Implementation of Nonlinear Site Response Tools for Surface Free-field Motion Simulations

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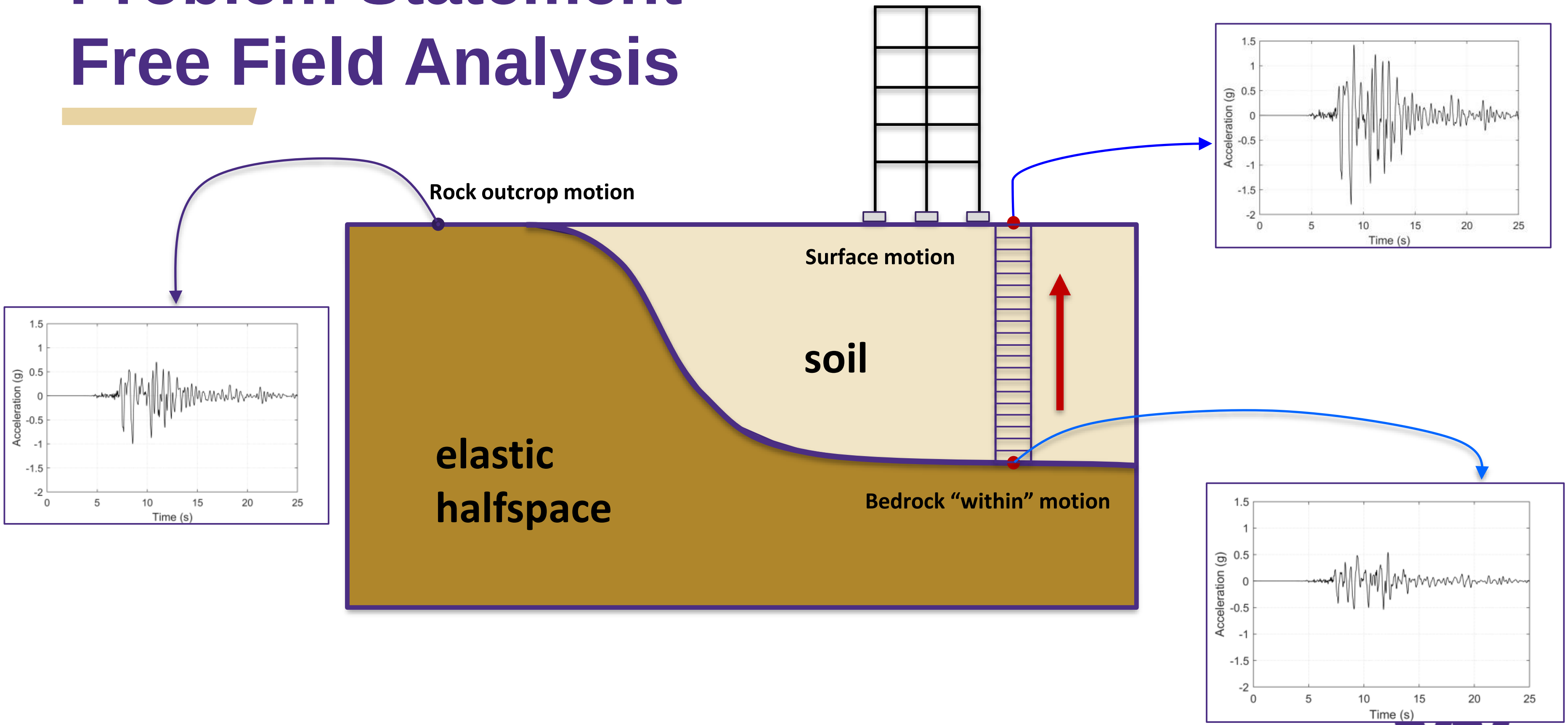
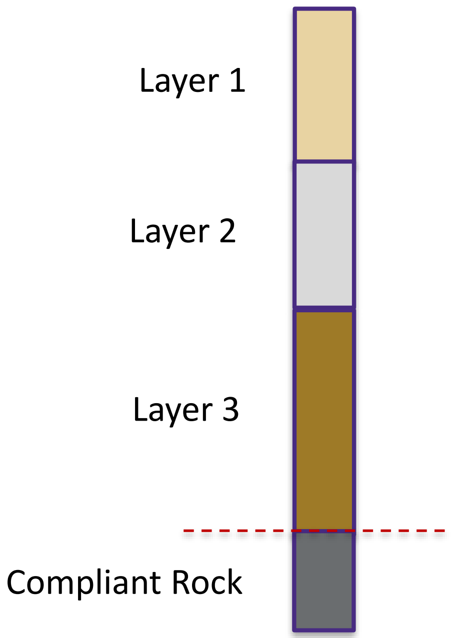
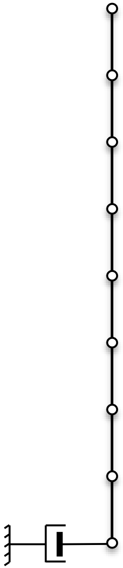
Problem Statement
Free Field Analysis



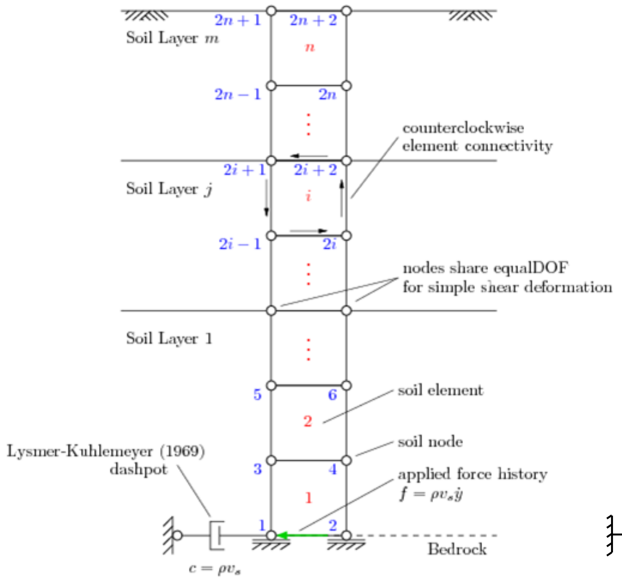
Free-Field Analysis
Numerical solution



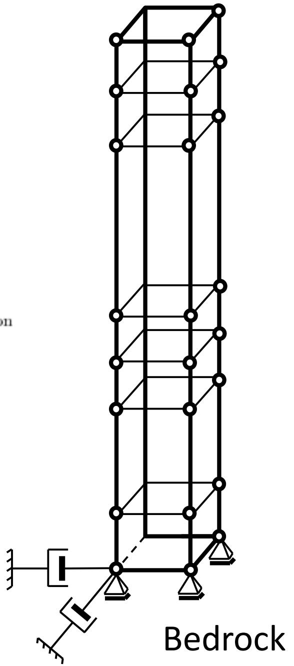
1D – 1C



1D – 2C



1D – 3C

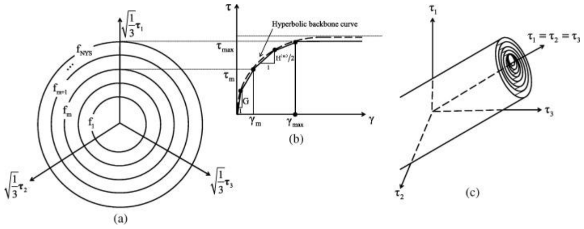


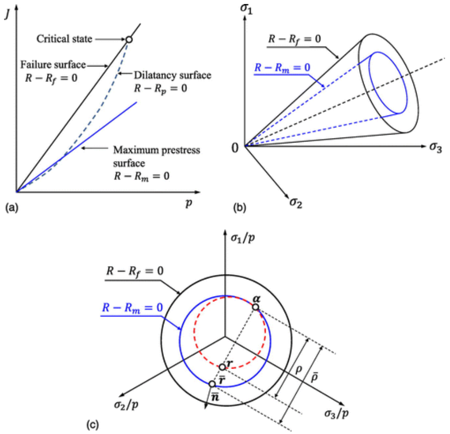
Numerical solution
Ingredients

- Computational framework
  - Equivalent linear, FEM (e.g OpenSees, Plaxis), FD (Flac)
  - Total stress or Effective Stress
- Appropriate finite elements
  - Coupled formulation (u-P most common for effective stress)
  - Robustness and efficiency (e.g. SSP-UPBrick element)
- Appropriate constitutive model
  - Formulation (e.g. multi-yield, bounding surface, hypoplasticity)
  - Implementation (explicit, implicit)
- Boundary conditions
  - Rock compliance
  - Absorbing boundaries
- Pre and post processors
- Capabilities to run in parallel for parametric analysis

Constitutive Models

- Formulation
  - Kinematic Hardening
    - Nested surfaces
      - Prevost, Elgamal
    - Bounding surfaces
      - Dafalias, Borja & Amies
      - Manzari-Dafalias, PM4Sand
- Implementation
  - Explicit
  - Implicit
  - Consistent tangent operator

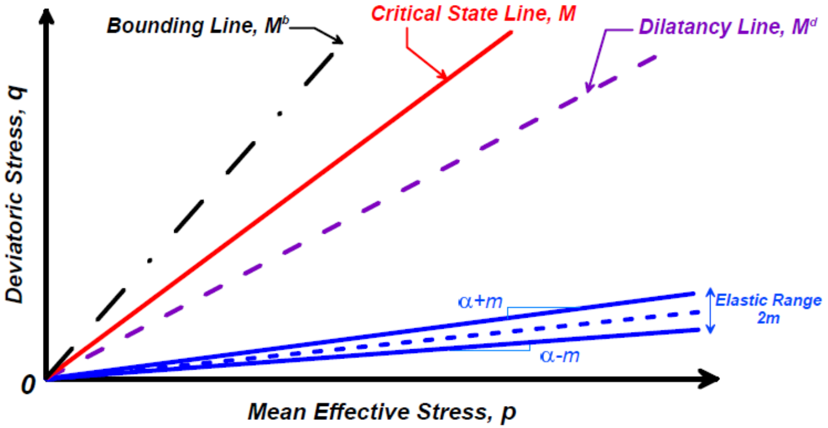


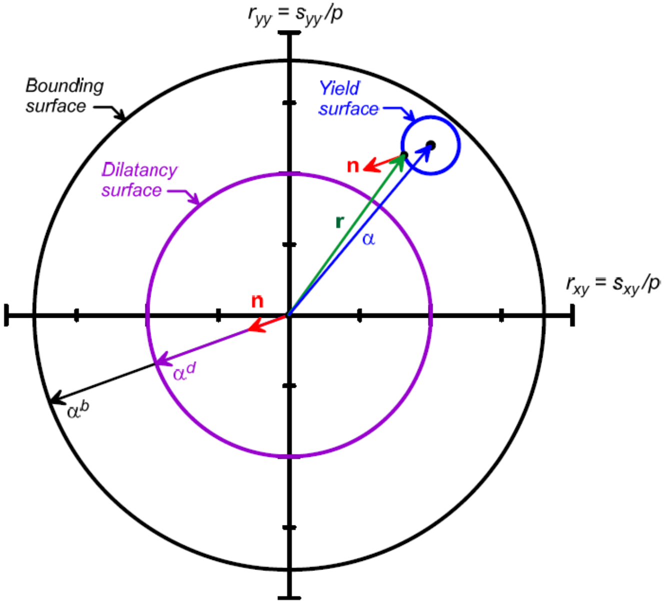


Constitutive Models
PM4Sand Model Description

- PM4Sand model is a 2D model proposed by Boulanger and Ziotopoulou(2015). It follows the plasticity framework proposed by Dafalias and Manzari (2004) and is based on bounding surface plasticity and critical state concepts.
- The model has 3 primary parameters:
  - Relative Density (Dr)
  - Shear modulus coefficient Go
  - Contraction rate parameter hpo
- And 21 optional secondary parameters.

