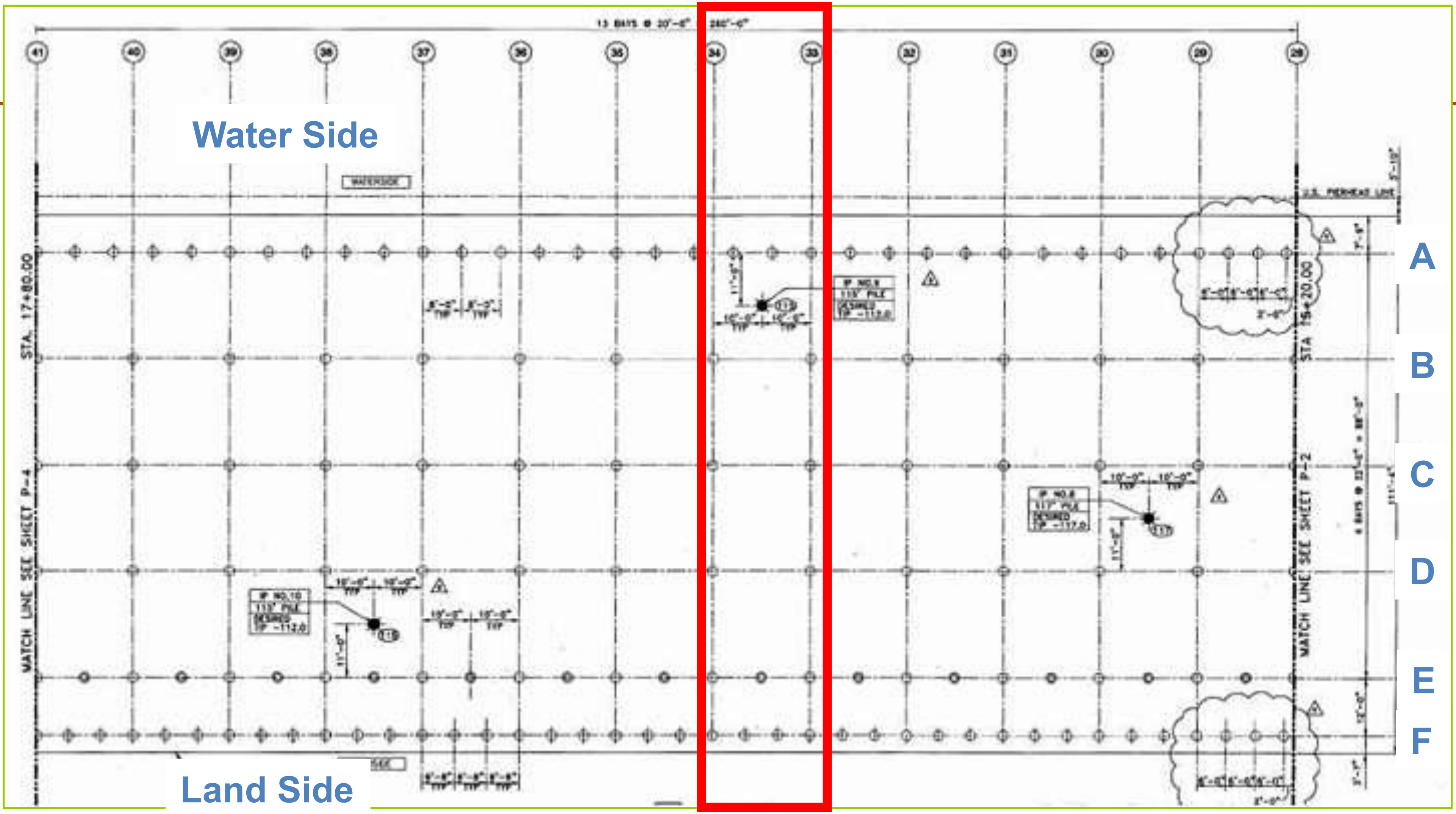
Configuration of Berth 100 Container Wharf at Port of LA

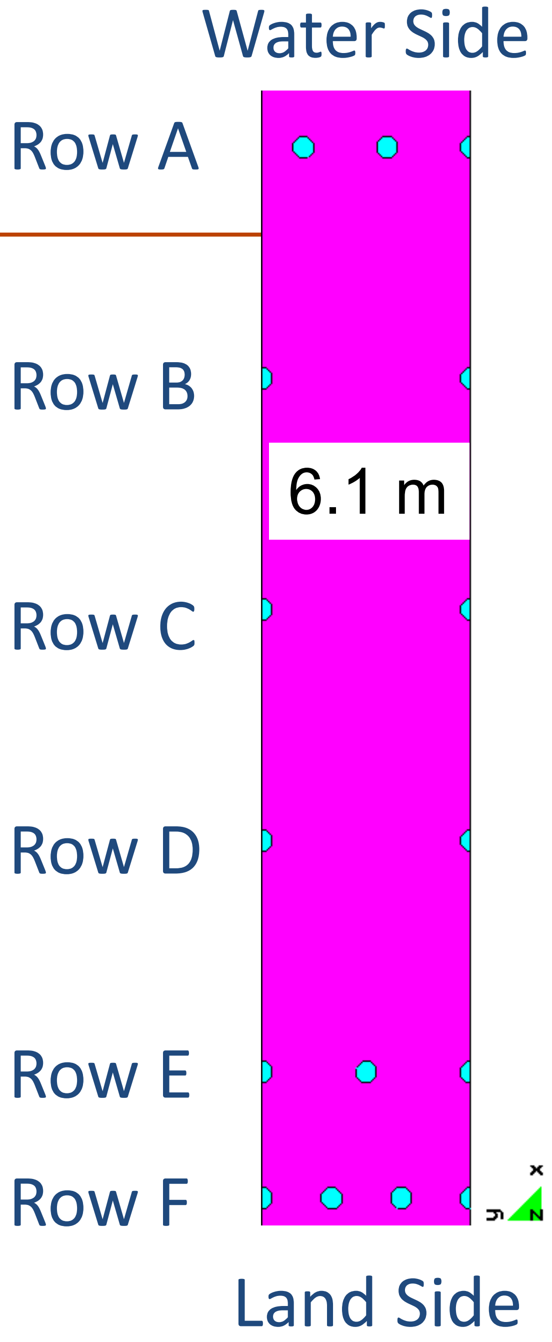


Plan View

3D Model

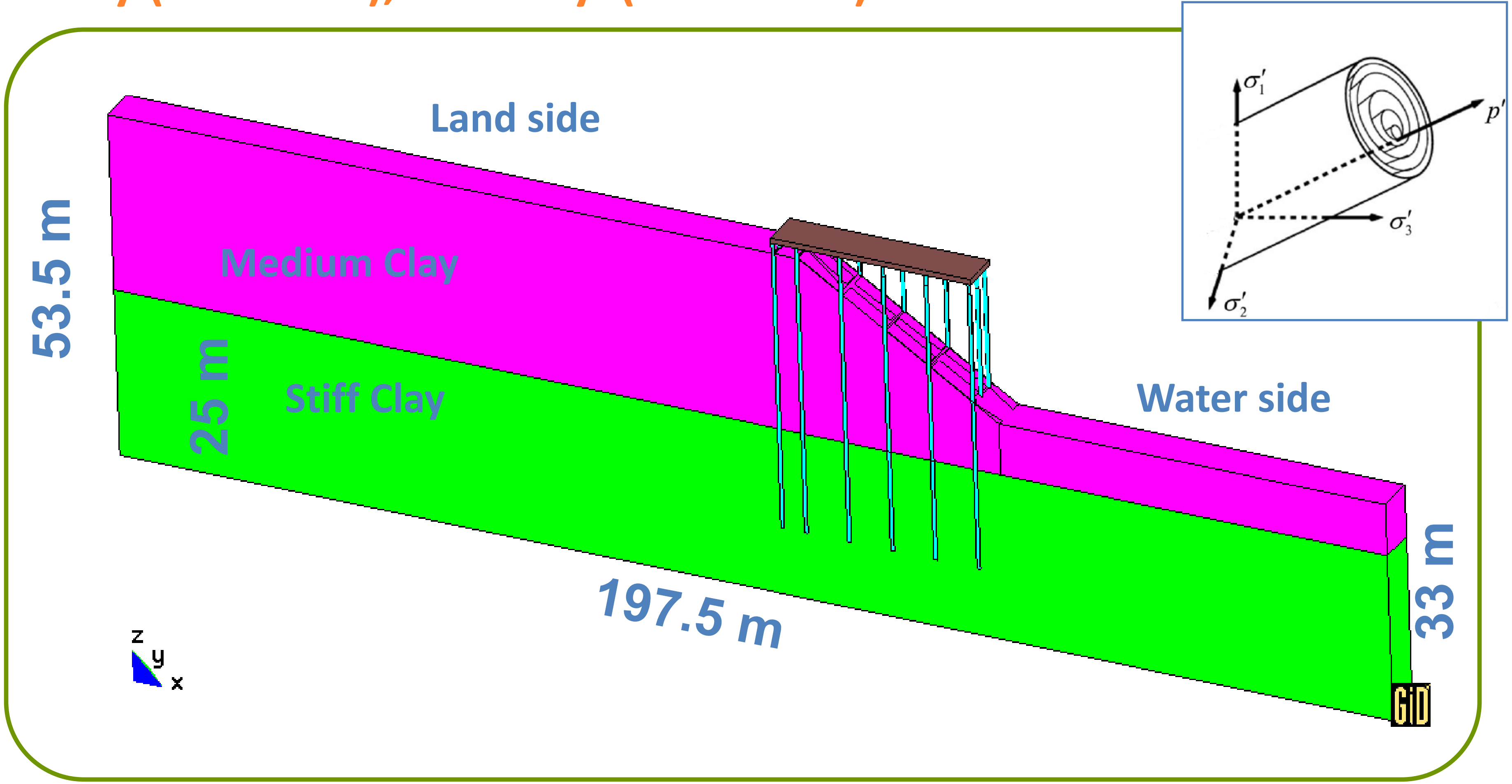
Wharf Structure (Plan view)

- stiff deck
- 16 piles in 6 rows
- 24 in Diameter (RC)
- 43 m long



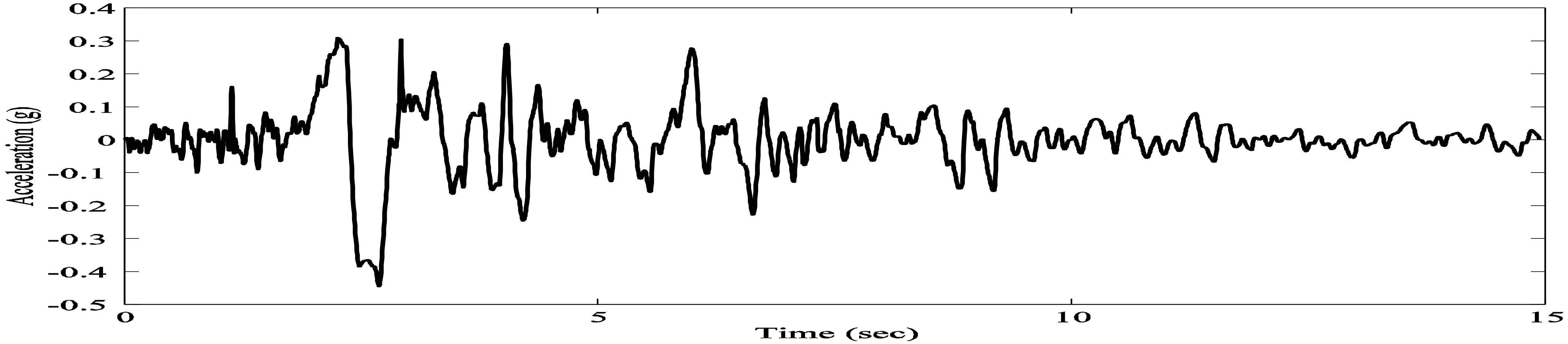
3D Idealized Pile-Supported Wharf Model

- Configurations typical of waterfront Wharf structures at the Port of LA
- Medium clay (c= 44 kPa), Stiff clay (c=225 kPa)

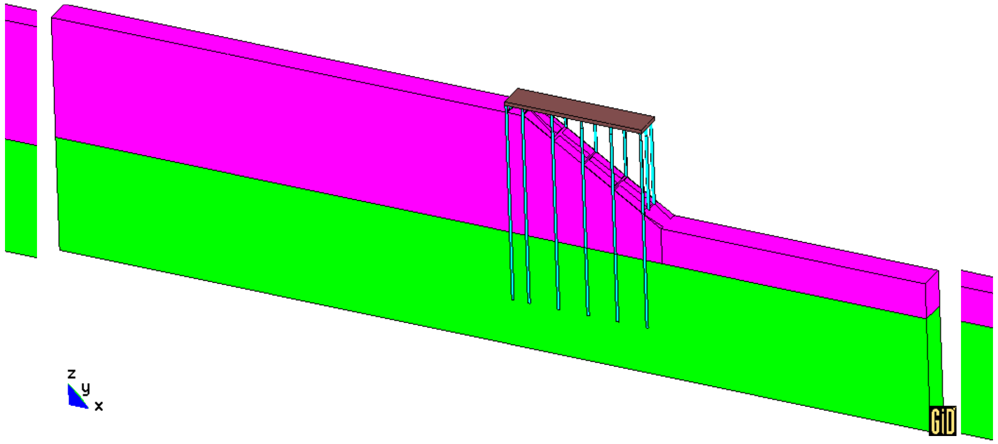


Input Motion and Boundary Conditions

➢ Base: 1994 Rinaldi Receiving Station record (1/2 Amplitude)