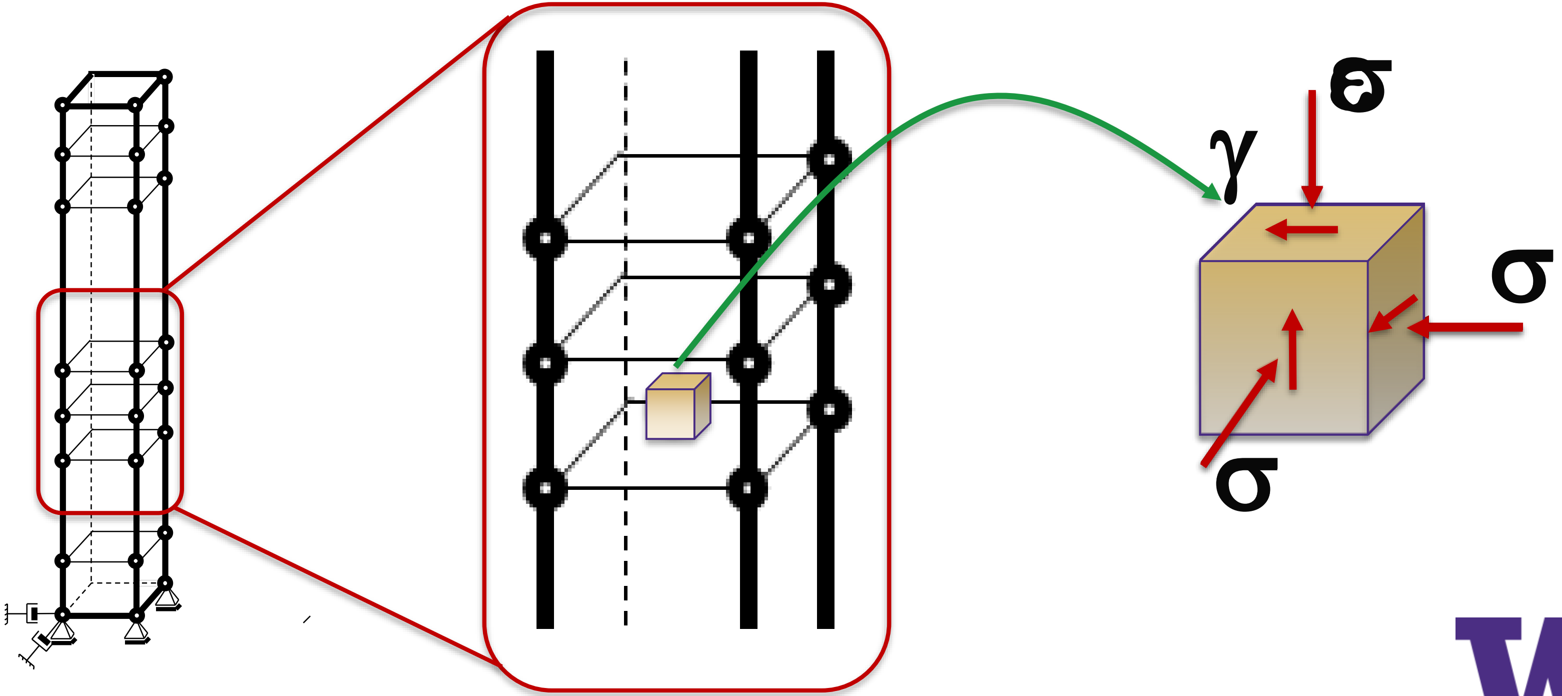
PM4Sand - Model Description
Surfaces (Yield, Bounding, Dilatancy, Critical)





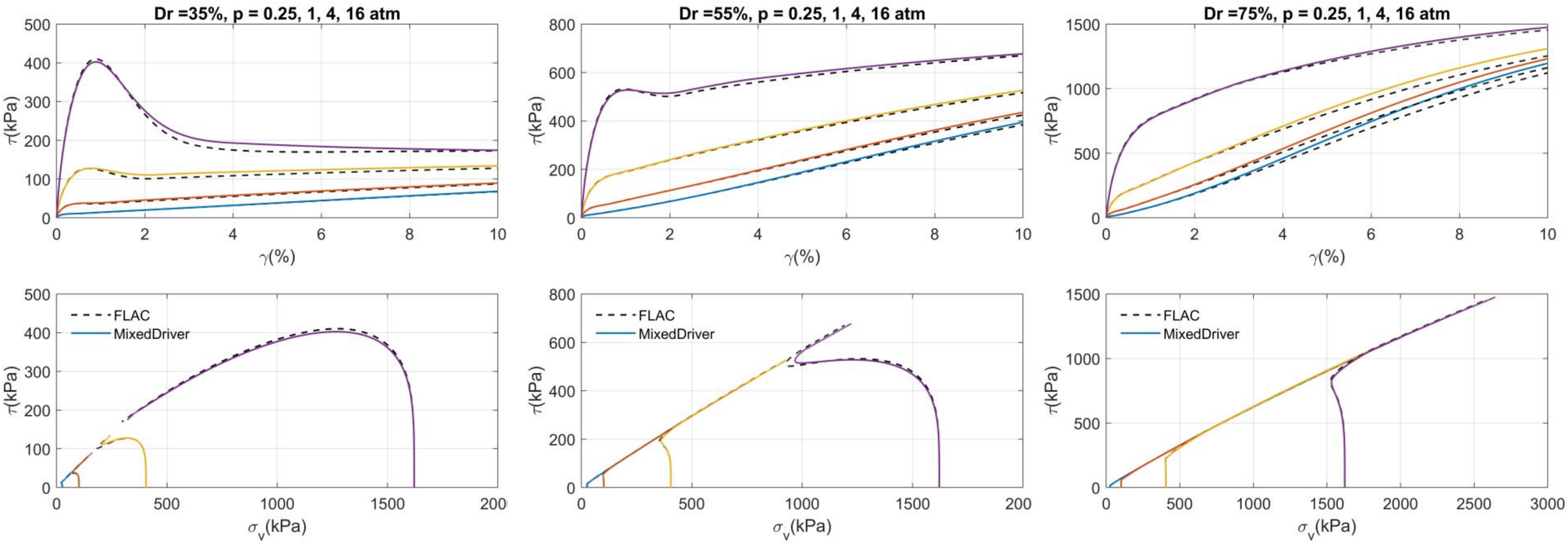
$$f = \sqrt{(r-\alpha):(r-\alpha)} - \sqrt{\tfrac{1}{2}}\,m = 0$$

Model Validation
Element test - Mixed Driver



Model Validation
Element test using MixedDriver

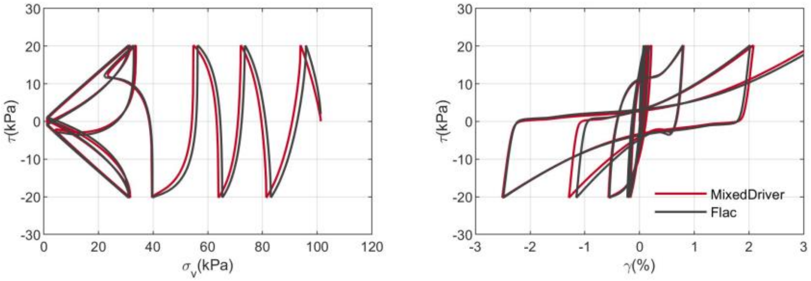
Monotonic tests



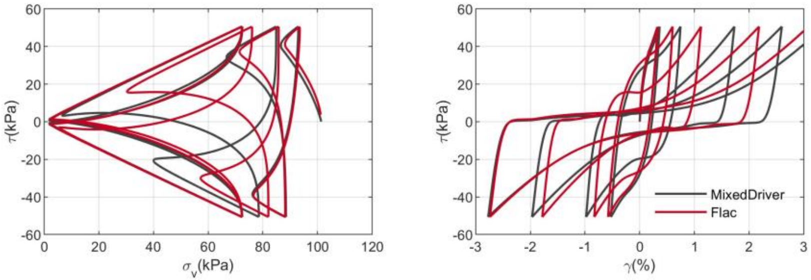
Undrained monotonic DSS loading responses for DR = 35, 55, and 75% with initial confining pressures of 0.25,1,4 and 16atm, K_0 = 1.0

Model Validation
Element test using MixedDriver

Cyclic tests



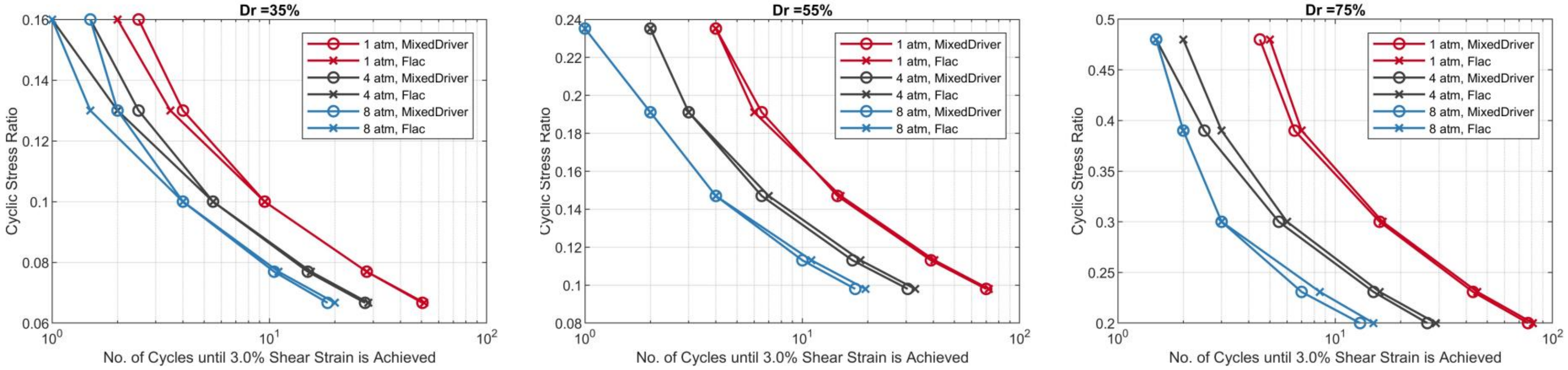
Undrained cyclic DSS loading responses for DR = 55% with initial confining pressure of 1 atm, using $C_D = 0.16$