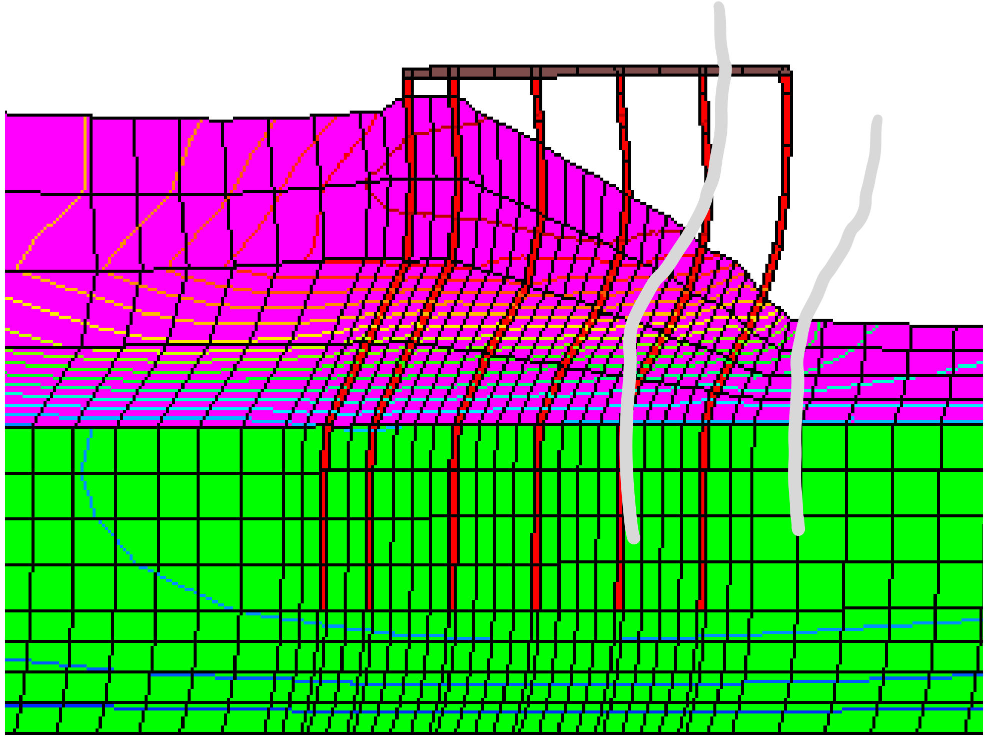


Computed accel. from 1D shear beam simulation



Computed accel. from 1D shear beam simulation

2D Final Deformed Meshes



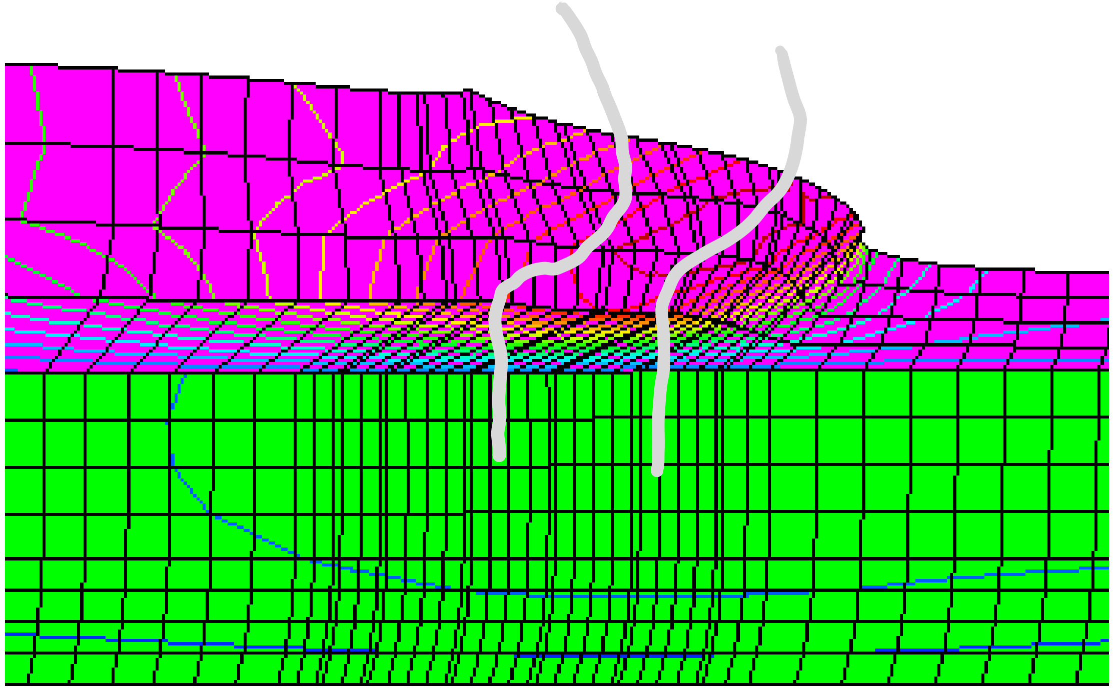


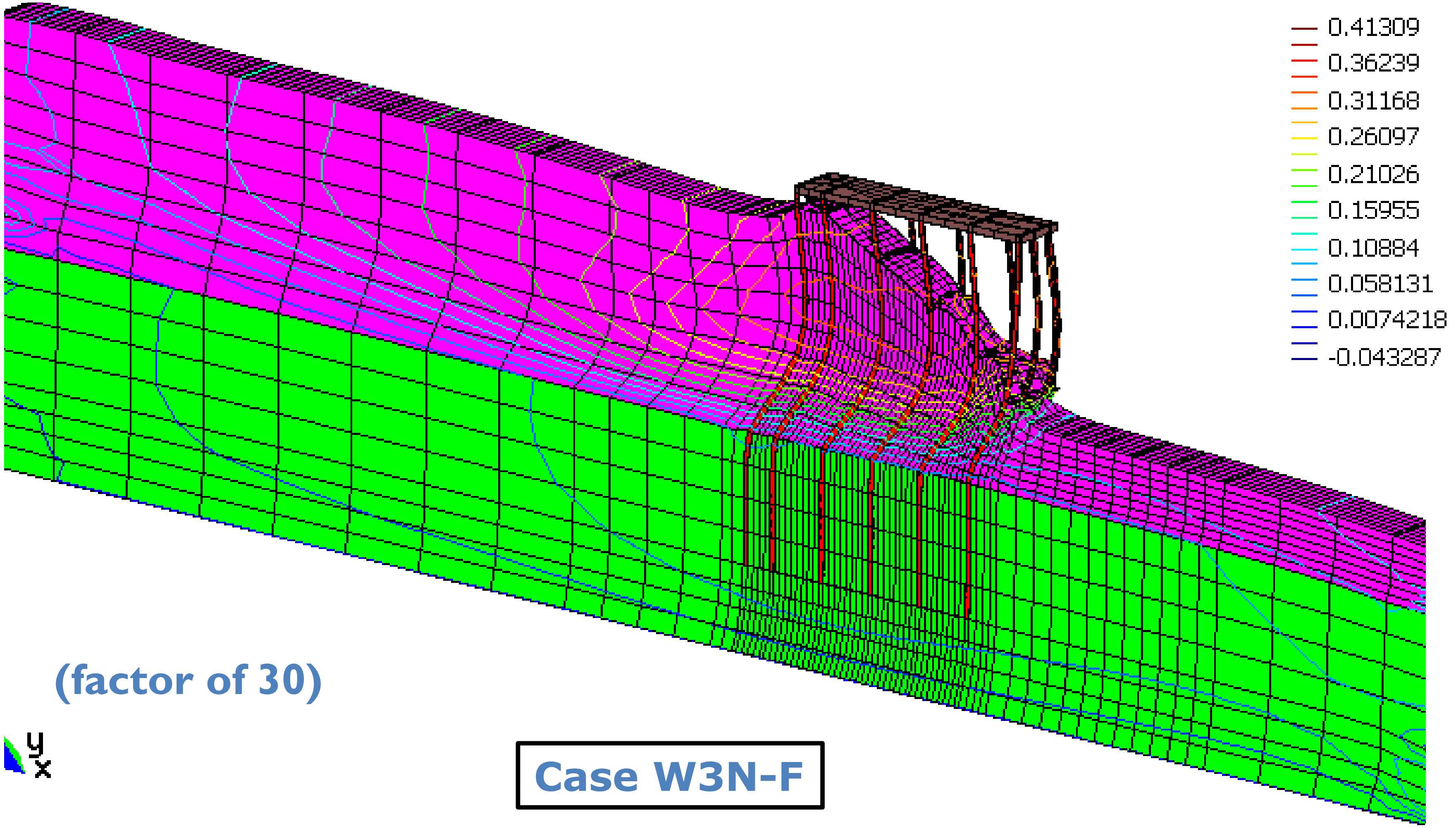
Illustration of Pile Pinning Effect (Close-up)

(factor of 30)

PEER

3D Final Deformed Mesh

Contour lines show longitudinal displacement in meters

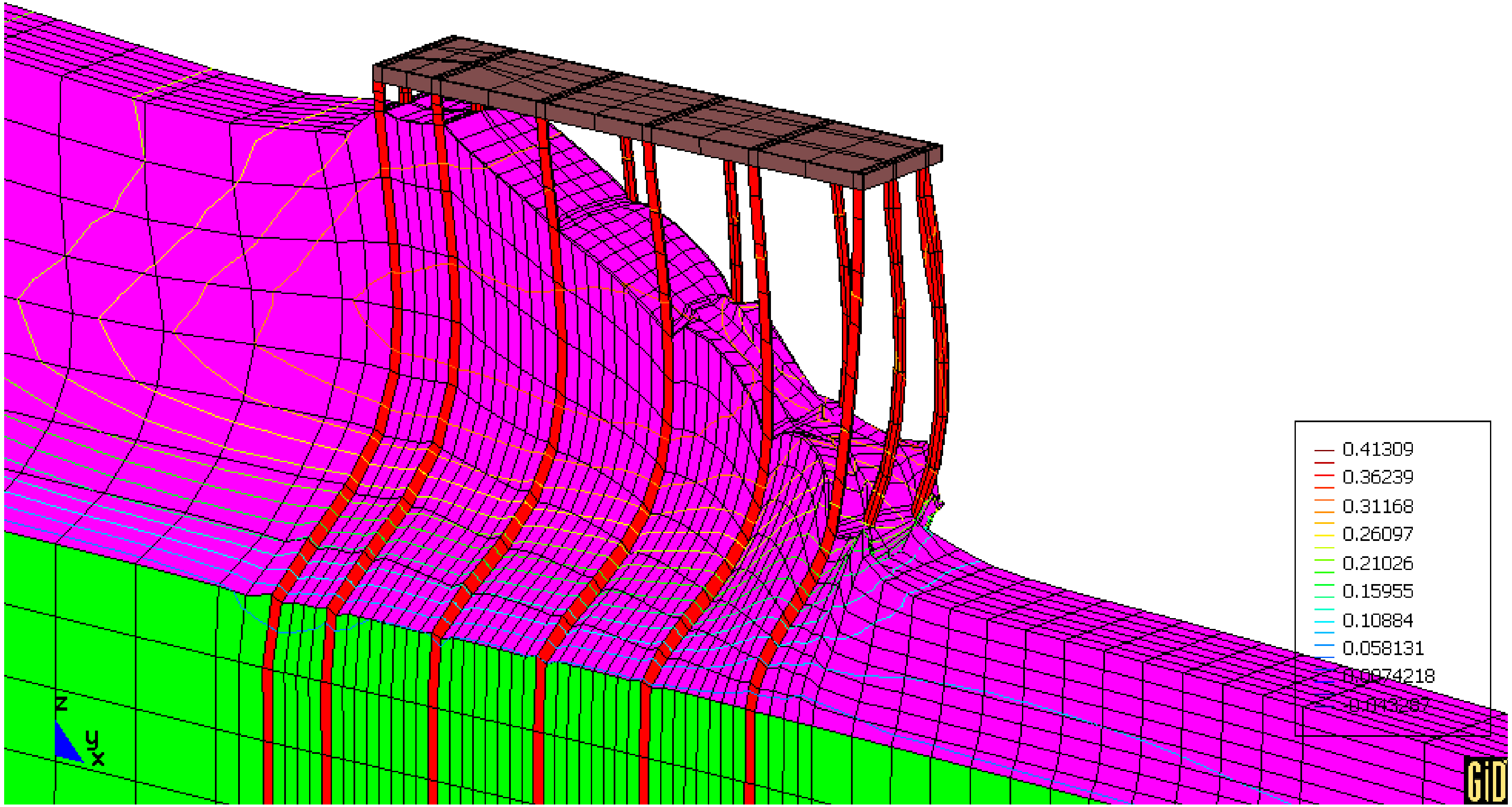


(factor of 30)

Case W3N-F

Close-up of Final Deformed Mesh

Contour lines show the longitudinal displacement in meters



(factor of 30)

Case W3N-F

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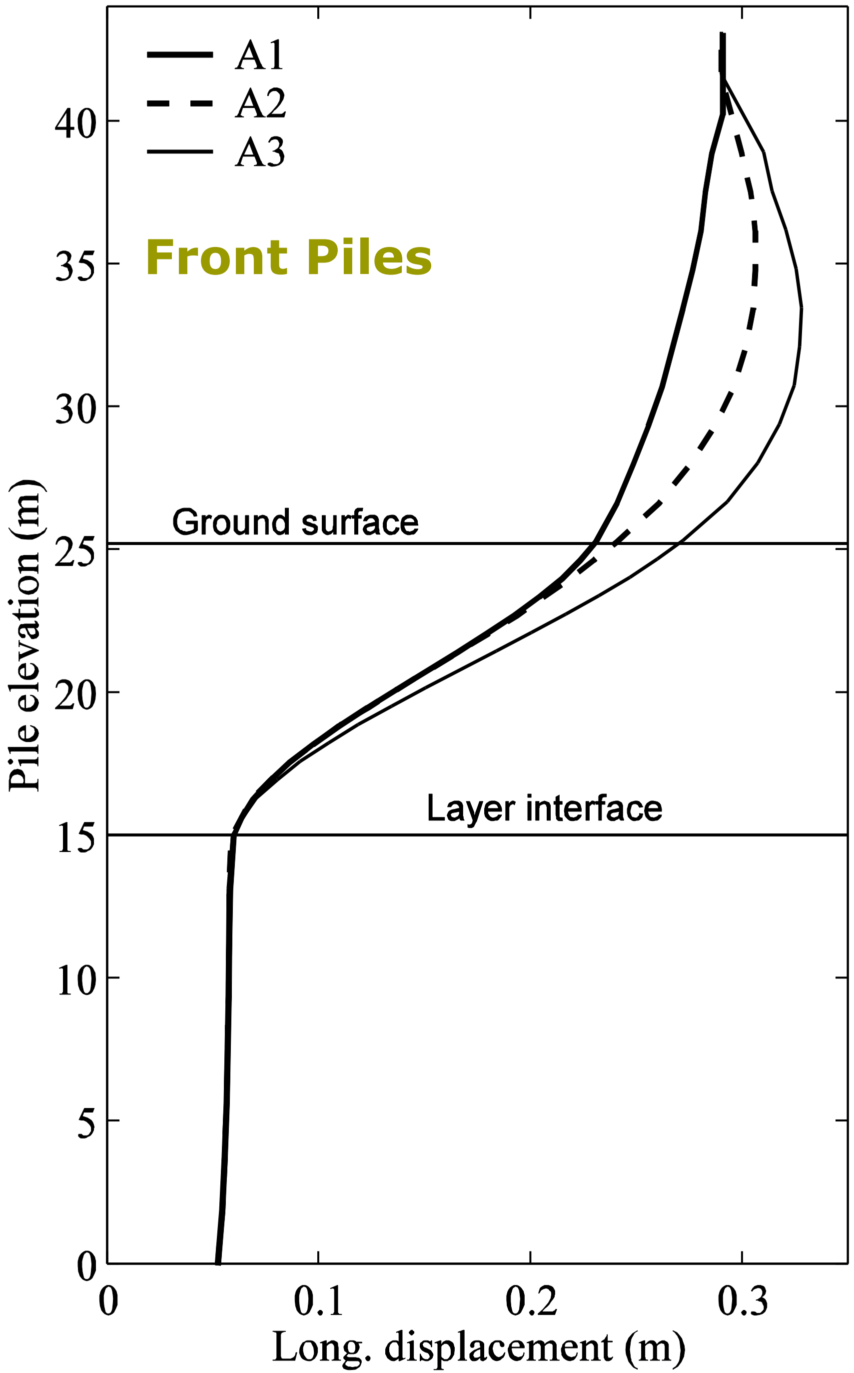
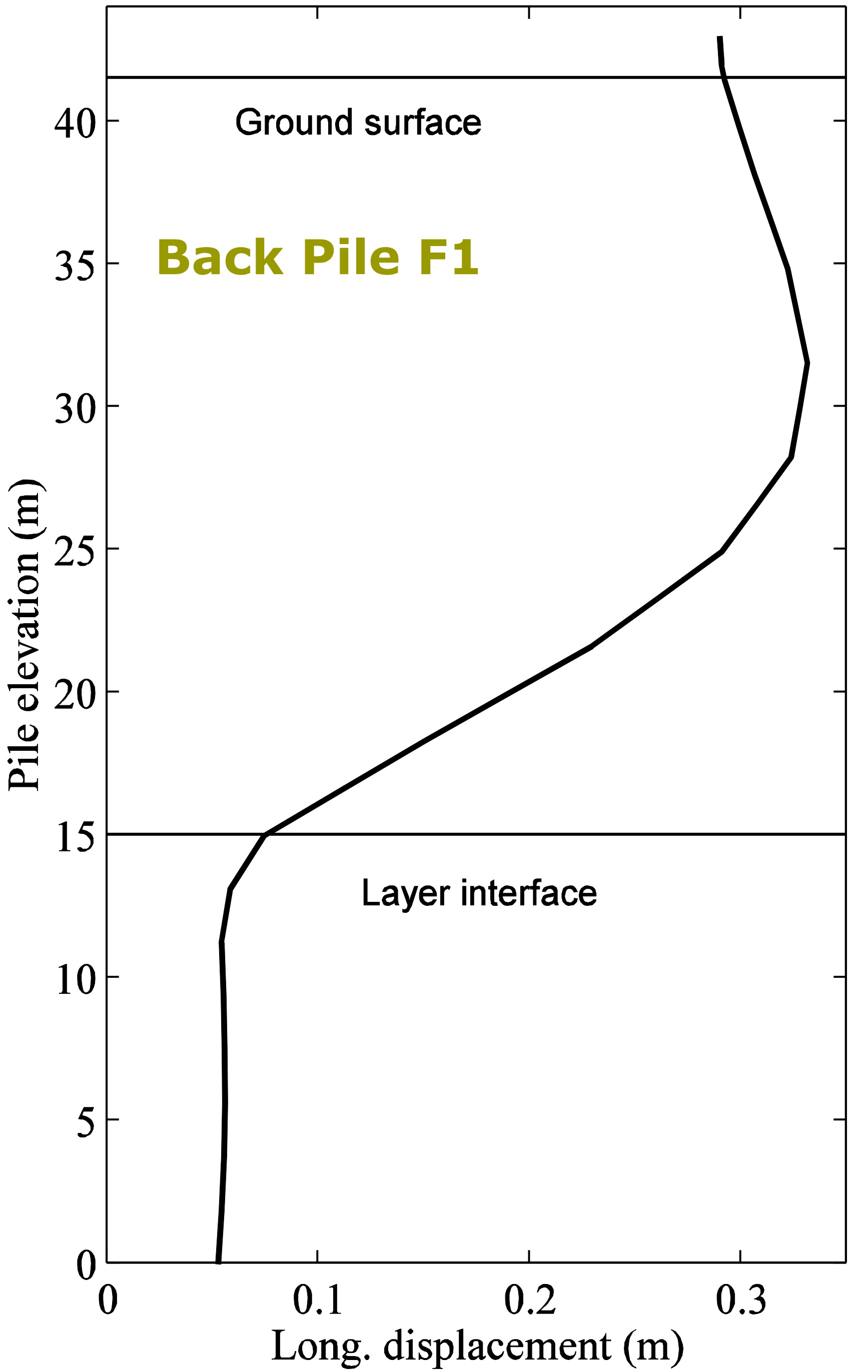

A1
A2
A3
Front Piles
Ground surface
Layer interface
Pile elevation (m)
Long. displacement (m)
0
5
10
15
20
25
30
35
40
0
0.1
0.2
0.3


Back Pile F1
Ground surface
Layer interface
Pile elevation (m)
Long. displacement (m)
0
5
10
15
20
25
30
35
40
0
0.1
0.2
0.3

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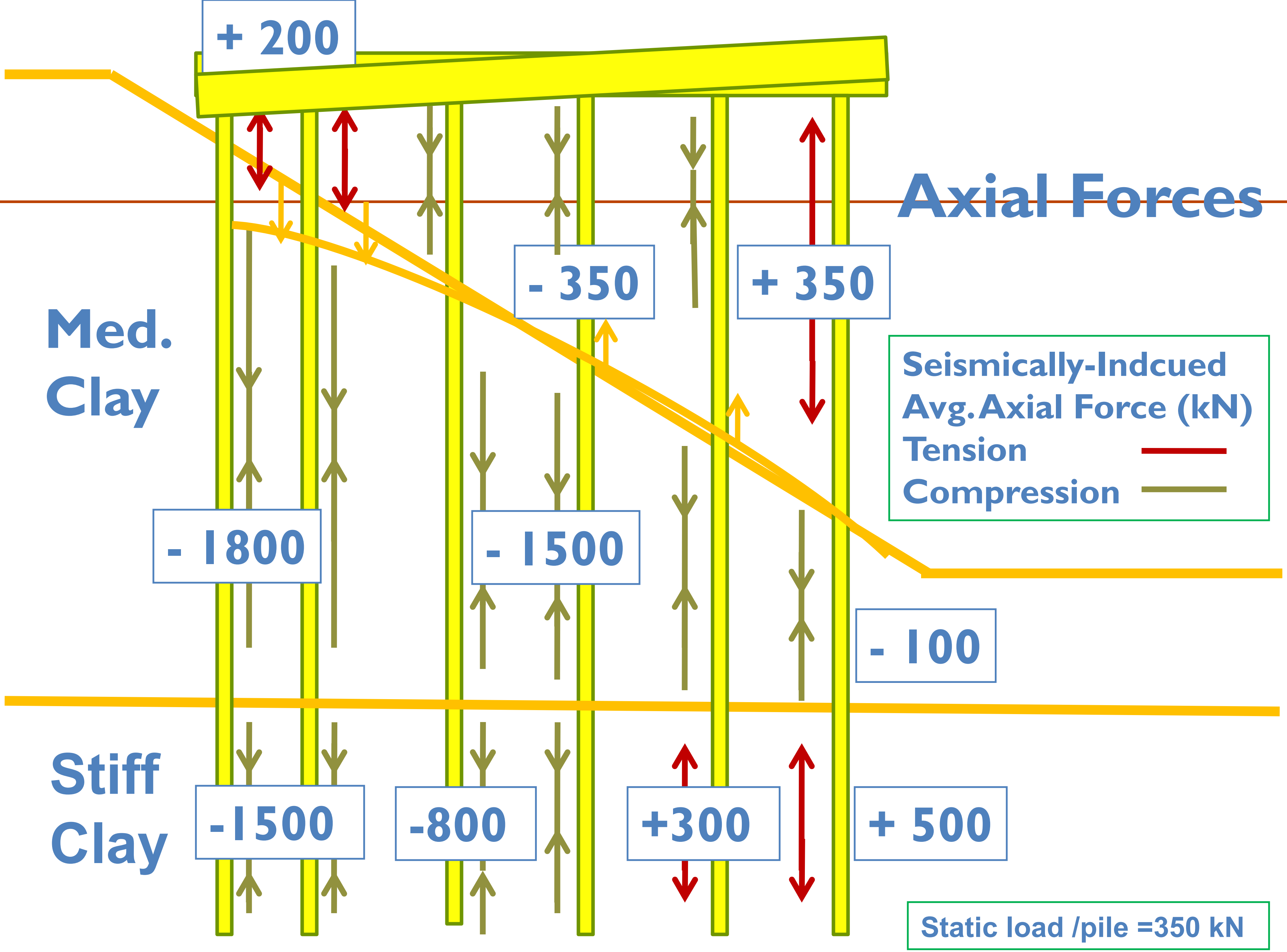
Axial Forces



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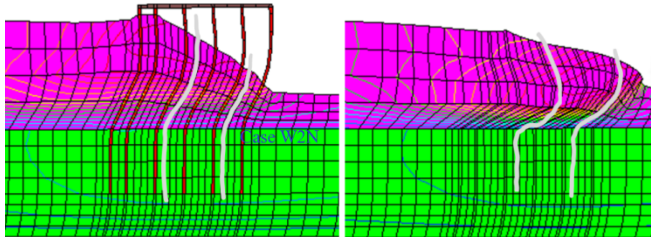
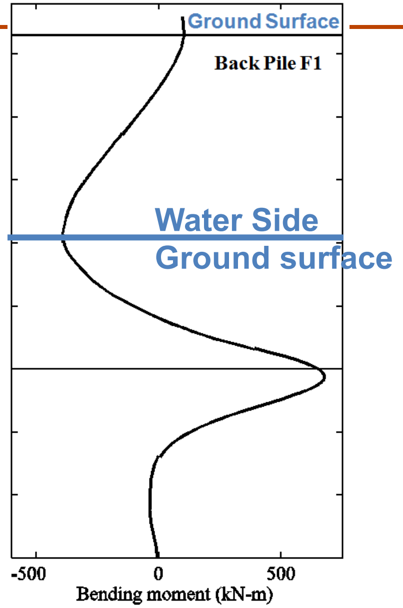
Su, L., Lu, J., Elgamal, A., & Arulmoli, A. K. (2017). Seismic performance of a pile-supported wharf: Three-dimensional finite element simulation. *Soil Dynamics and Earthquake Engineering*, *95*, 167-179.
https://www.sciencedirect.com/science/article/pii/S0267726117300313?casa_token=9f1pGjEoVfcAAAAA:kSDLmos50EZBNbDcgcoR4MaHTpGE_53usLtVh-8WZGfr4v_sx3HpUuyJm2v_ZPcfesO66lKWiA



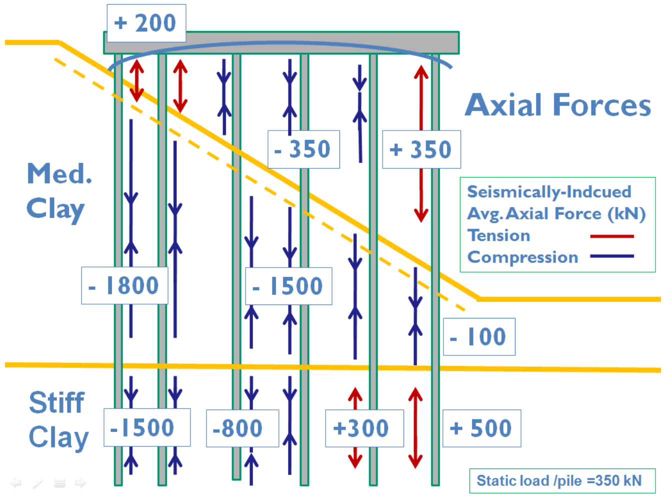
For the investigated scenario



Pattern of slope deformation without the piles may be significantly different . Pile bending deformations influence the slope deflection pattern

Front piles with longest free length and back piles with shortest free length were both subjected to approximately equal patterns of shear forces and moments. Moment peak values occur near the water side ground elevation and at the soft-stiff soil interface

Seismically-induced axial tensile forces in the wharf piles may be quite substantial. More effort is needed to investigate such axial response mechanisms.



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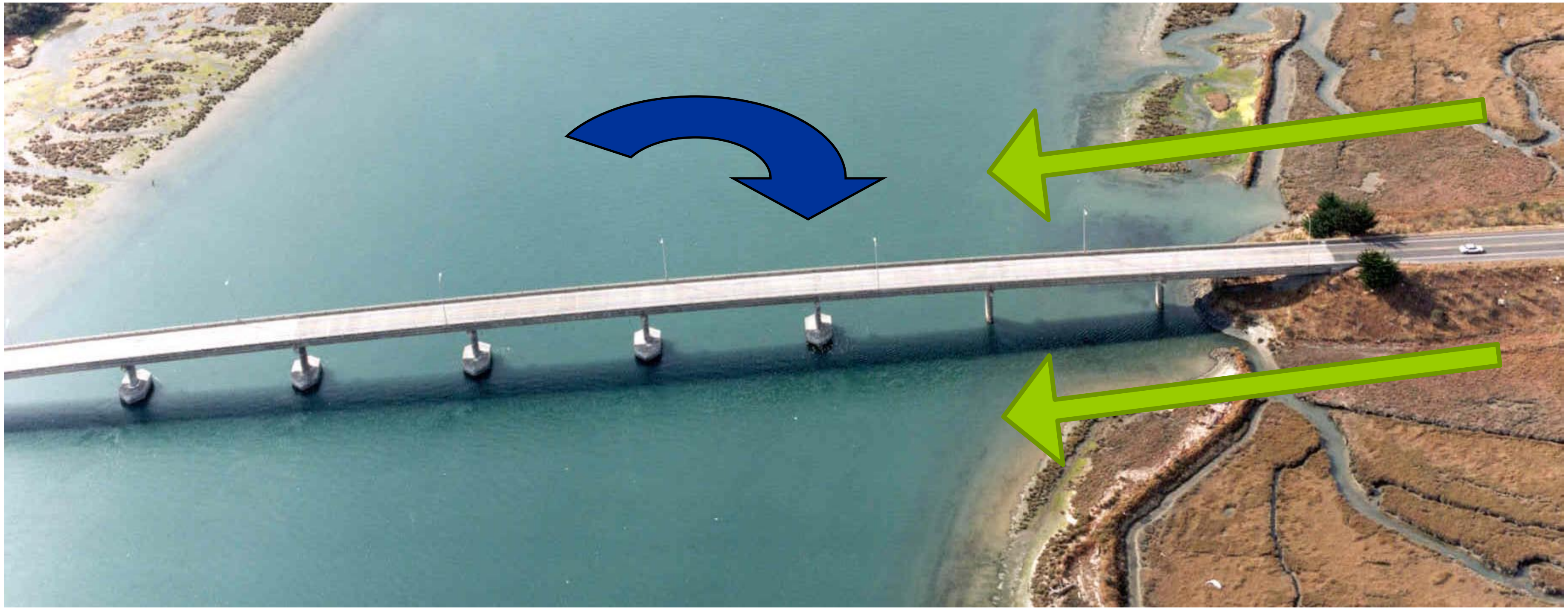
3-Dimensional Simulation

Bridge-Ground System

PEER

Humboldt Bay Middle Channel Bridge



- Pile foundations in soft soil
- PEER Testbed: Nonlinear soil-foundation-structure interaction

Three-Dimensional Seismic Response of Humboldt Bay Bridge-Foundation-Ground System, A. Elgamal, L. Yan, Z. Yang, and J. P. Conte, Journal of Structural Engineering, 134, 7, July , 2008.

Zhang, Y., Conte, J.P., Yang, Z., Elgamal, A., Bielak, J. and Acero, G. (2008). Two-Dimensional Nonlinear Earthquake Response Analysis of a Bridge-Foundation-Ground System, Earthquake Spectra, 24, 2, 343–386, May.