Undrained cyclic DSS loading responses for DR = 75% with initial confining pressure of 1 atm, using $C_D = 0.16$

Model Validation
Element test using MixedDriver

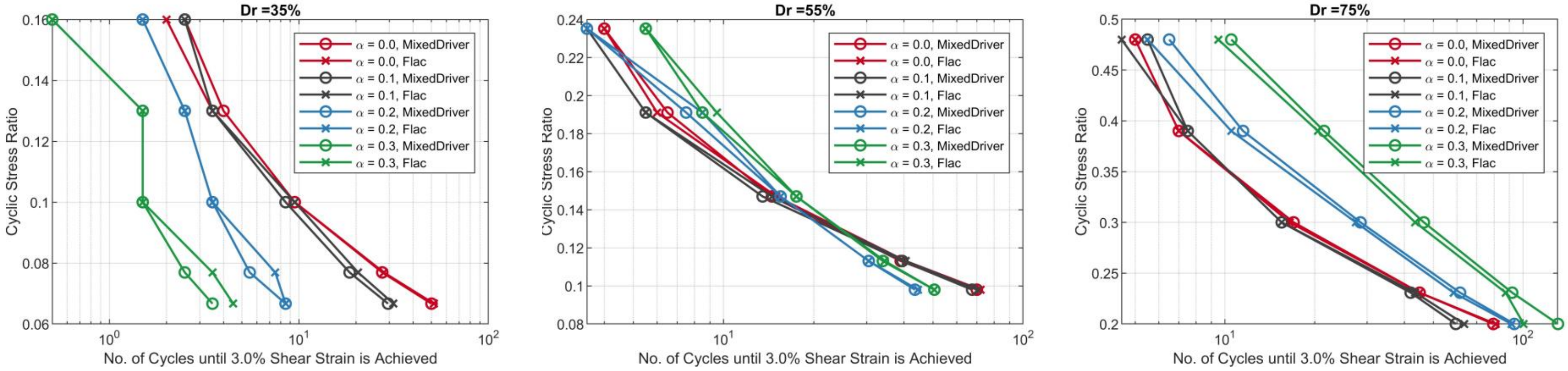
Effect of Kσ



Cyclic stress ratios vs. number of cycles to reach 3% shear strain for D_R = 35, 55 and 75% with vertical consolidation stresses of 1, 4 and 8 atm. $K_0 = 0.5$

Model Validation
Element test using MixedDriver

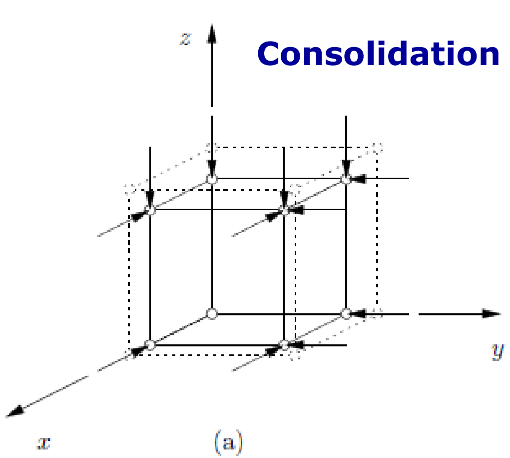
Effect of Kα



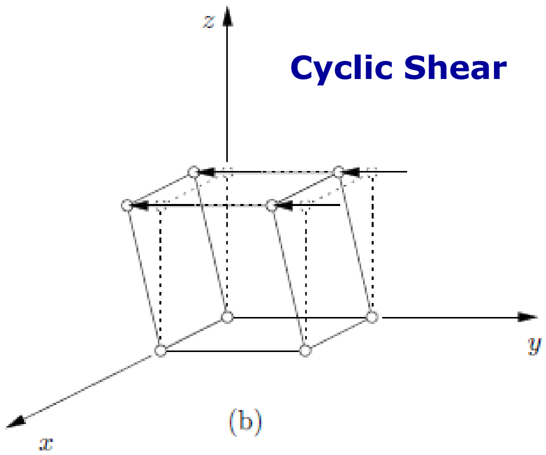
Cyclic stress ratios vs. number of cycles to reach 3% shear strain for D_R = 35, 55 and 75% with vertical consolidation stress of 1 atm and initial static shear stress ratios of 0.0, 0.1,0.2, and 0.3. K_0 = 0.5

Validation
Element test in FE framework (OpenSees)

- Strain controlled undrained simple shear test using SSPquadUP or SSPbrickUP elements
  - a. Consolidation phase
  - b. Cyclic shear phase

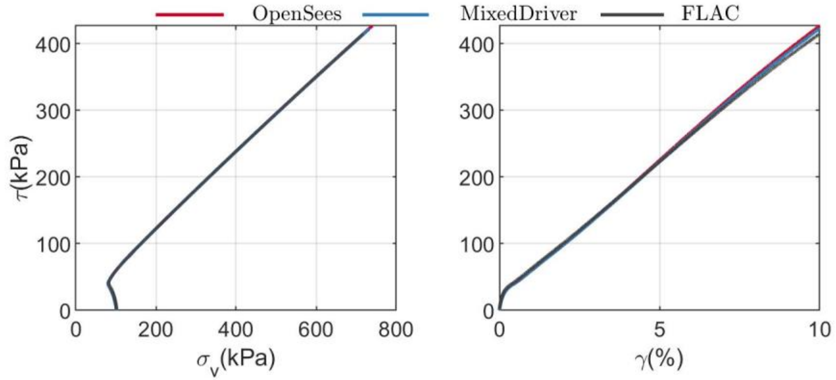


(a)

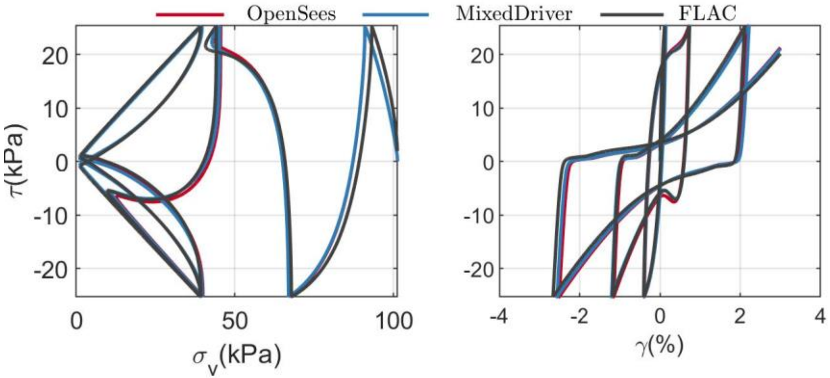


(b)

Validation
Element test in OpenSees



Undrained monotonic DSS loading responses for DR = 55% with initial vertical stress 1atm and K0 = 0.5



Undrained cyclic DSS loading responses for DR = 55% with initial vertical stress 1atm and K0 = 0.5

Validation: 1D Free-Field Analysis: Synthetic soil profiles

ID	L2 [m] Liquefiable layer	N160
N5-T3	3.0	5
N5-T6	6.0	5
N10-T3	3.0	10
N10-T6	6.0	10
N20-T3	3.0	20
N20-T6	6.0	20

Geometry

L1 : Crust (2.0 m)

L2 : Liquefiable layer

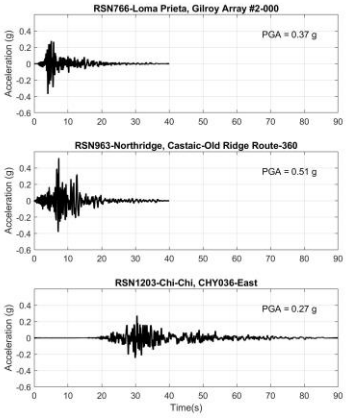
L3 : Linear elastic layer (1.0m)

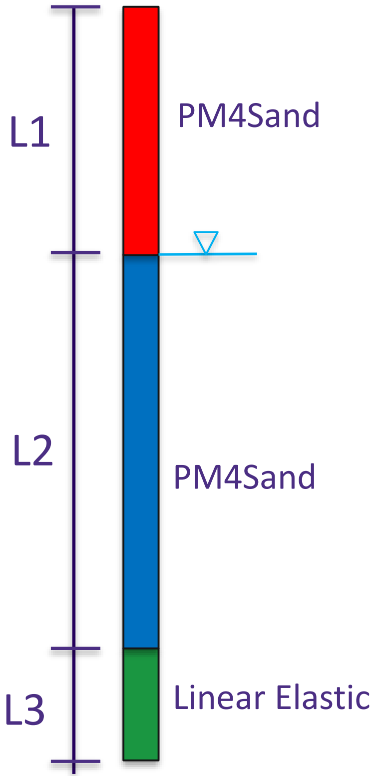
Motions

M1 : Gilroy

M2 : Northridge

M3 : Chi-chi

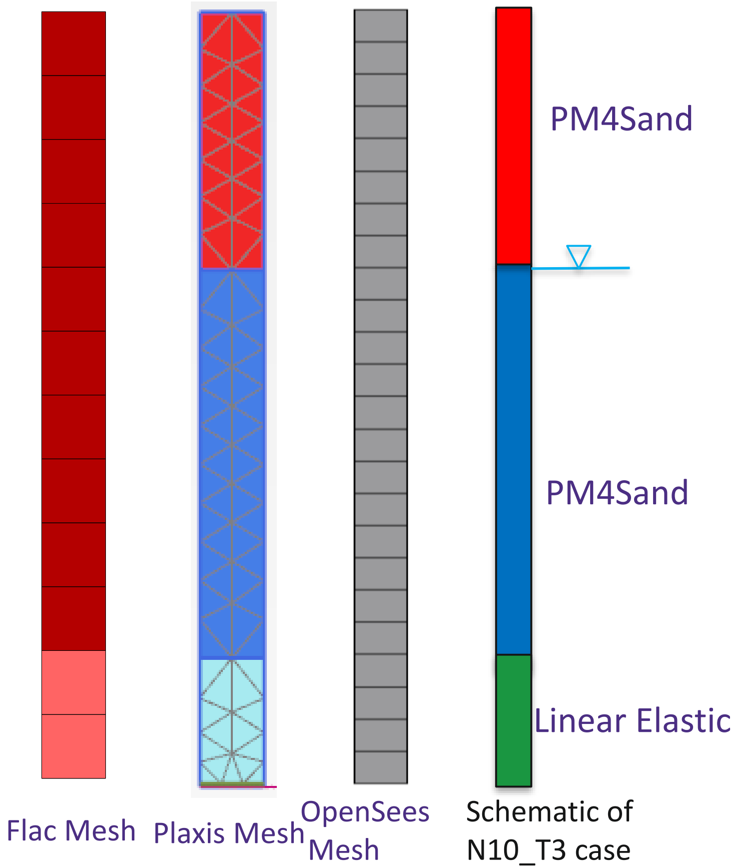




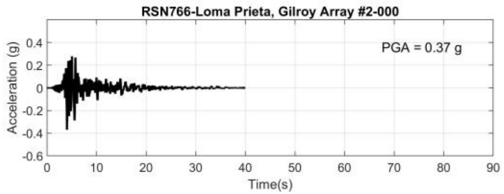
Schematic of N10_T3 case

Validation:1D analysis numerical model

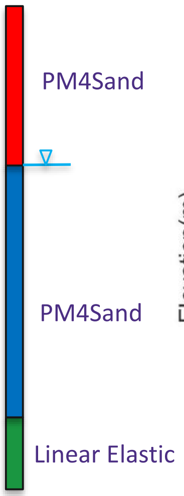
– SSPquadUP elements with size of 0.25m
– Boundary Conditions:
  > Nodes on the bottom fixed in vertical displacement DOFs
  > Input motion is applied using dashpot
  > Nodes at the same elevation tied together for displacement DOFs, but not tied for the pore pressure DOF
  > Nodes above ground water table fixed in pore pressure DOF
– Model is verified with ProShake and DeepSoil using scaled motion RSN766(PGA = 0.02g)