PEER

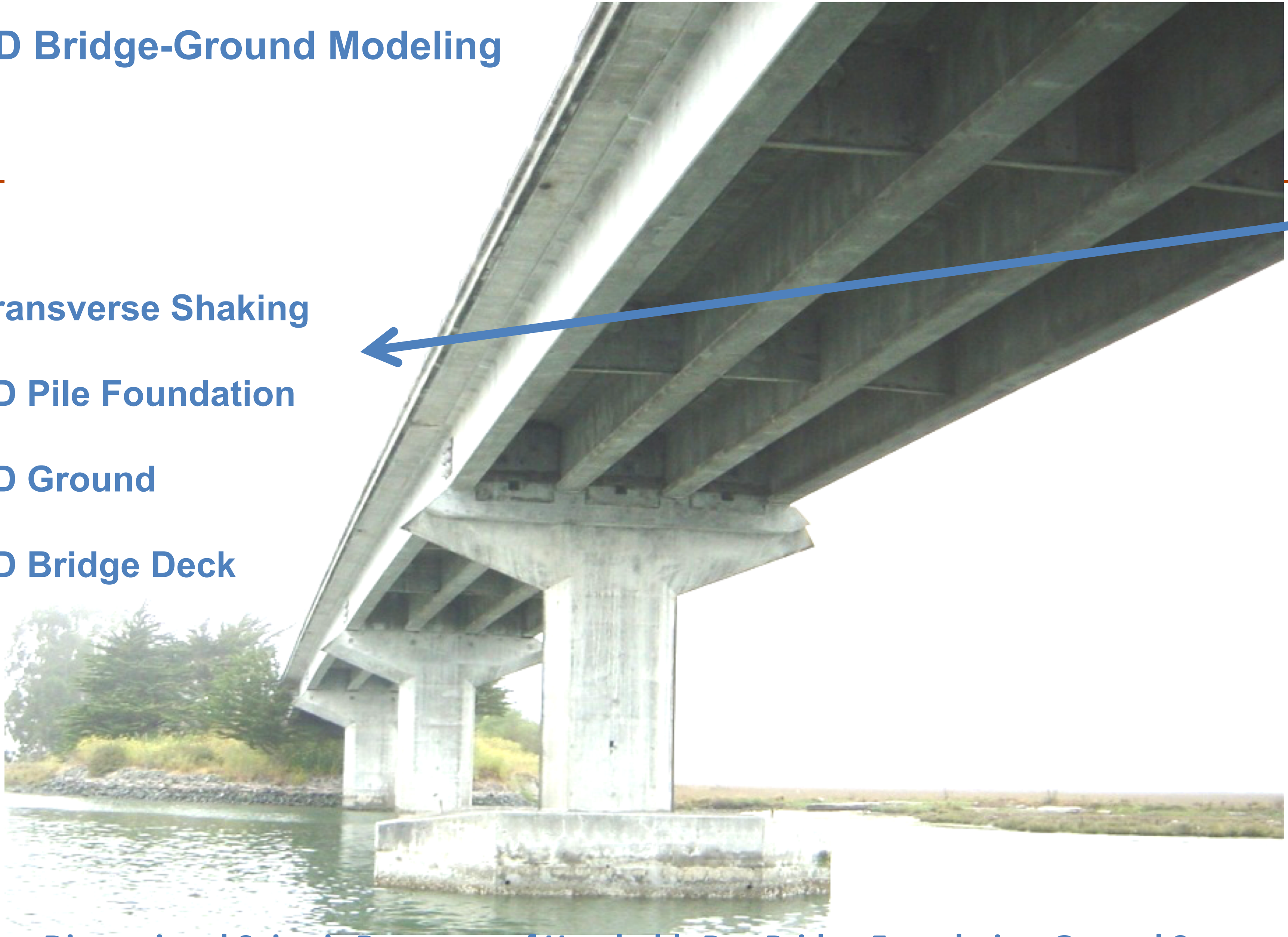
3D Bridge-Ground Modeling

Transverse Shaking

3D Pile Foundation

3D Ground

3D Bridge Deck



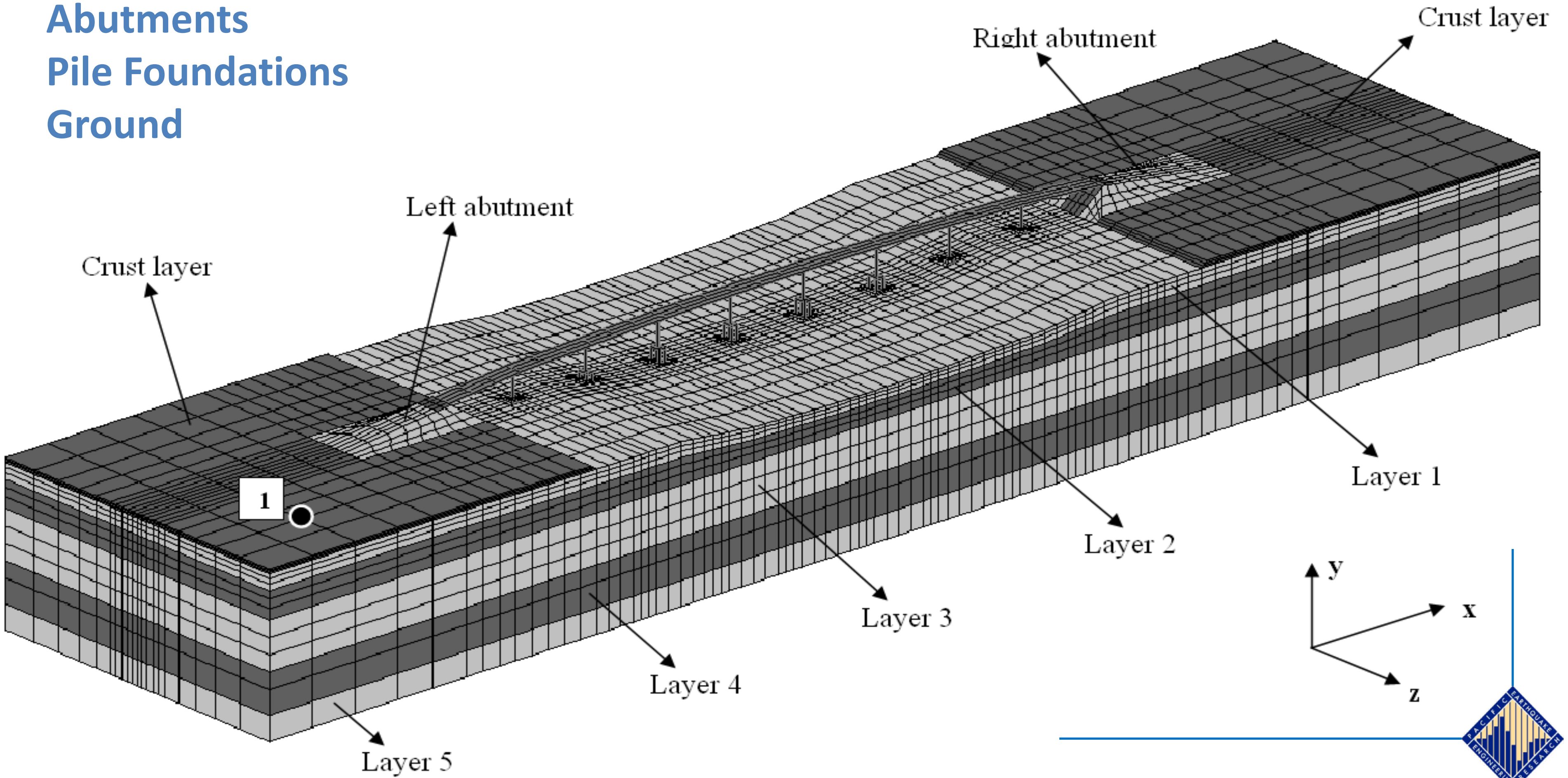
Three-Dimensional Seismic Response of Humboldt Bay Bridge-Foundation-Ground System, A. Elgamal, L. Yan, Z. Yang, and J. P. Conte, Journal of Structural Engineering, 134, 7, July , 2008.

OpenSees 3D FE Model

Ref: Three-Dimensional Seismic Response of Humboldt Bay Bridge-Foundation-Ground System, A. Elgamal, L. Yan, Z. Yang, and J. P. Conte, Journal of Structural Engineering, Vol. 134, No. 7, July 1, 2008.

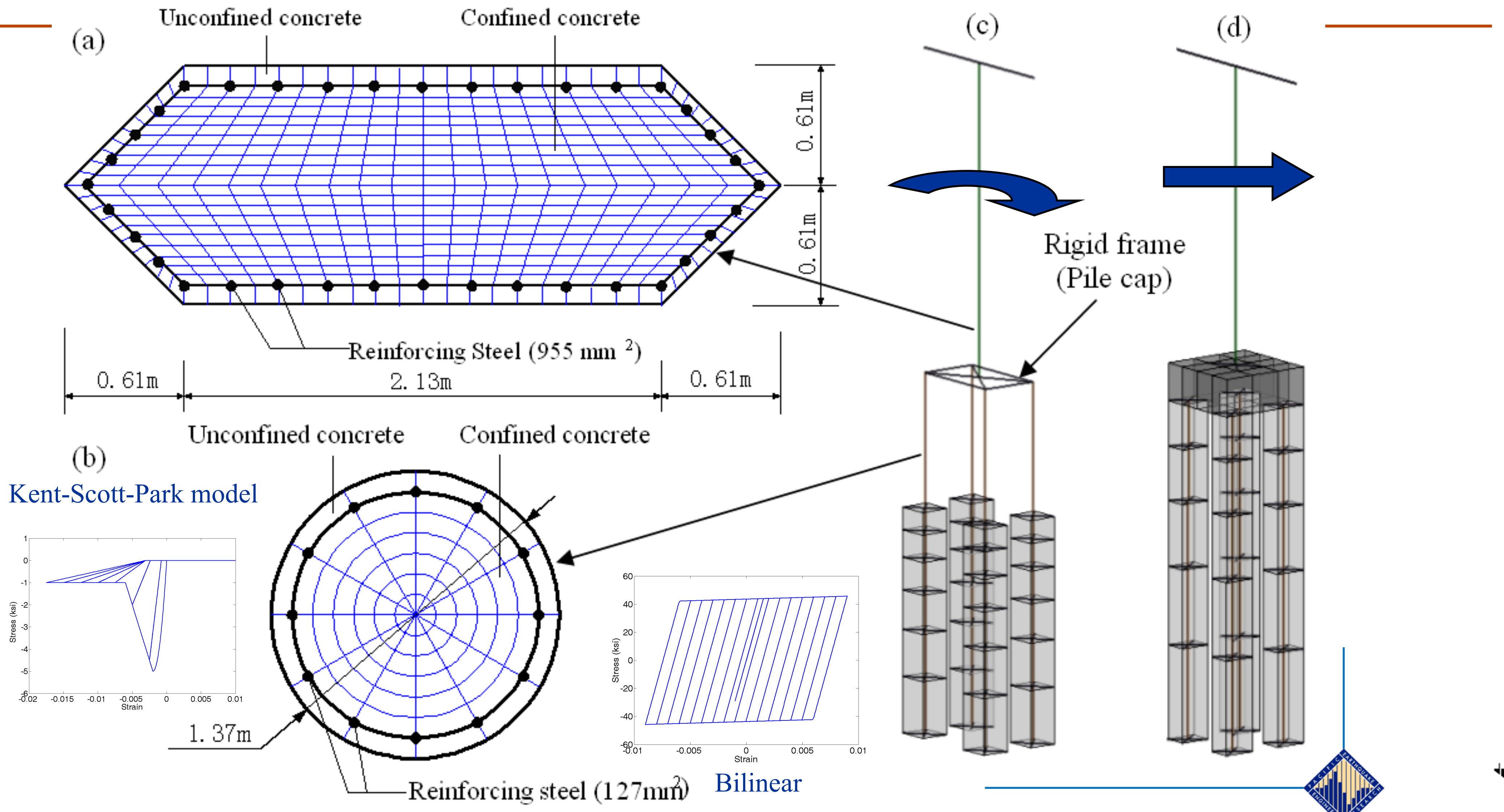
- 30,237 nodes
- 1,140/280 linear/nonlinear beam-column elements
- 81 linear shell elements
- 23,556 solid brick elements
- 1,806 zero-length elements

Transverse and Longitudinal Response
3D Spatial Configuration
Abutments
Pile Foundations
Ground

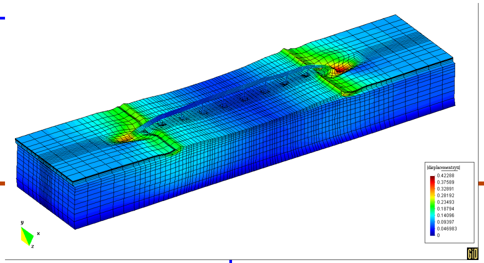


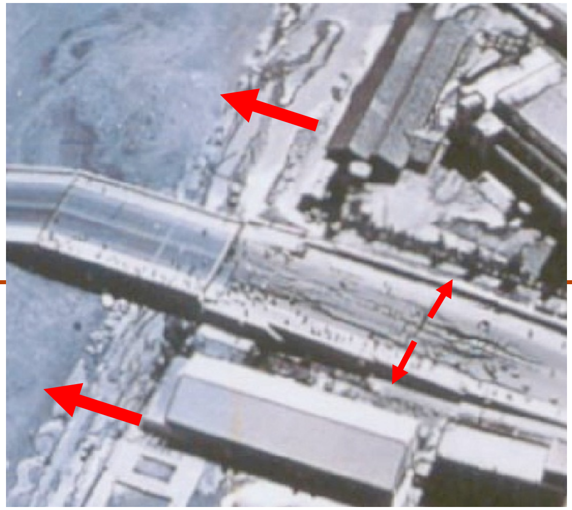
PEER

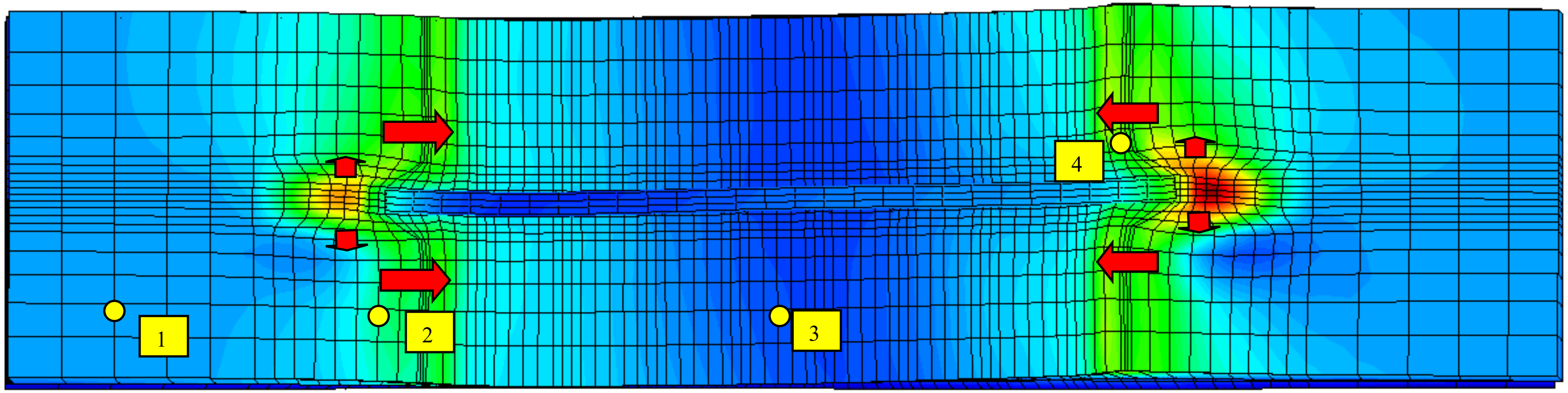
Piers and Pile Groups (Fiber Discretization of Pier and Pile Cross-Sections) (Prof. P. Fillippou)

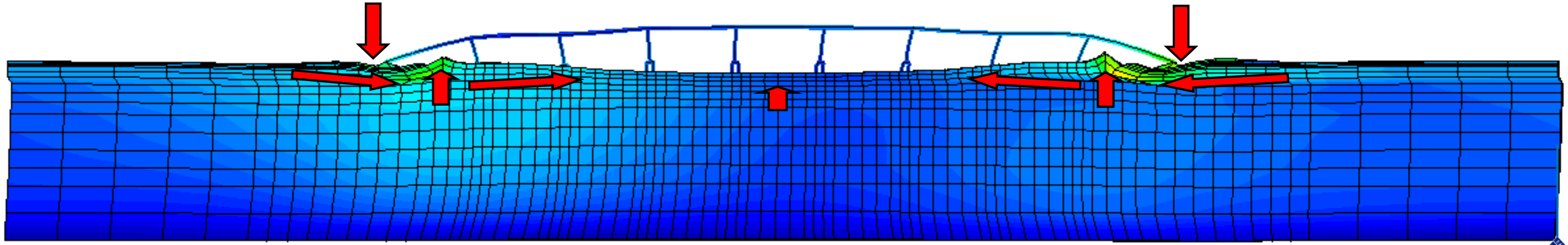


Elevation and plan view of residual deformation (Scale factor = 50)









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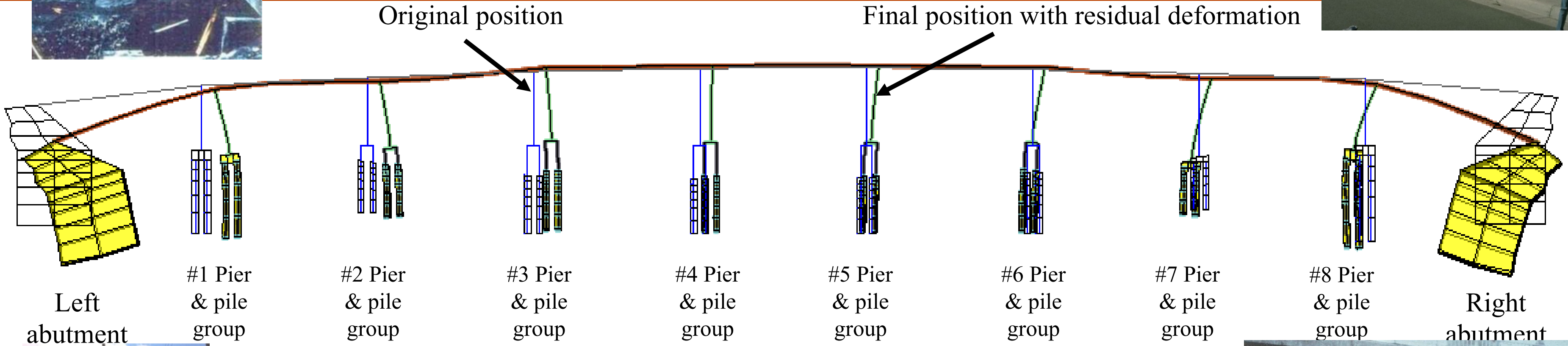
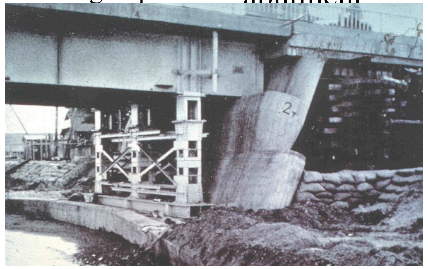
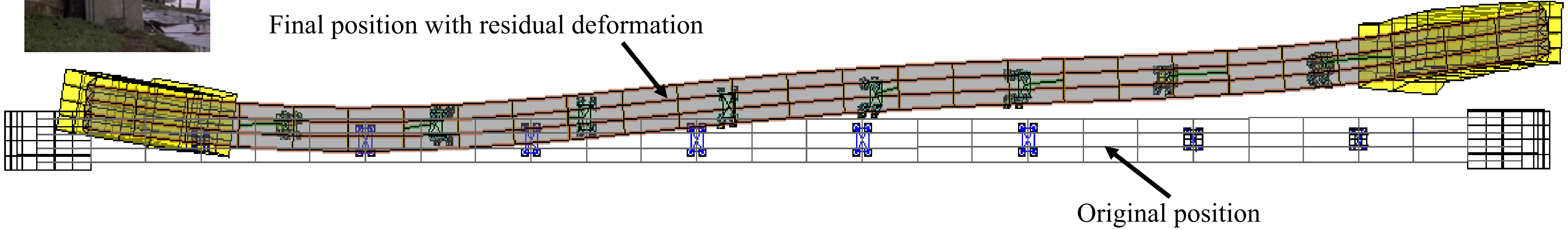
Permanent Deformation of Bridge, Foundations, and Abutments





(a) Elevation view (exaggerated scale by a factor of 50)



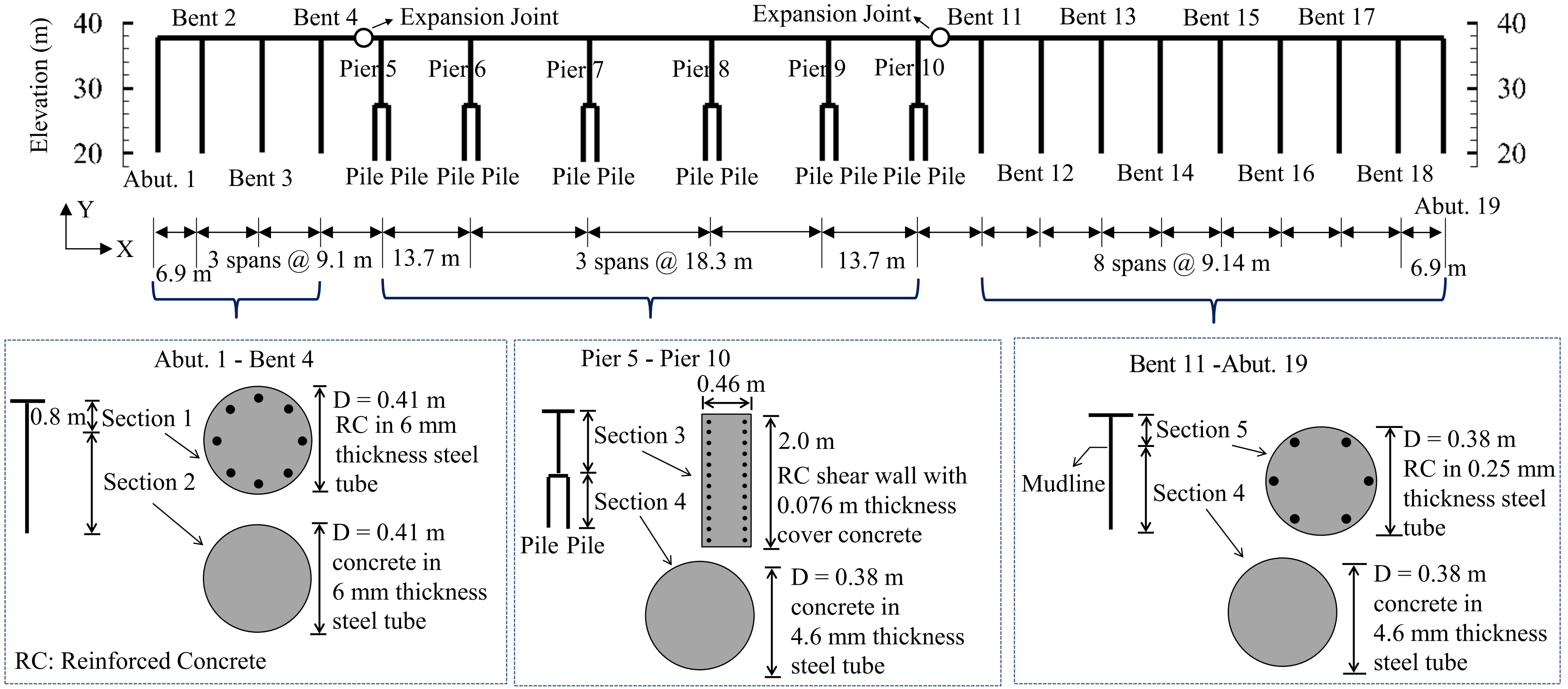
(b) Plan view (exaggerated scale by a factor of 150)

3-Dimensional Simulation

Bridge-Ground Systems and Liquefaction

Multi-span Bridge-ground System (liquefaction)

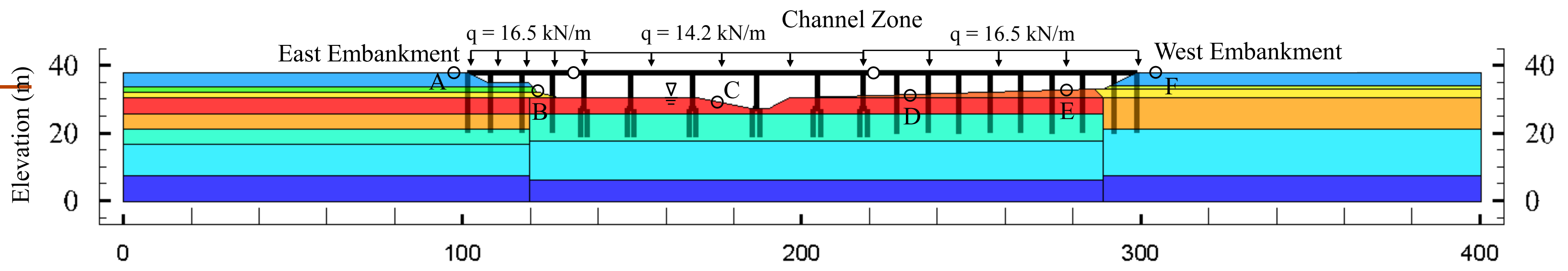
This 18-span reinforced concrete bridge (Caltrans 2017) is approximately 197 m long and 9.9 m wide



Qiu, Z., Ebeido, A., Almutairi, A., Lu, J., Elgamal, A., Shing, P.B. and Martin, G., 2020. Aspects of bridge-ground seismic response and liquefaction-induced deformations. *Earthquake Engineering & Structural Dynamics*, *49*(4), 375-393.

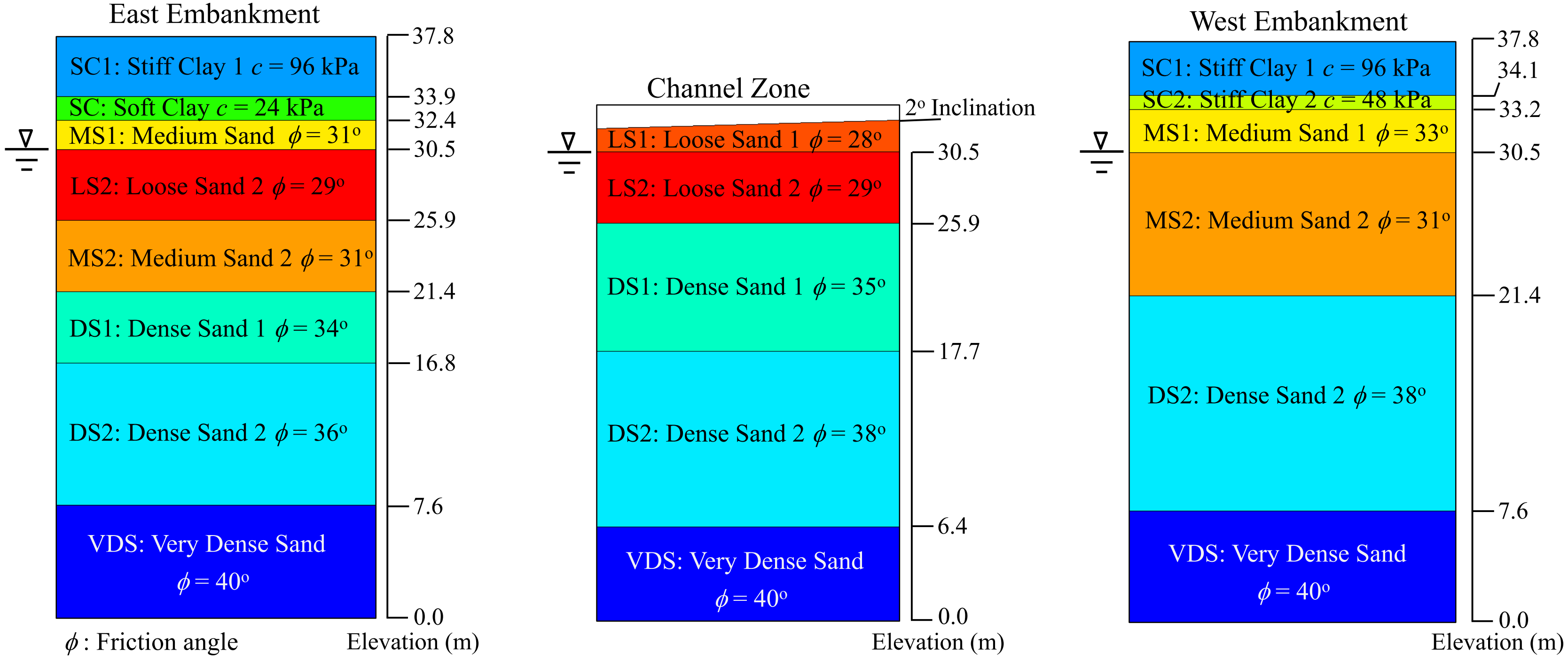
Multi-span Bridge-ground System

- **Ground configuration**



q: Linear self-weight of deck

(Caltrans 2017)



ϕ : Friction angle

c : Cohesion

Qiu, Z., Ebeido, A., Almutairi, A., Lu, J., Elgamal, A., Shing, P.B. and Martin, G., 2020. Aspects of bridge-ground seismic response and liquefaction-induced deformations. *Earthquake Engineering & Structural Dynamics*, *49*(4), 375-393. https://onlinelibrary.wiley.com/doi/full/10.1002/eqe.3244

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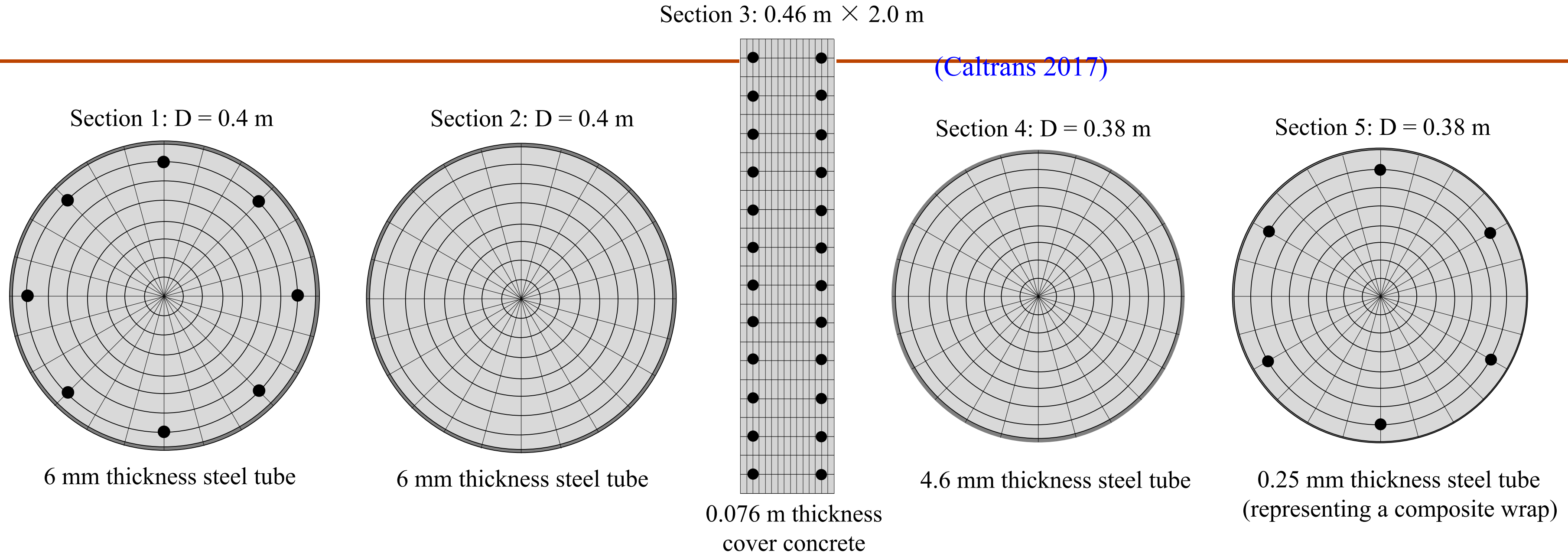
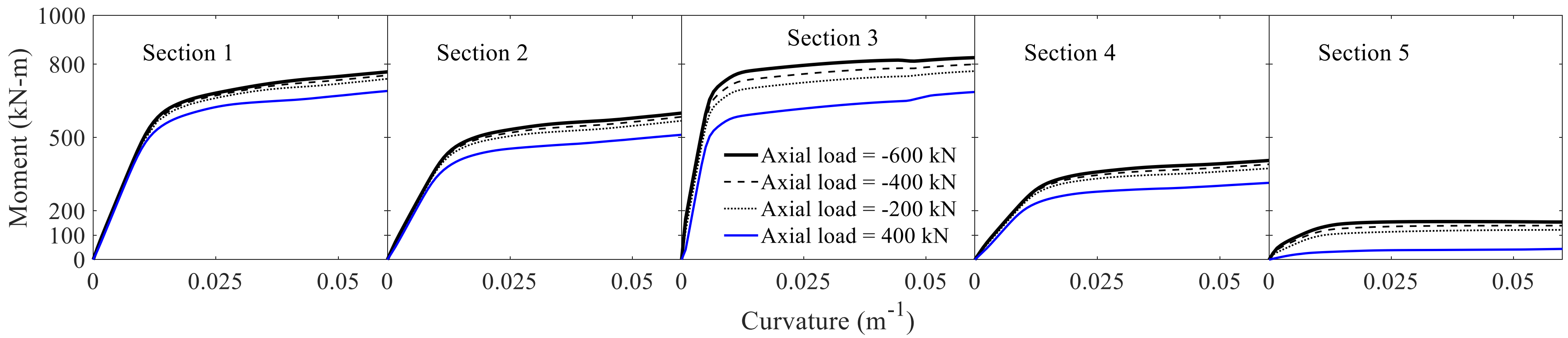
Multi-span Bridge-ground System

- **Bridge cross sections**

(Caltrans 2017)