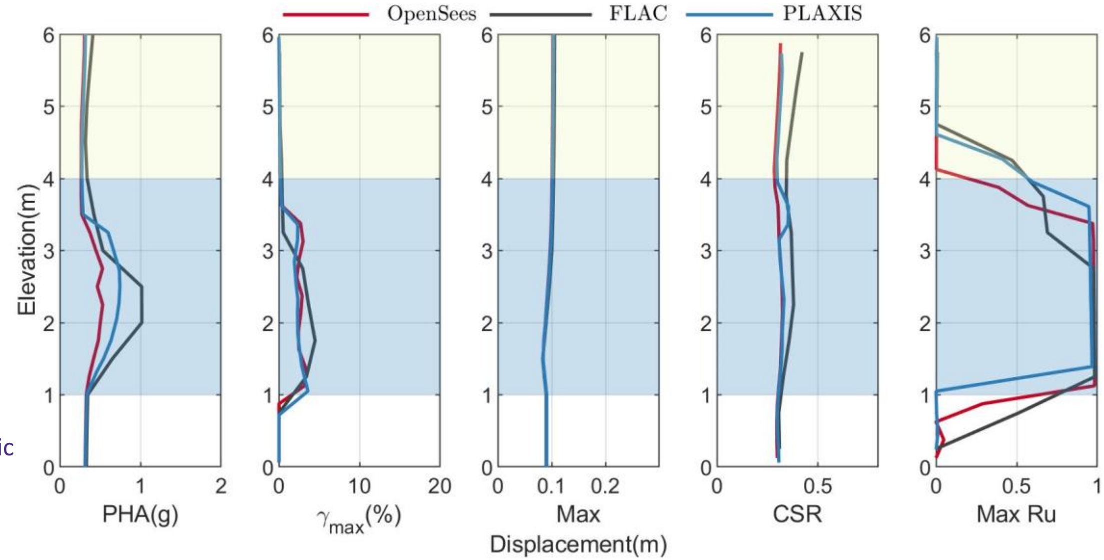


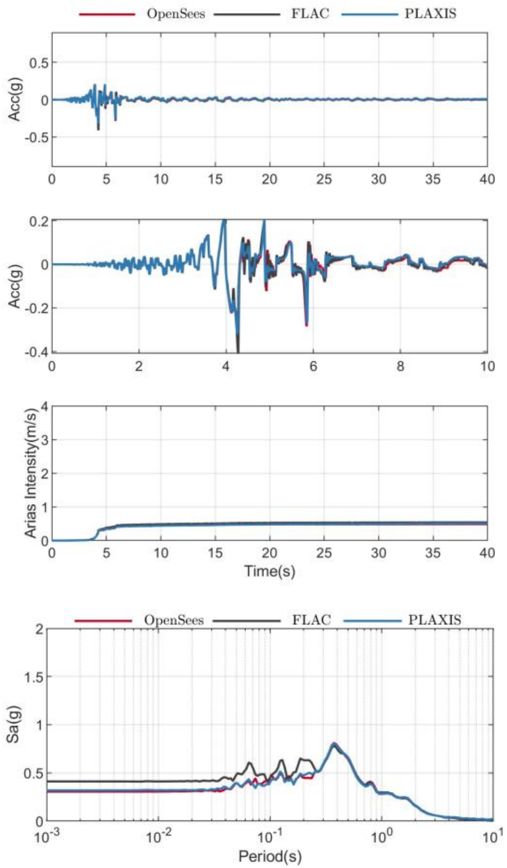
N10_T3



Input Motion

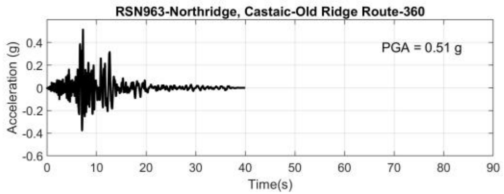




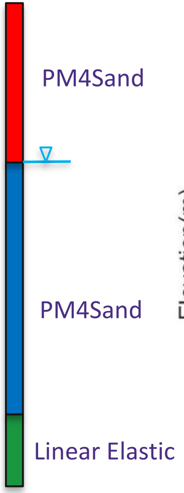


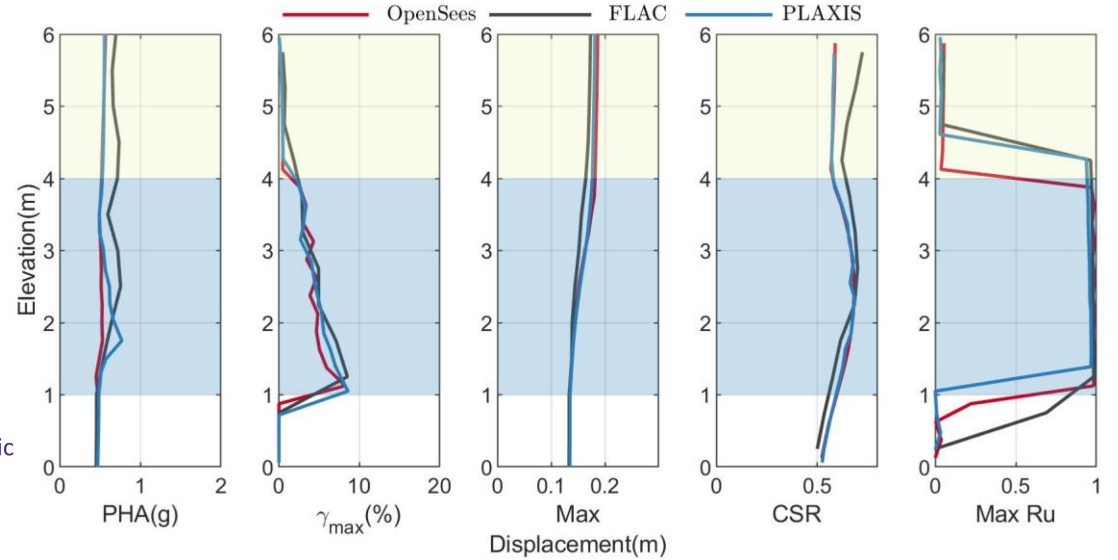
Acceleration response at surface

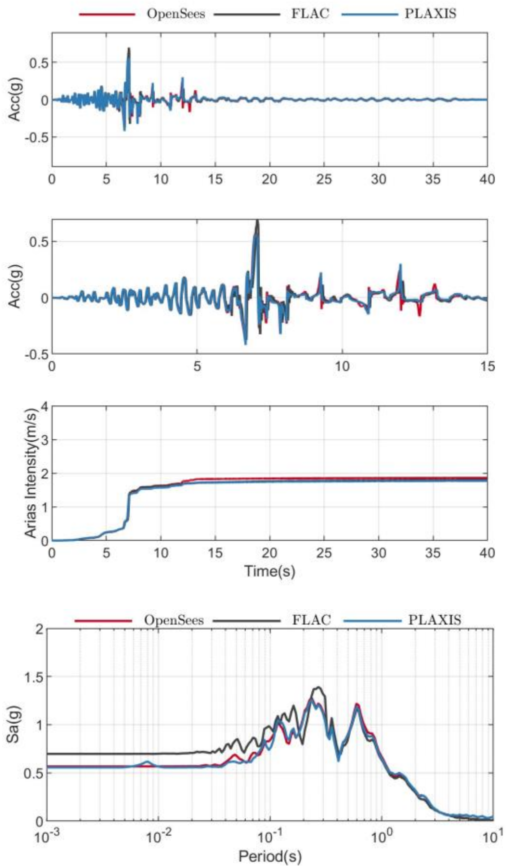
N10_T3



Input Motion

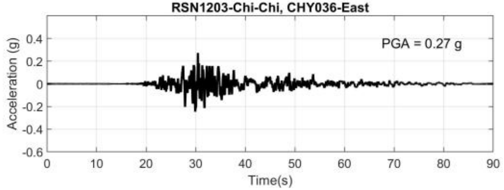




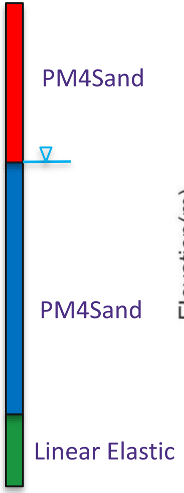


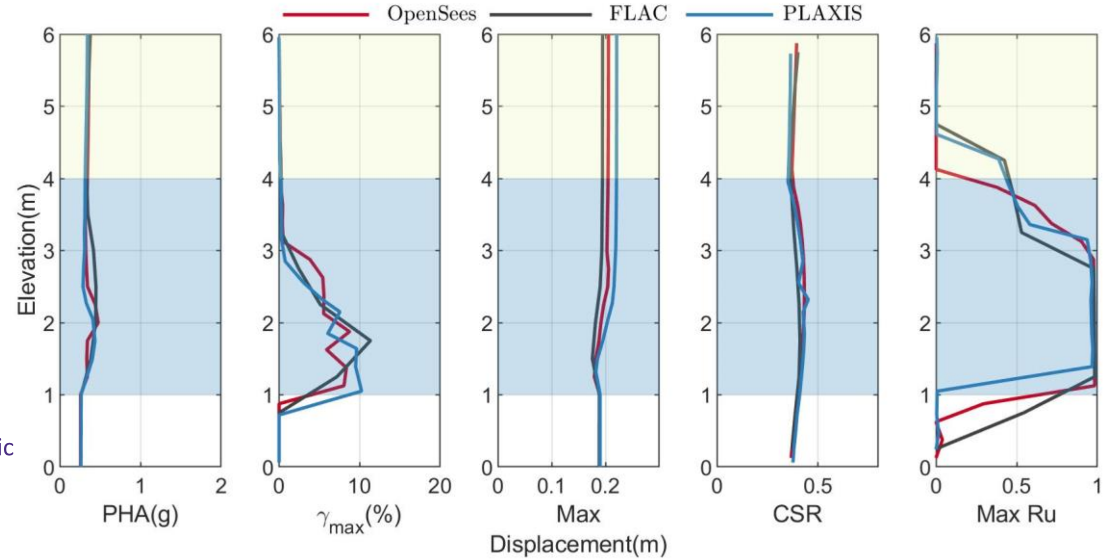
Acceleration response at surface

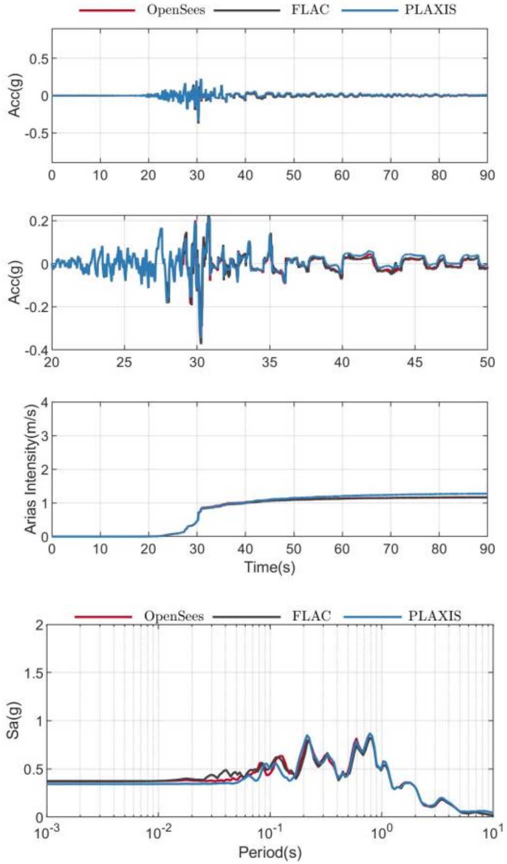
N10_T3



Input Motion



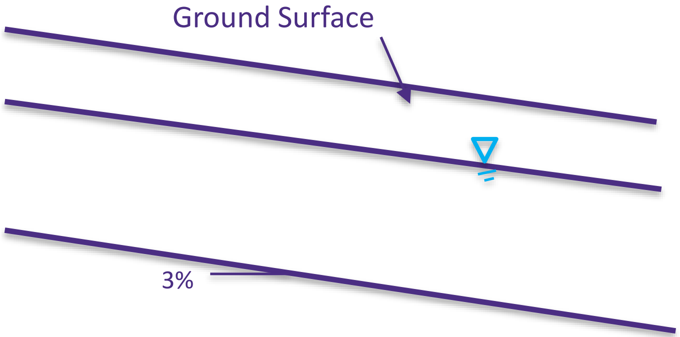


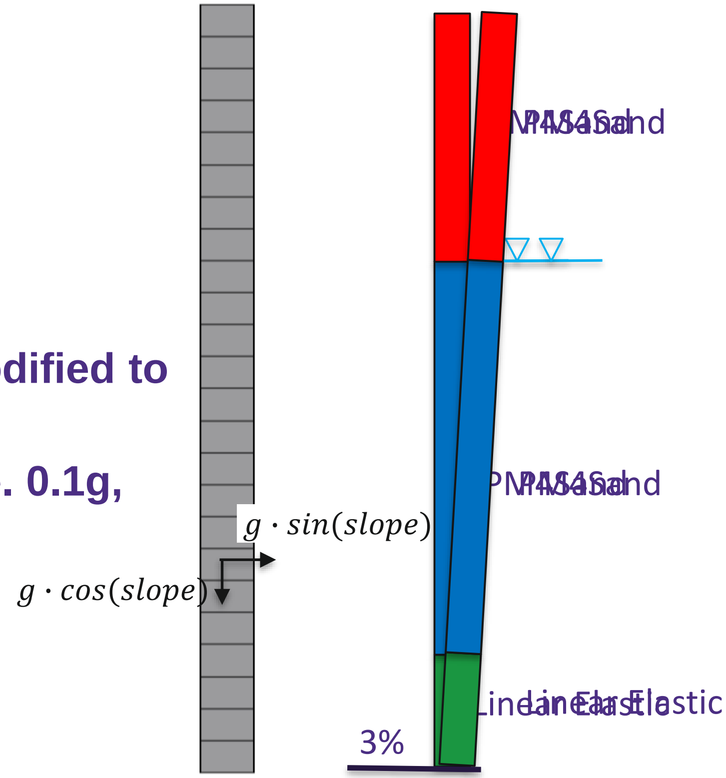


Acceleration response at surface

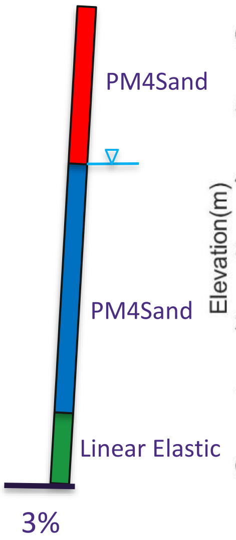
Validation: 1D analysis Sloping ground

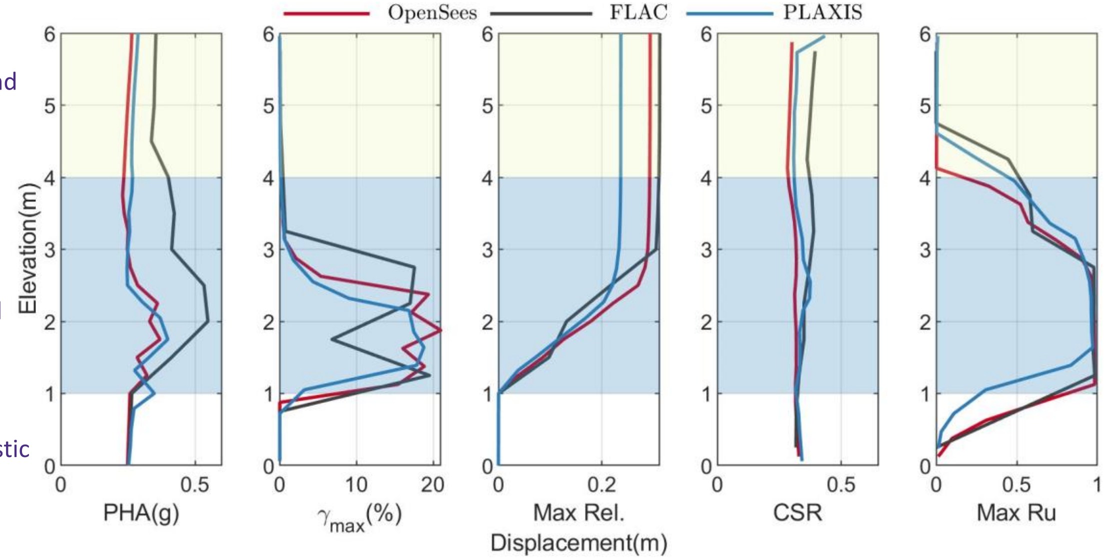
- N10T3 case is chosen
- Direction of gravitational acceleration is modified to simulate constant slope