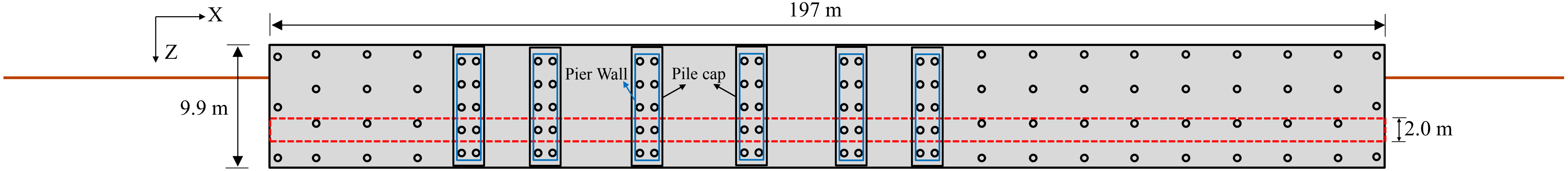


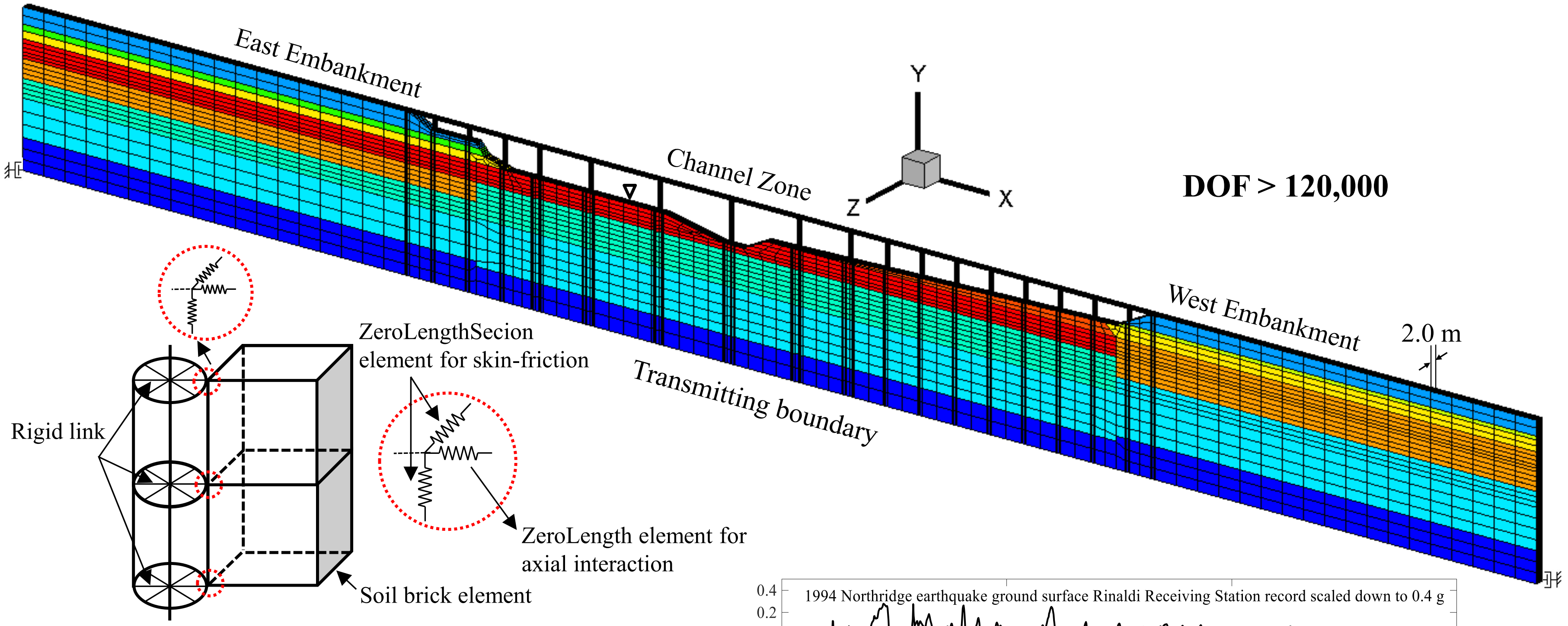


Qiu, Z., Ebeido, A., Almutairi, A., Lu, J., Elgamal, A., Shing, P.B. and Martin, G., 2020. Aspects of bridge-ground seismic response and liquefaction-induced deformations. *Earthquake Engineering & Structural Dynamics*, *49*(4), 375-393. https://onlinelibrary.wiley.com/doi/full/10.1002/eqe.3244

Multi-span Bridge-ground System

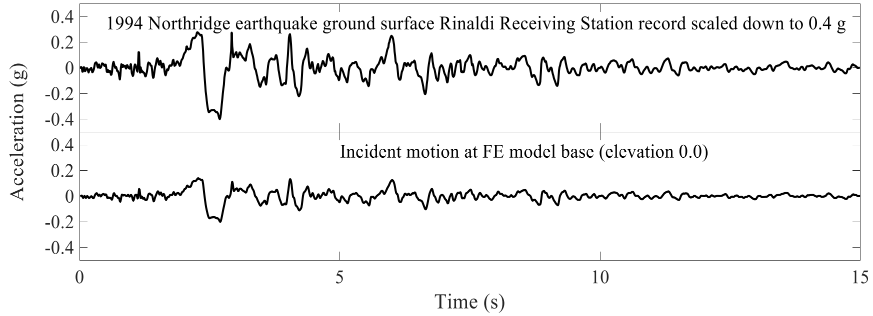
- **Slice: 3D FE model**





DOF > 120,000

22,050 nodes, 17,415 brick elements;
464 nonlinear and 90 linear elastic beam-column elements;
1,856 rigid beam-column links, 1,856 zerolength elements and
1,856 zerolengthSection elements.



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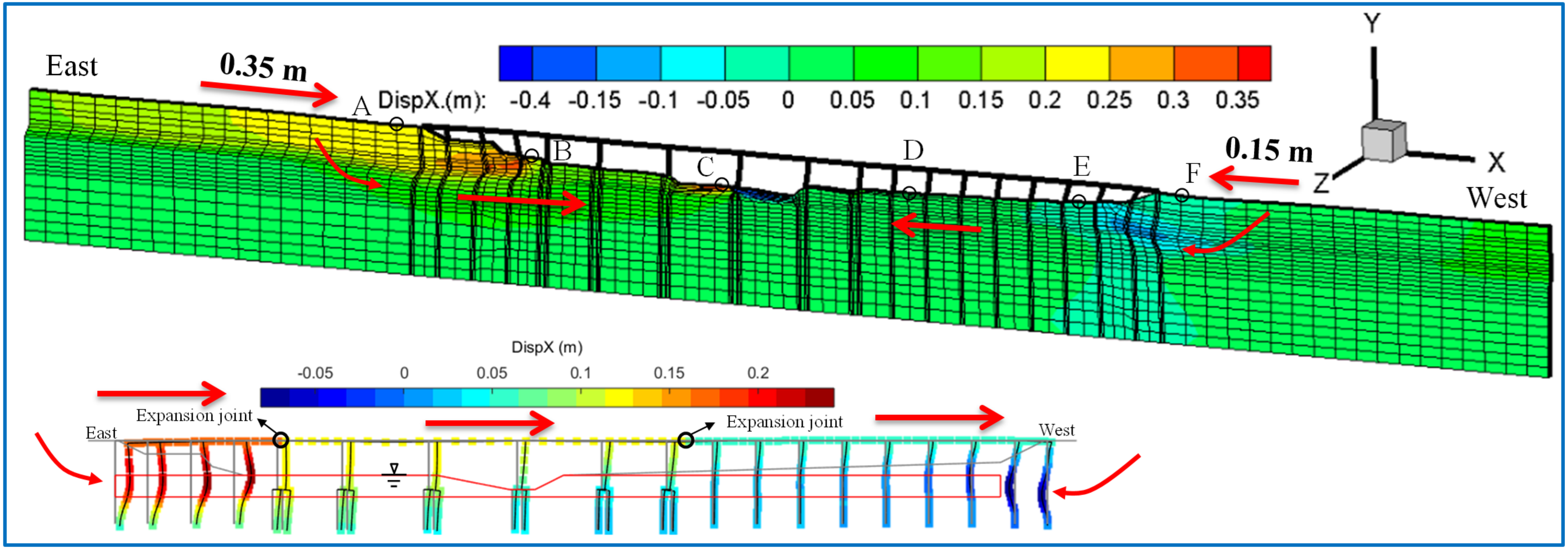
Multi-span Bridge-ground System

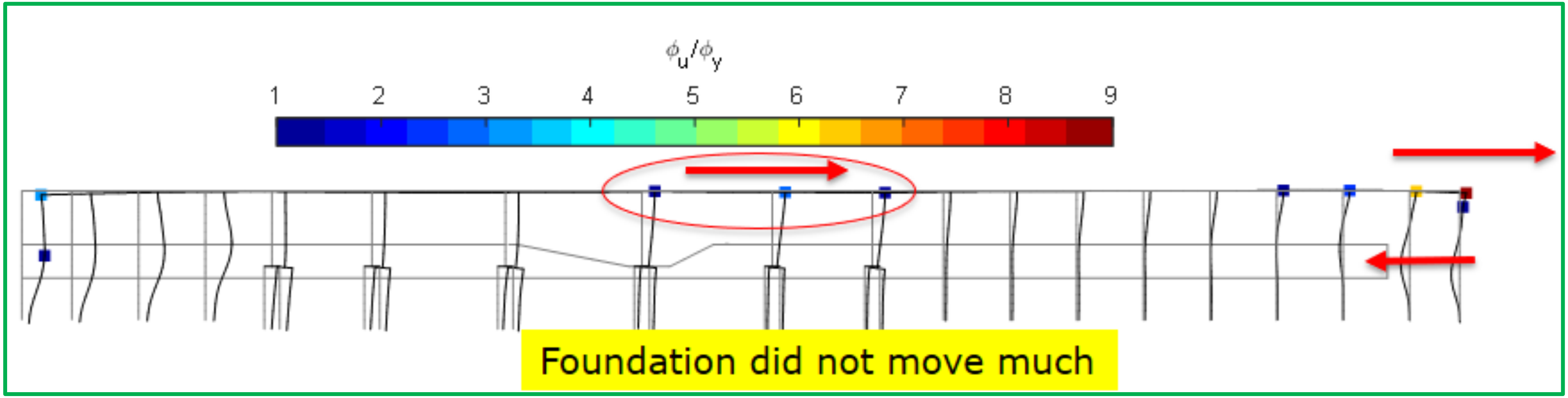
- **Computed deformation at end of shaking**



Qiu, Z., Ebeido, A., Almutairi, A., Lu, J., Elgamal, A., Shing, P.B. and Martin, G., 2020. Aspects of bridge-ground seismic response and liquefaction-induced deformations. *Earthquake Engineering & Structural Dynamics*, *49*(4), 375-393.

Ductility Demand

At end of shaking



Characteristics of observed response

Near Field motion and overall lurch in permanent displacement

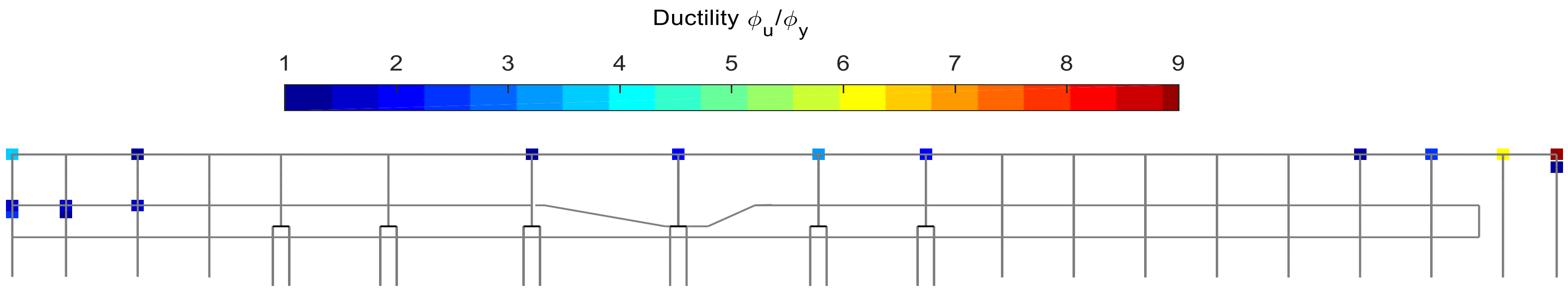
Polarity of imparted input motion

Damage near right slope influenced by the larger deformation of left side

Middle span foundations do not move much leading to possible column drift from deck translation

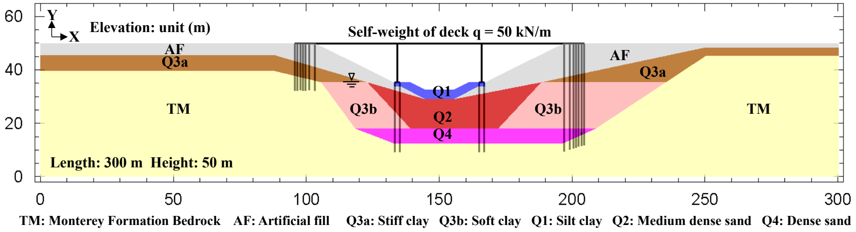
Tensile axial forces in pile groups during peak deck displacements

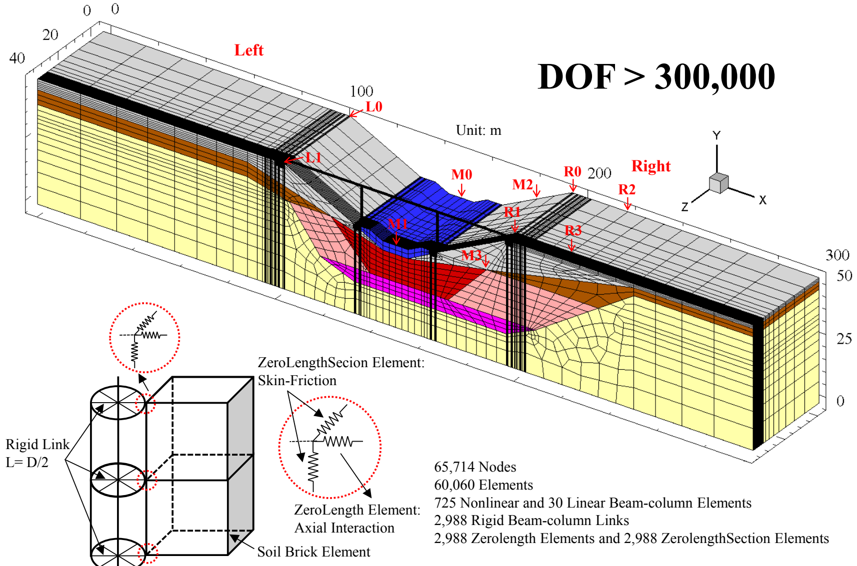
Compressive forces in Deck should be checked

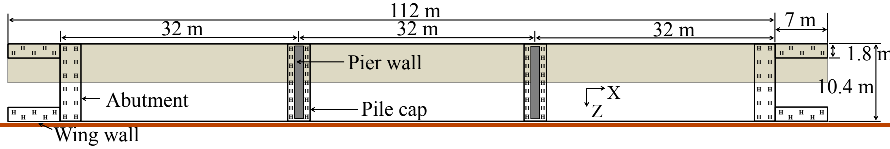


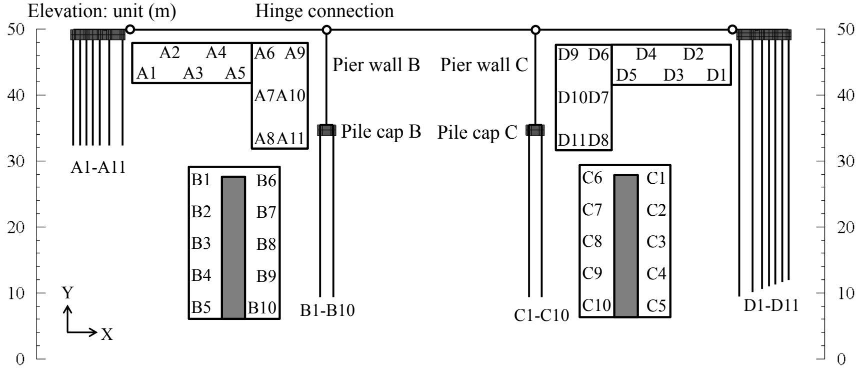
Short-span Bridge-ground System

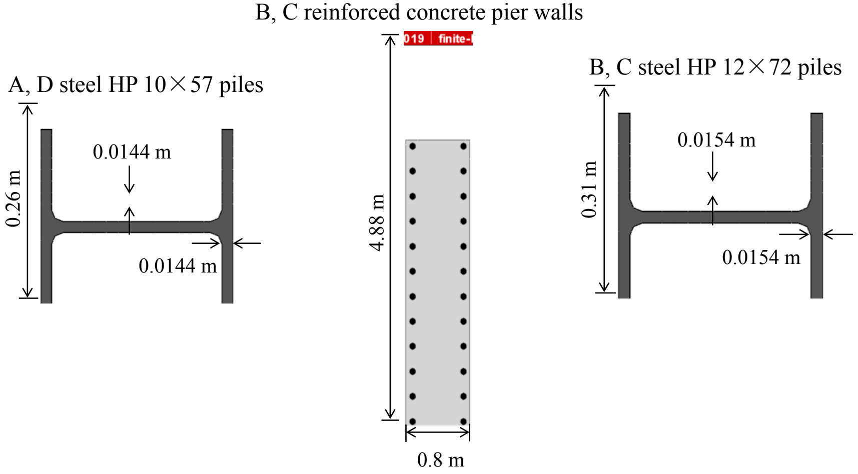
Three-span reinforced concrete bridge, approximately 96 m long and 11.4 m wide (Caltrans 2017)











Qiu, Z., Lu, J., Ebeido, A., Elgamal, A., Uang, C. M. and Martin, G. (submitted). "Bridge-ground seismic response and liquefaction-induced deformations (narrow canyon configuration ……).