- Three motions are scaled to same PGAs, i.e. 0.1g, 0.2g and 0.3g.



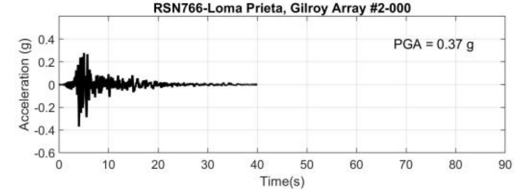


Validation: 1D analysis
Sloping ground

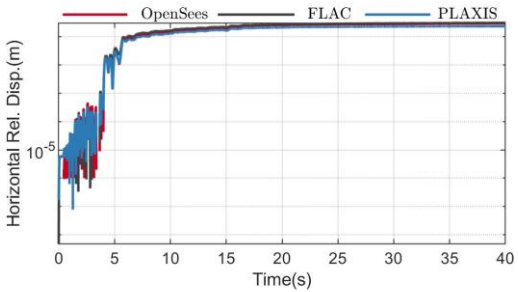




Comparison of PGA, max shear strain, max horizontal displacement, cyclic stress ratio and maximum excess pore pressure ratio profile between OpenSees and Flac(Gilory02 scaled to 0.3g).

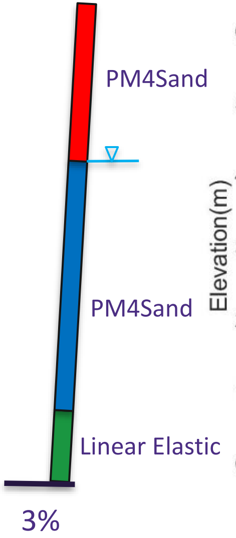


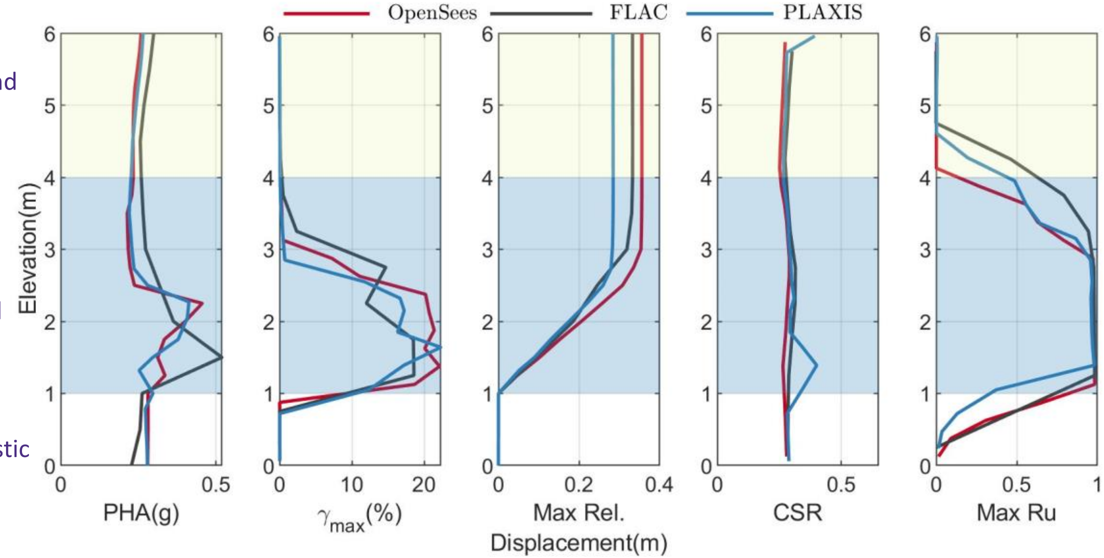
Input Motion



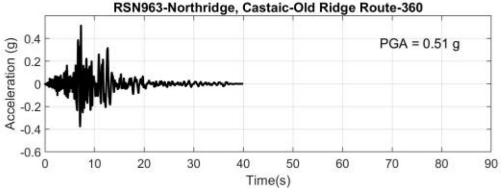
Comparison of lateral displacement at surface

Validation: 1D analysis
Sloping ground

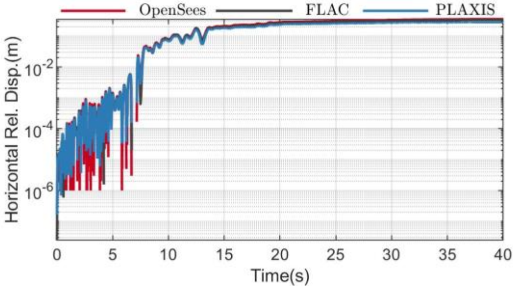




Comparison of PGA, max shear strain, max horizontal displacement, cyclic stress ratio and maximum excess pore pressure ratio profile between OpenSees and Flac(NorthRidge scaled to 0.3g).

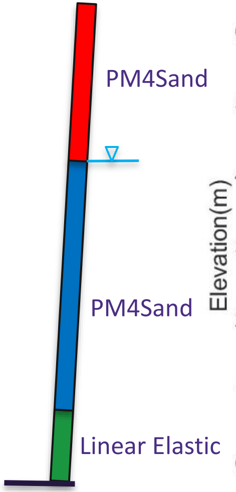


Input Motion

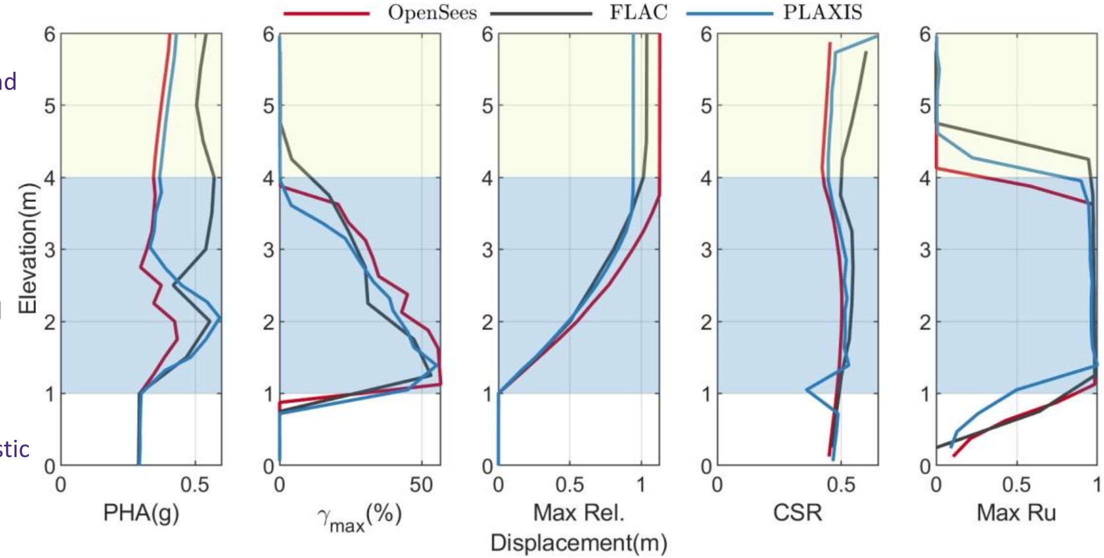


Comparison of lateral displacement at surface

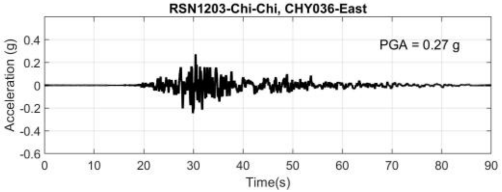
Validation: 1D analysis
Sloping ground



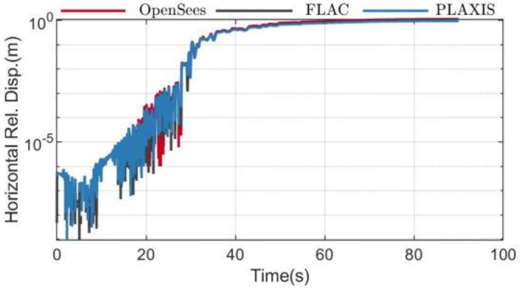
3%



Comparison of PGA, max shear strain, max horizontal displacement, cyclic stress ratio and maximum excess pore pressure ratio profile between OpenSees and Flac(ChiChi scaled to 0.3g).

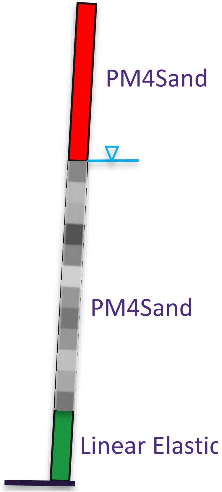


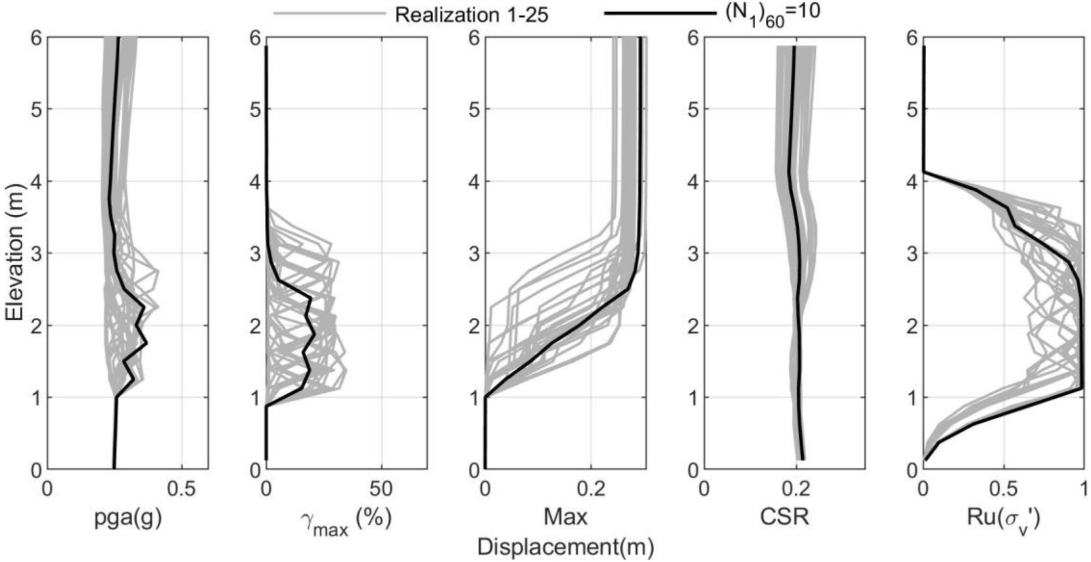
Input Motion



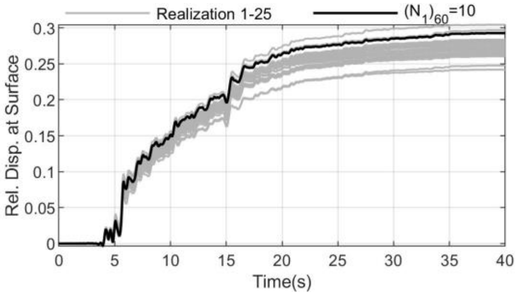
Comparison of lateral displacement at surface

1D analysis: sloping ground with randomized properties for liquefiable layer





Comparison of PGA, max shear strain, max horizontal displacement, cyclic stress ratio and maximum excess pore pressure ratio profile between deterministic and stochastic cases(Gilory02 scaled to 0.3g).



Comparison of lateral displacement at surface

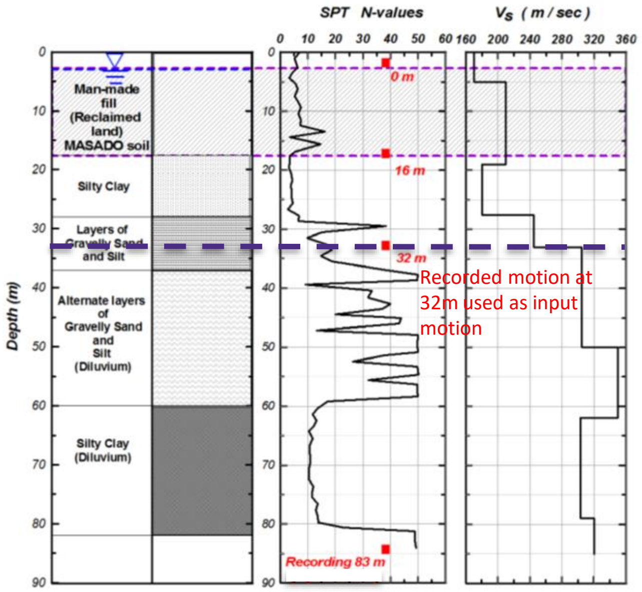
Verification: 1D Analysis Port Island array

Port Island array during 1995 Kobe earthquake is simulated using OpenSees. Only the top 32m of this profile is modeled and the recorded North-South motion at 32m is applied as within motion. Top Masado sand layers are modeled using PM4Sand material while the silty clay and silt layers are modeled using PM4Silt model.

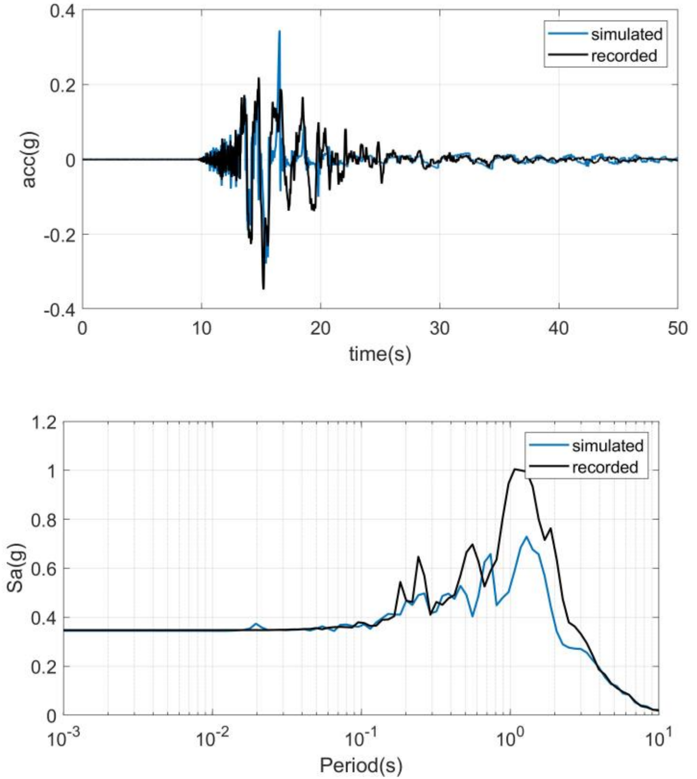
Material models and input parameters for Port Island Array(after Ziotopoulou(2012), Sideras(2011), and Ziotopoulou(2018))

Depth(m)	Material Model	Primary Parameters		
		Dr	G0	hpo
0-3	PM4Sand	0.47	729.0	0.7
3-5	PM4Sand	0.47	729.0	0.7
5-14	PM4Sand	0.39	695.51	0.8
14-17.5	PM4Sand	0.47	507.53	0.9
		Su_rate	G0	hpo
17.5-26.5	PM4Silt	0.25	588.0	20.0
26.5-32	PM4Silt	0.75	1076.0	50.0