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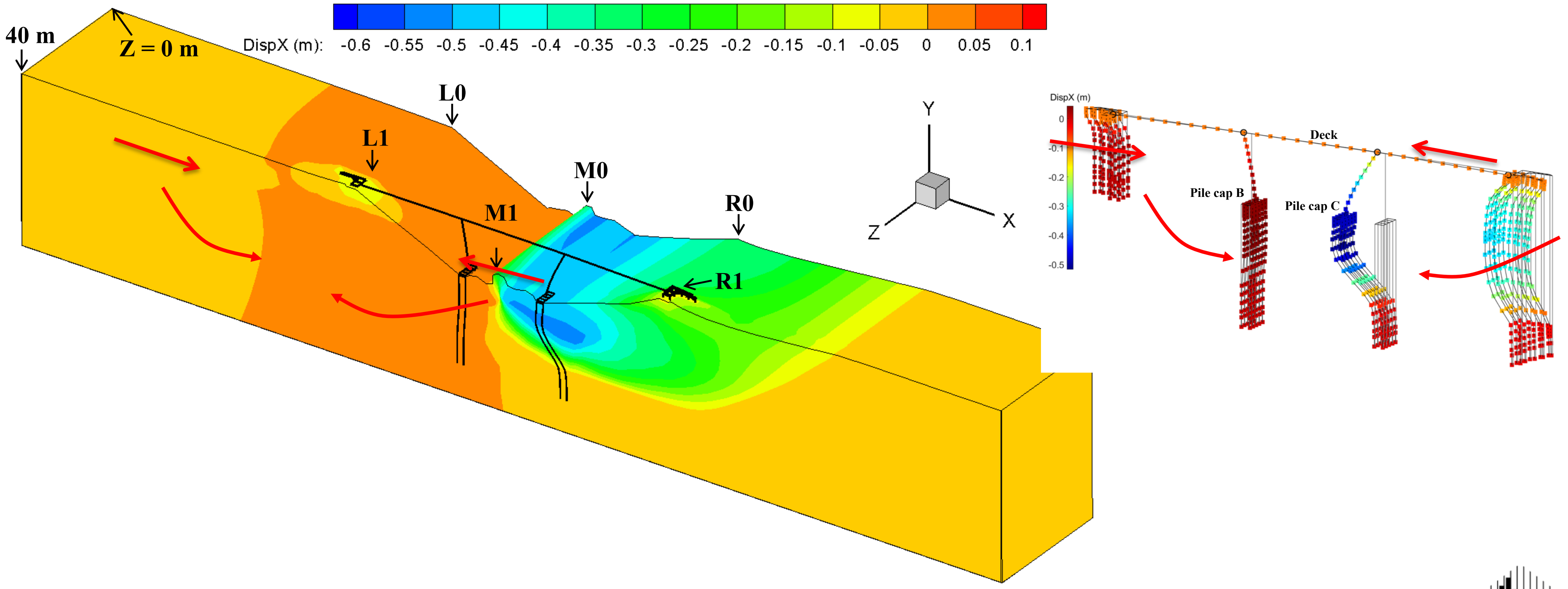
Short-span Bridge-ground System



Qiu, Z., Lu, J., Ebeido, A., Elgamal, A., Uang, C. M. and Martin, G. (*In preparation and ready for submission on November*). "Bridge-ground seismic response and liquefaction-induced deformations in narrow canyon configuration.

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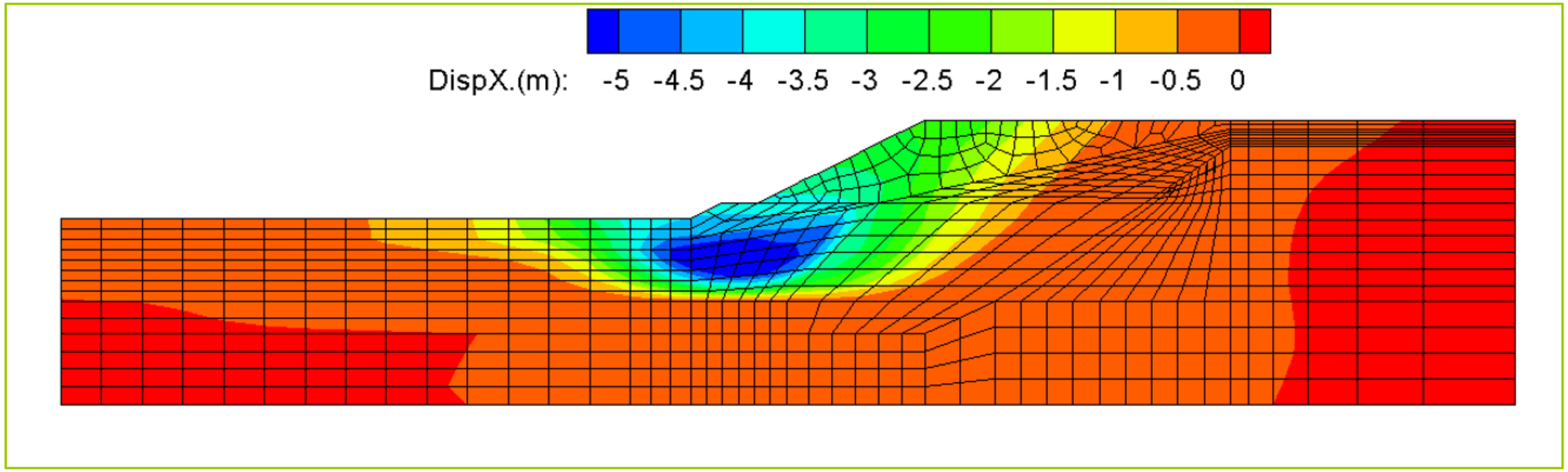
Need for fully-integrated bridge-canyon system modeling

FE Simulation of right-side slope only **for Comparison**

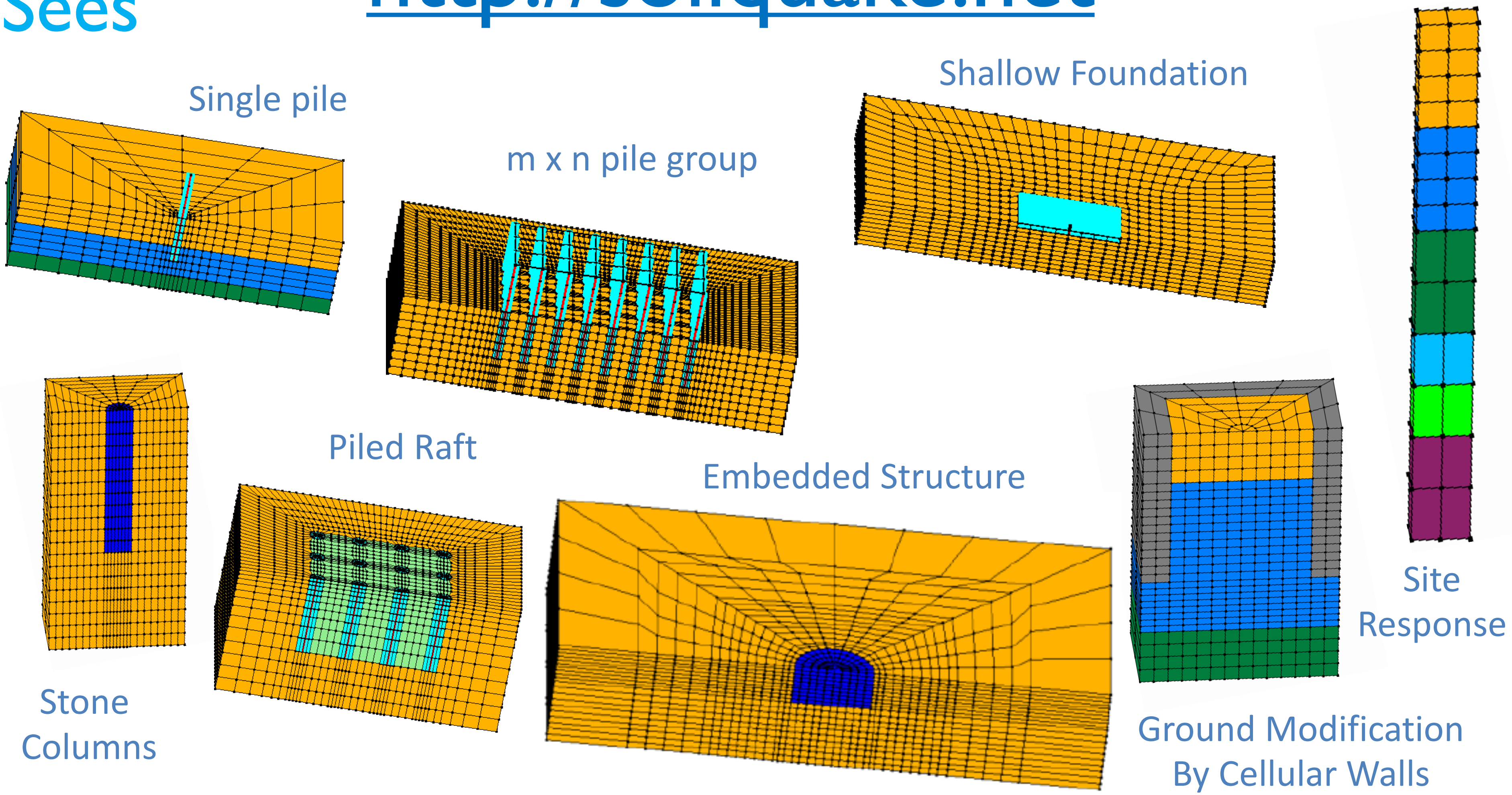


Full-Canyon Simulation: deformation = 0.65 m
Right-side slope only: deformation = 5.20 m

Geotechnical/SSI Simulation Tools

OpenSees

http://soilquake.net



http://soilquake.net

UCSD Soil Models for Seismic Analysis

for FLAC / FLAC3D, LS-DYNA, DIANA, Abaqus

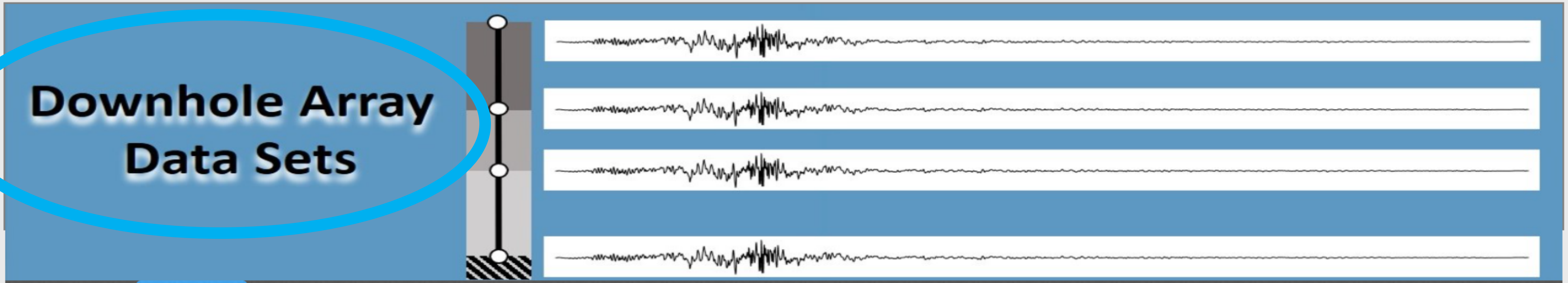
Home | **Main** | OpenSees | FLAC | FLAC3D | LS-DYNA | Parameters

UCSD Soil Models

The UCSD soil models **UCSDSAND3** and **UCSDCLAY** are three-dimensional (3D) elasto-plastic material models for the simulation of cohesionless and cohesive soils, respectively. These models have been evolving over the past two decades with extensive calibration through numerous sources including downhole-array records, laboratory tests, shake-table and centrifuge experiments. These soil models have been available in OpenSees since the early 2000s.

The UCSD soil models have now been implemented into a number of analysis packages including **FLAC/FLAC3D**, **LS-DYNA**, **DIANA** and **Abaqus** as user defined materials. Please click the corresponding item in the menu above for detailed information regarding implementation in the various numerical codes. For illustration purposes, one-dimensional (1D) site response analysis examples utilizing these soil models are provided on this website. If you have any question, please contact Prof. Ahmed Elgamal (E-mail: elgamal AT ucsd DOT edu).

http://soilquake.net



Home Main

Prepared by Ahmed Elgamal, Zhijian Qiu, and Jinchi Lu

Please click below for each individual data set:

Lotung Downhole Array

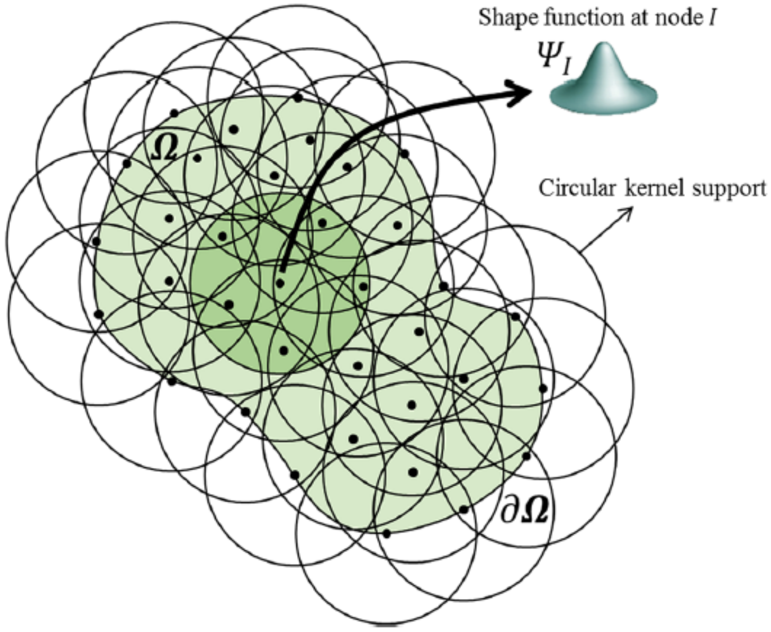
Wildlife Refuge, Imperial County, CA, USA

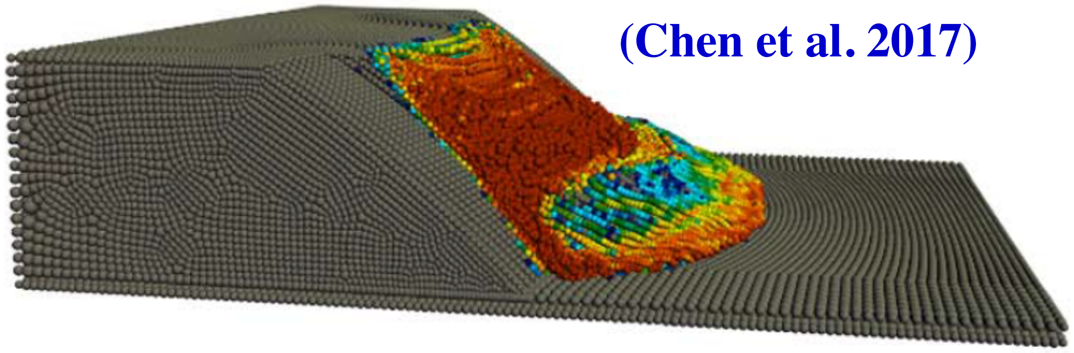
Ongoing: PEER Project Meshfree methods (with UCSD Prof. JS Chen)

RKPM2D: An Open-Source Implementation of Nodally Integrated Reproducing Kernel Particle Method for Solving Partial Differential Equations

Published: 29 Jul 2020 | **Version 3** | **DOI:** 10.17632/prfxg9cbrx.3

Contributor(s): Jiun-Shyan Chen, Michael Hillman, Tsung-Hui Huang, Haoyan Wei





(Chen et al. 2017)

Chen, J.S., Hillman, M. and Chi, S.W., 2017. Meshfree methods: progress made after 20 years. *Journal of Engineering Mechanics*, *143*(4), p.04017001.