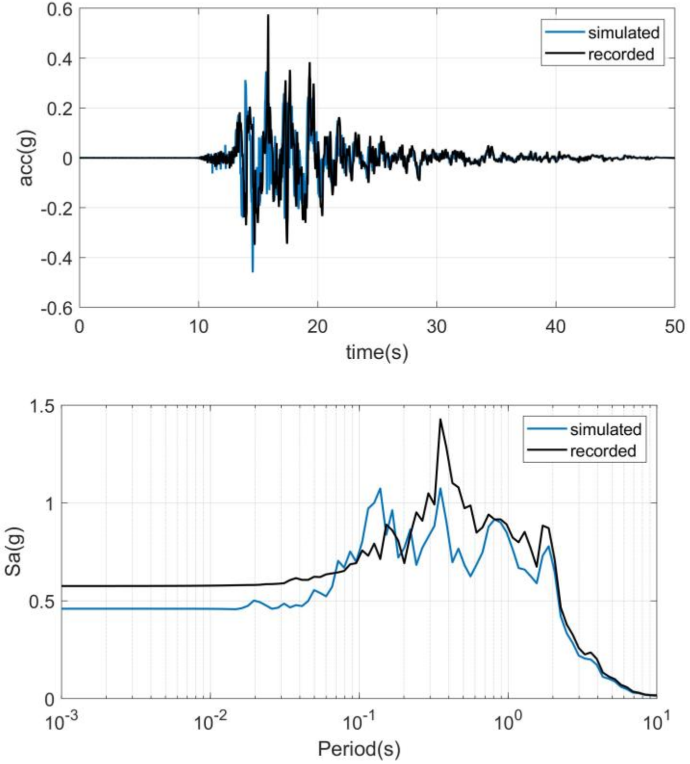
* All secondary input parameters are kept as default values



Soil profile at the Port Island site showing SPT N-values, shear wave velocities(from Ziotopoulou(2012))



Comparison of recorded and simulated response spectra at **surface**

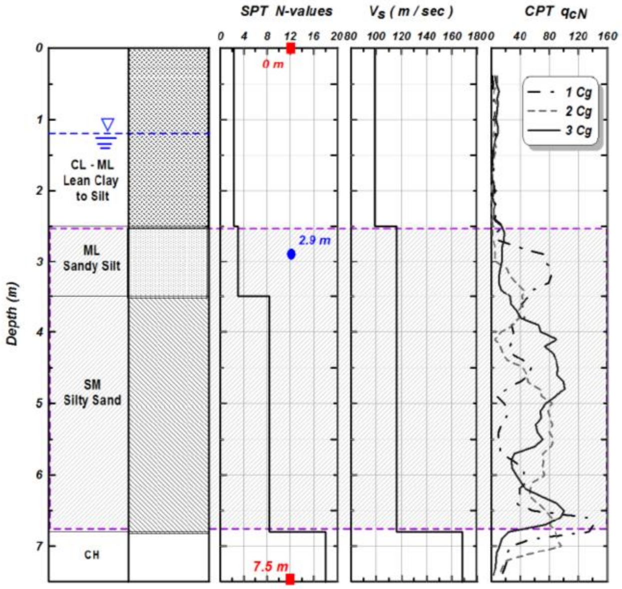


Comparison of recorded and simulated response spectra at depth of **16m**

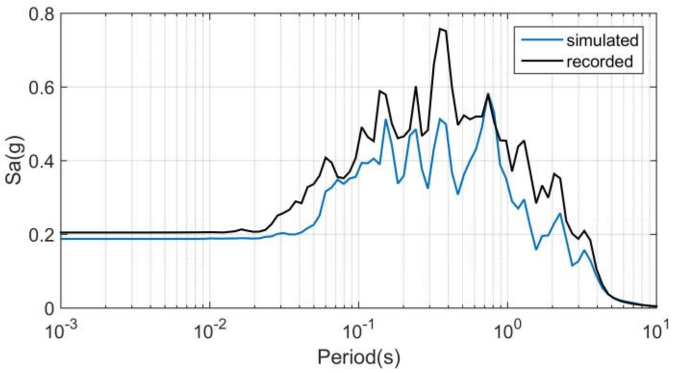
Verification: 1D analysis WildLife Array

Wildlife Liquefaction array(WLA) during 1987 Superstition Hills earthquake is simulated using OpenSees. Nonliquefiable layers are modeled using PressureIndependMultiYield material and the material properties are adopted from Sideras(2011). Liquefiable layers are modeled using PM4Sand material. PM4Sand material properties are listed below. All secondary parameters are kept as default.

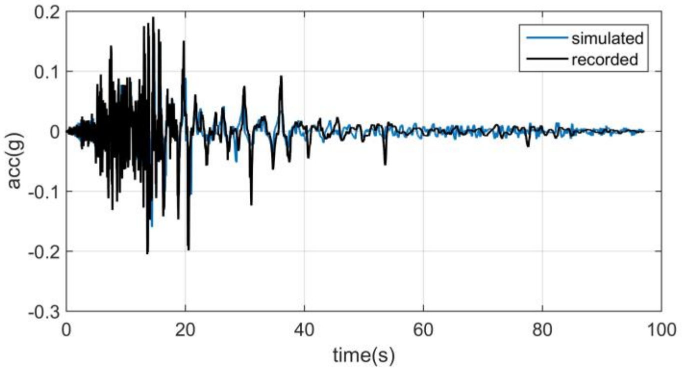
Layer #	Material Model	Primary Parameters		
		Dr	G0	hpo
3	PM4Sand	0.46	580.0	0.1
4	PM4Sand	0.57	697.0	0.1



Soil profile at the WildLife site showing SPT N-values, shear wave velocities(from Ziotopoulou(2012))

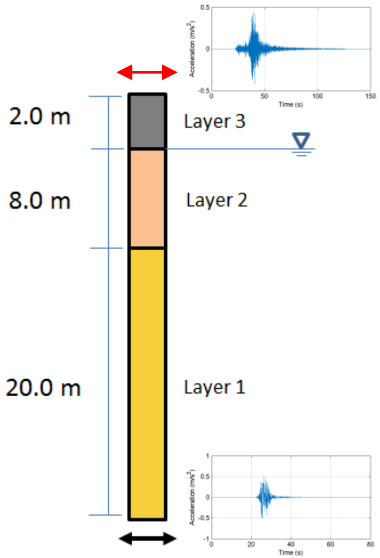


Comparison of recorded and simulated acceleration response spectra at surface



Comparison of recorded and simulated acceleration time history at surface

Resources: DesignSafe Jupyter notebooks



Workflow:

a) Run OpenSees
b) Postprocess results
c) Create report
d) Explore use of interactive plots

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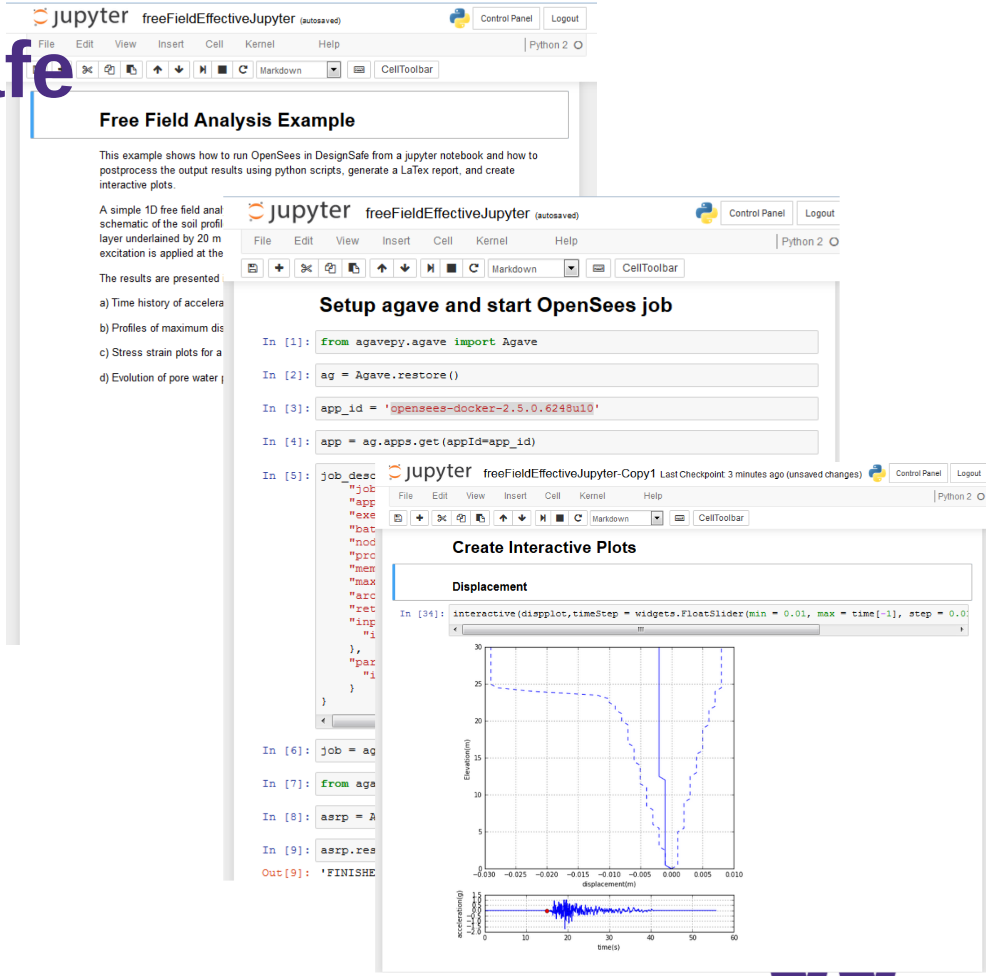
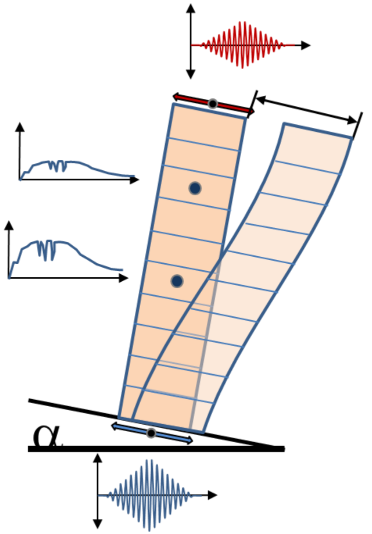
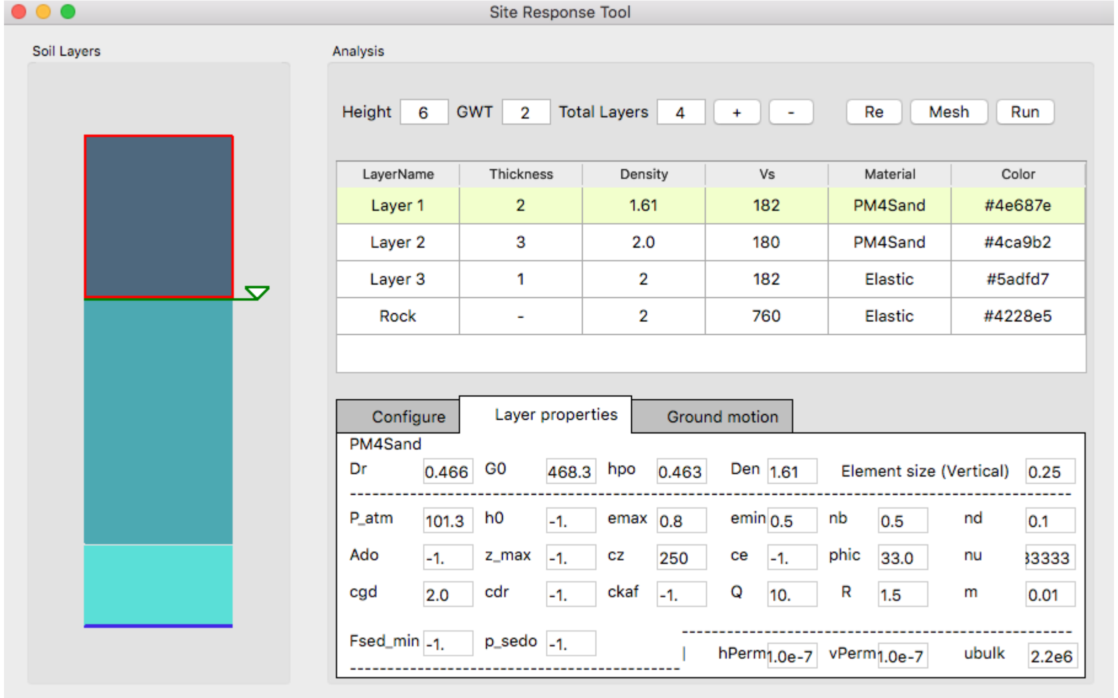
jupytercon



Resources: SimCenter Site Response App





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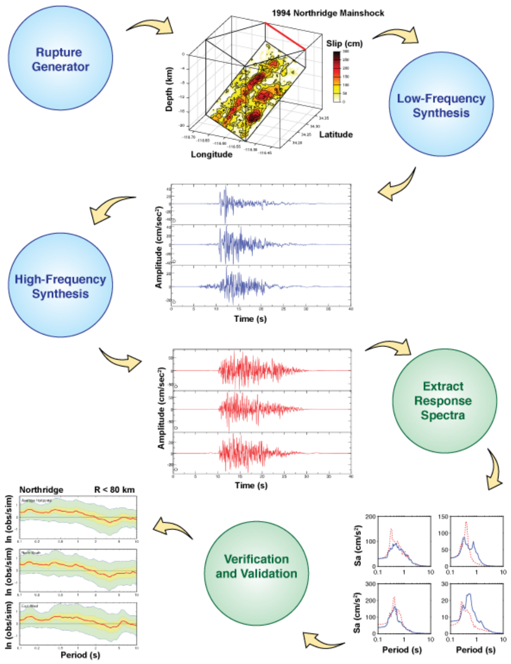
Broad Band Platform
Site Response module



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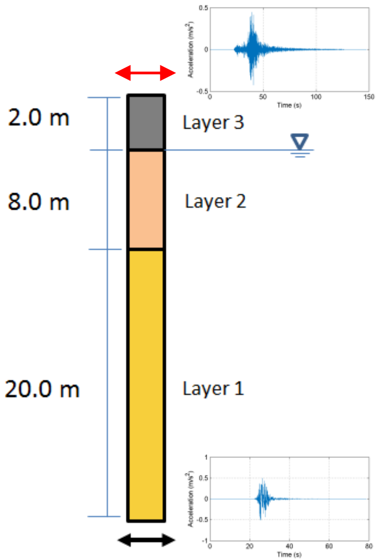
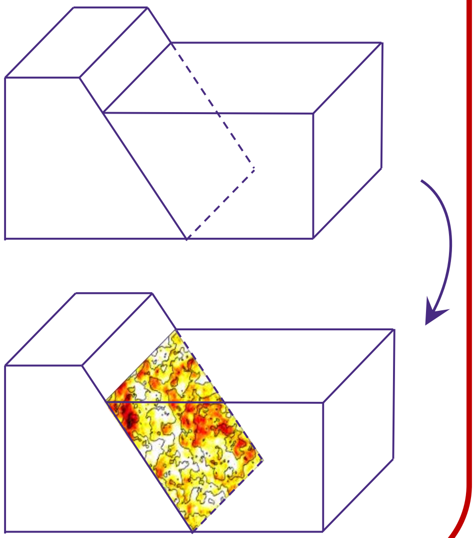


OpenSees

Broad Band Platform
Site Response module

.src file



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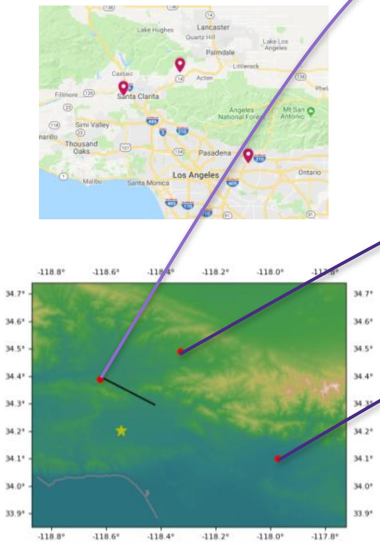

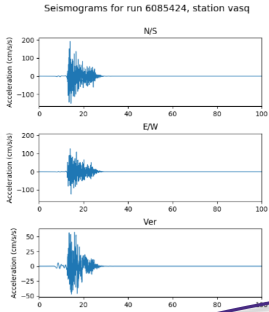

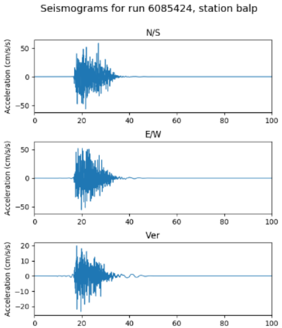

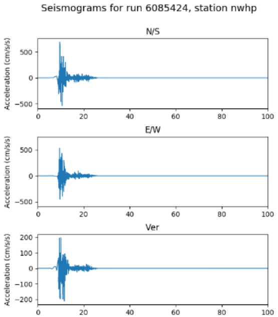

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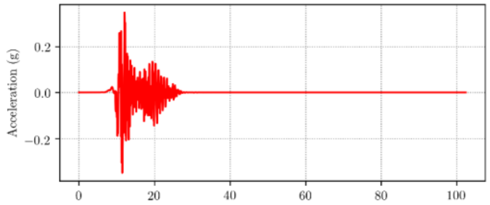
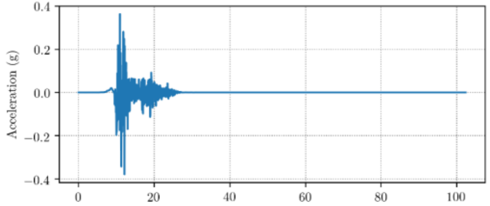
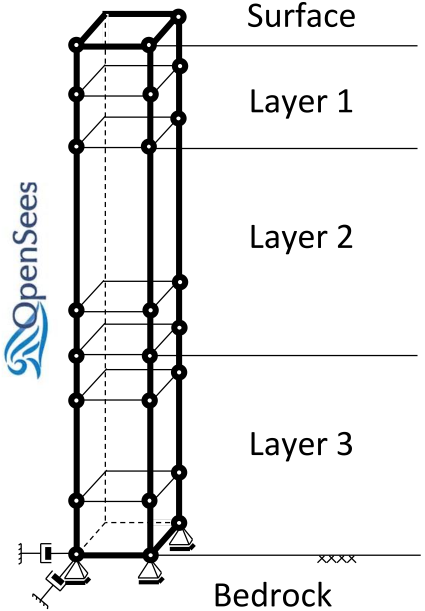
Broad Band Platform Site Response module

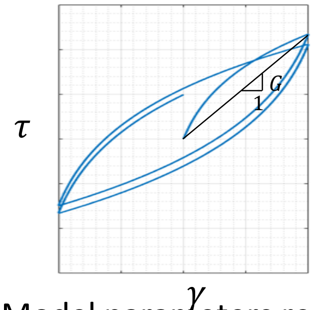




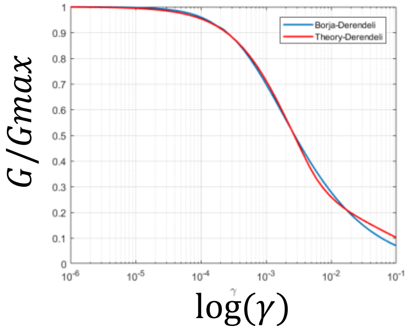


OpenSees model of soil layer

Nonlinear soil response

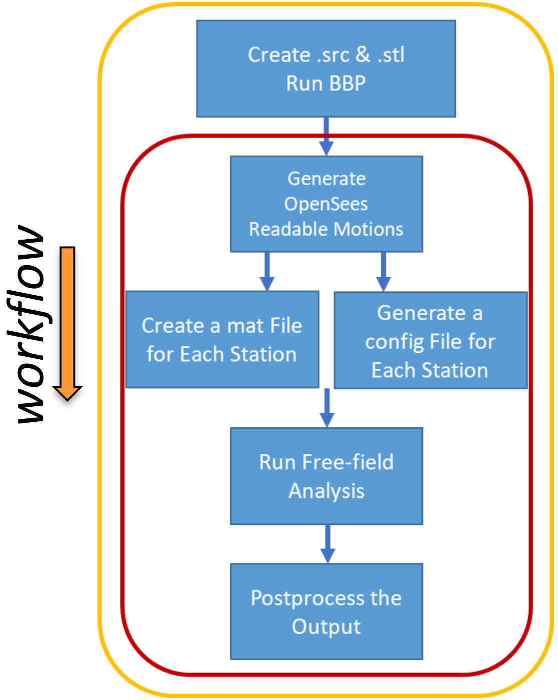


Model parameters related to laboratory evidence

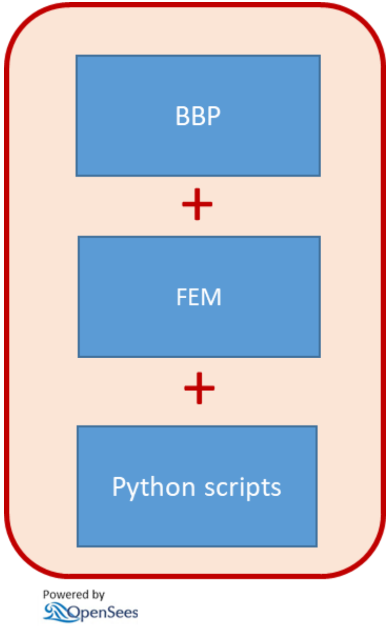


Broad Band Platform
Site Response module

Bash file



Updated BBP



Thanks

OpenSees

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