Huang, T.H., Wei, H., Chen, J.S. and Hillman, M.C., 2020. RKPM2D: an open-source implementation of nodally integrated reproducing kernel particle method for solving partial differential equations. Computational Particle Mechanics, 7(2), pp.393-433.

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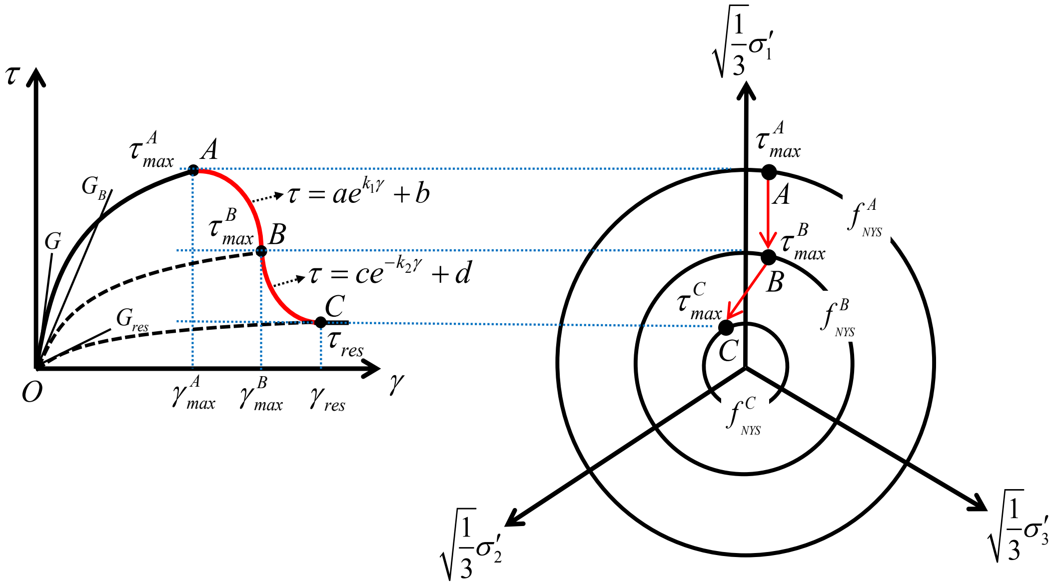
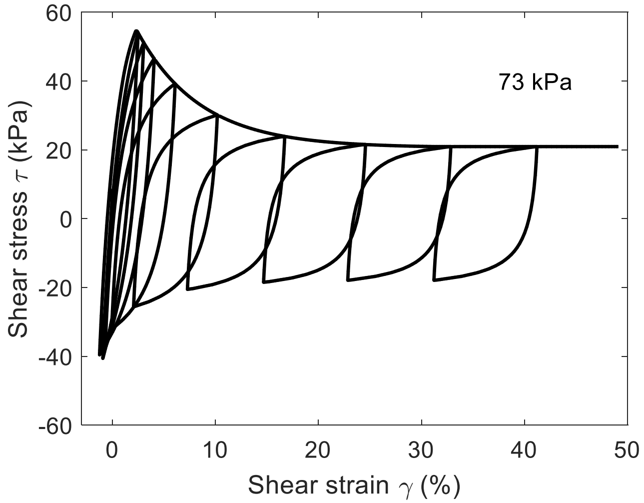
Meshfree framework for seismic response of earth systems (Elgamal, Chen PEER Co-PIs)

- **Strain Softening model (Qiu and Elgamal et al. 2020)**





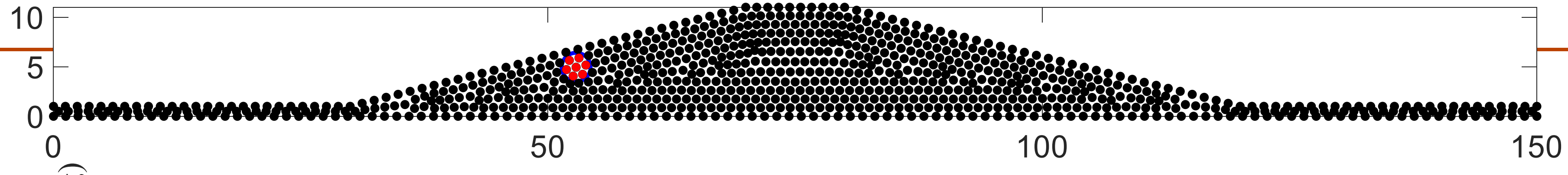
- Bring the capabilities and advantages of the meshfree method within a dedicated open-source framework for use in earthquake engineering applications

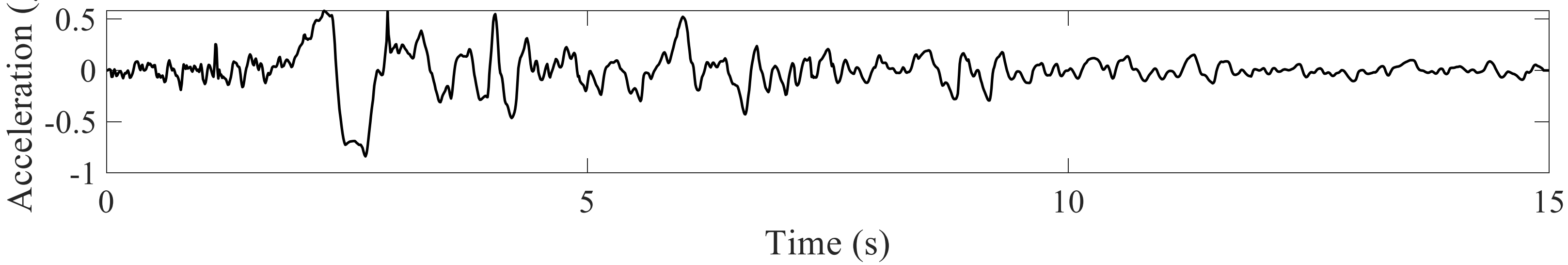
- Ultimately, provide an open-source meshfree 2D MATLAB-based large-strain computational tool for conducting nonlinear 2D static/dynamic analyses for geotechnical and Soil-Foundation-Structure-Interaction (SFSI) earthquake engineering applications.

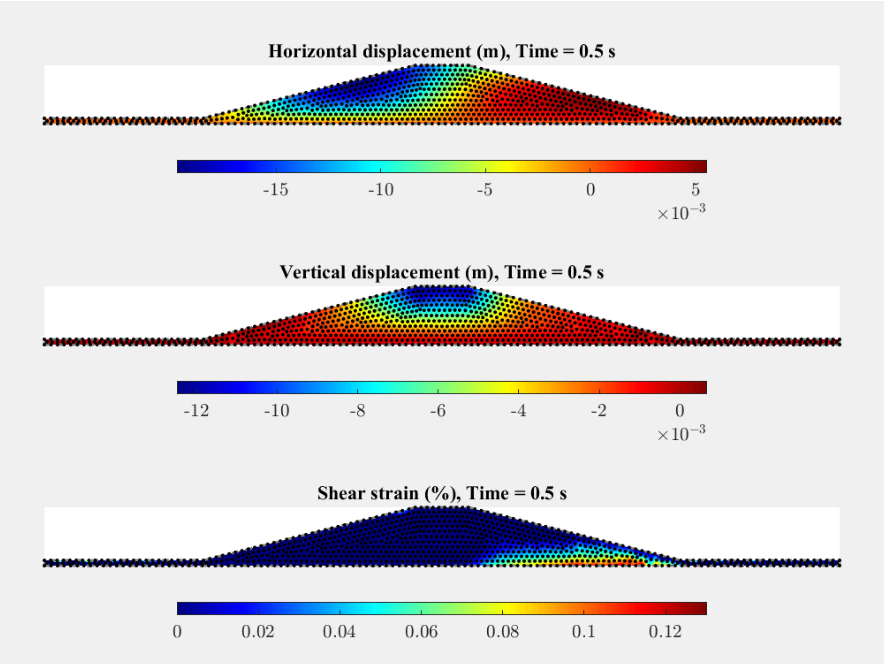
Qiu, Z. and Elgamal, A., 2020. Three-Dimensional Modeling of Strain-Softening Soil Response for Seismic-Loading Applications. Journal of Geotechnical and Geoenvironmental Engineering, 146(7), p.04020053. https://ascelibrary.org/doi/full/10.1061/%28ASCE%29GT.1943-5606.0002282?casa_token=Df_LYZUCnmcAAAAA%3Actf2pa86ZfpwLcsUG2gld0BdYyWCSBV8RVq73kkc_-GuRTtgRjp_iirdmYmmU2HZjabsKaPq_UI

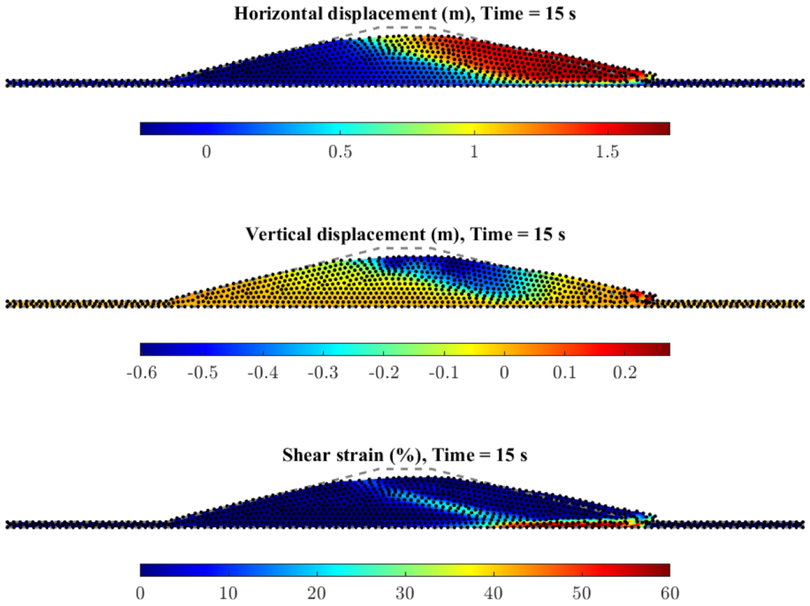
PEER

Large-deformation nonlinear 2D dynamic analysis of single-material earthdam









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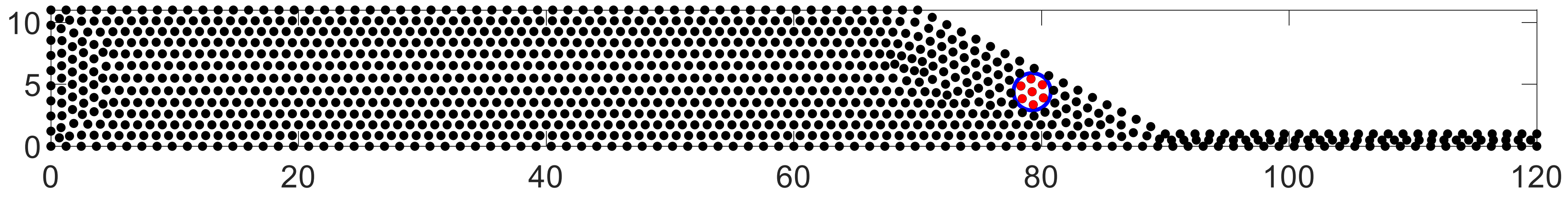
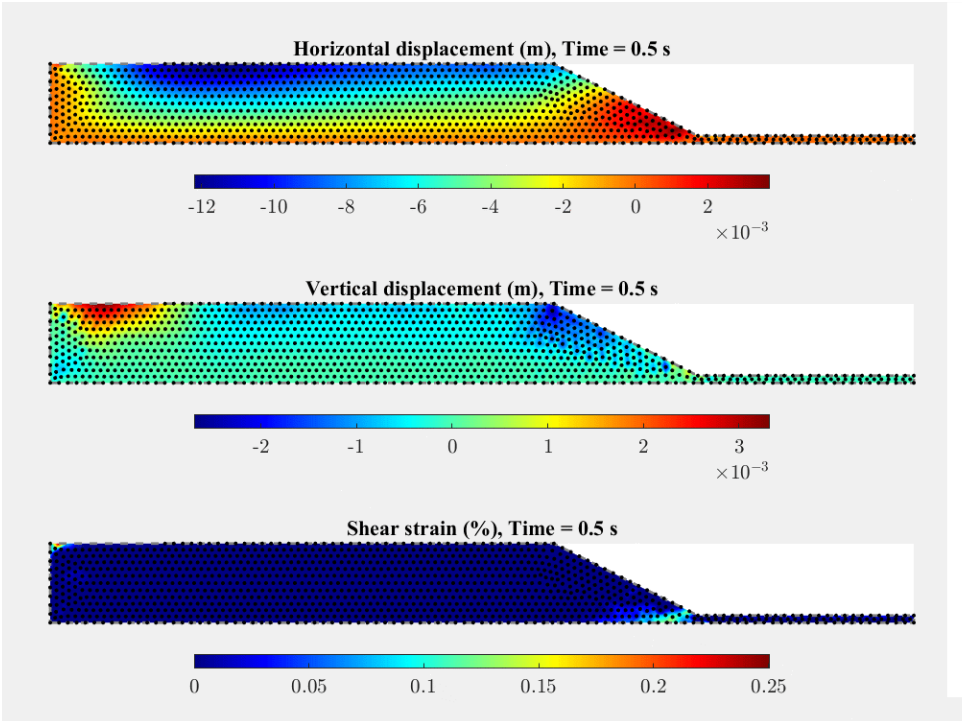
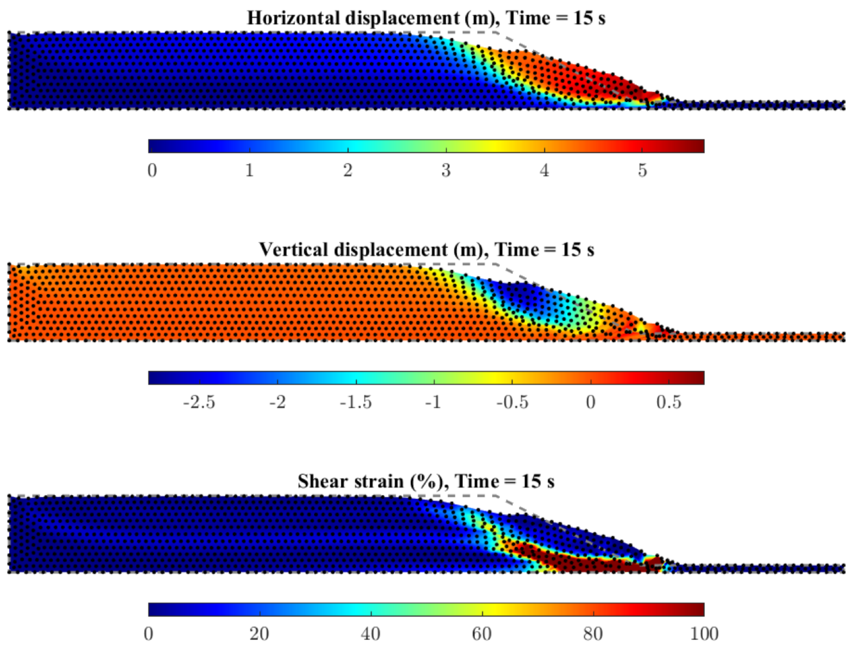
Large-deformation nonlinear 2D dynamic analysis of single-layer slope







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Ongoing/Future Research

- **Meshfree Public domain MATLAB-Code (ongoing)**
- Multi-layered soil profiles
- Liquefaction analysis
- Inclusion of structural components (beam-column elements)

Thanks!

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