

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

Pedro Arduino

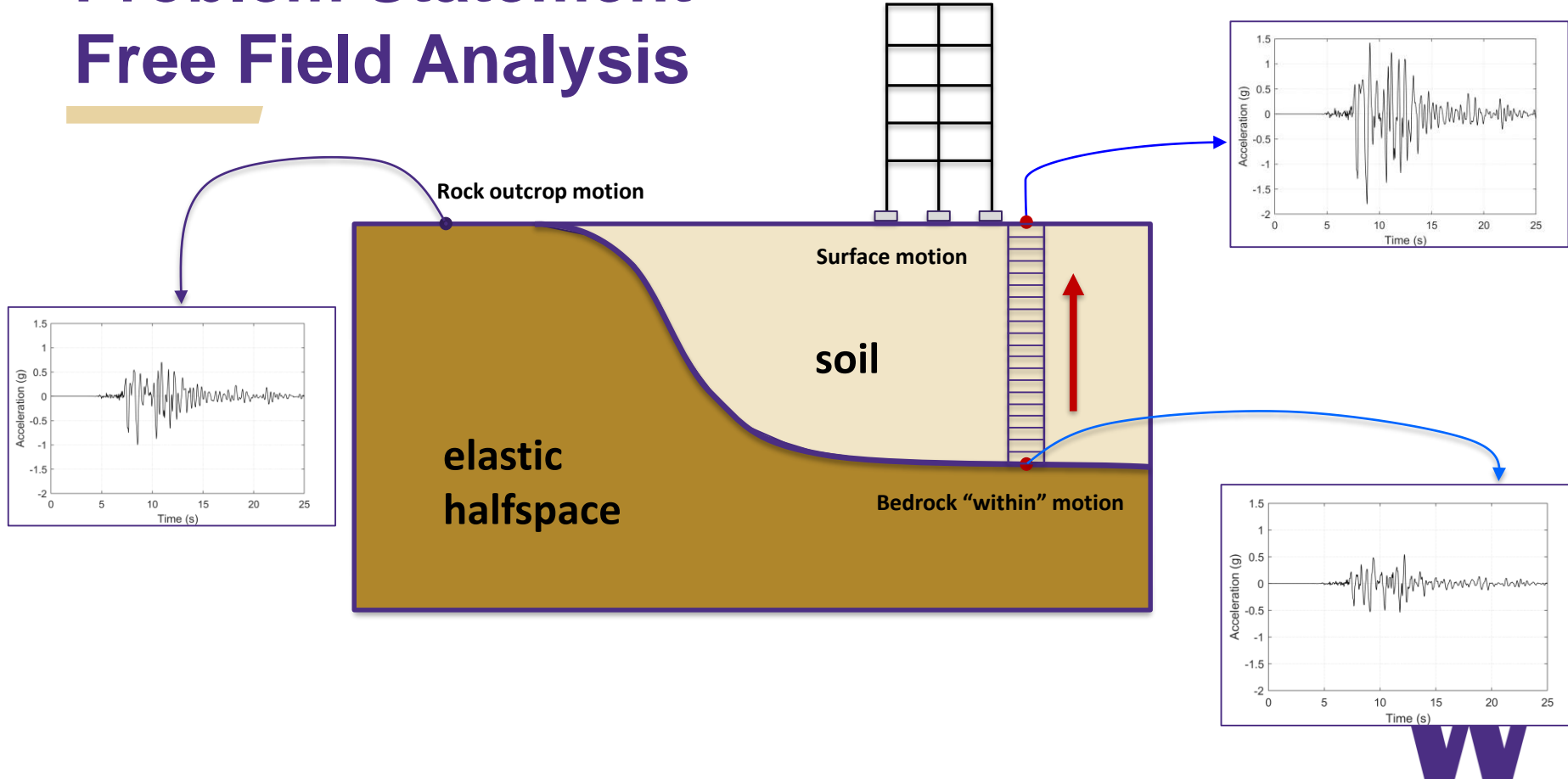
Long Chen

University of Washington



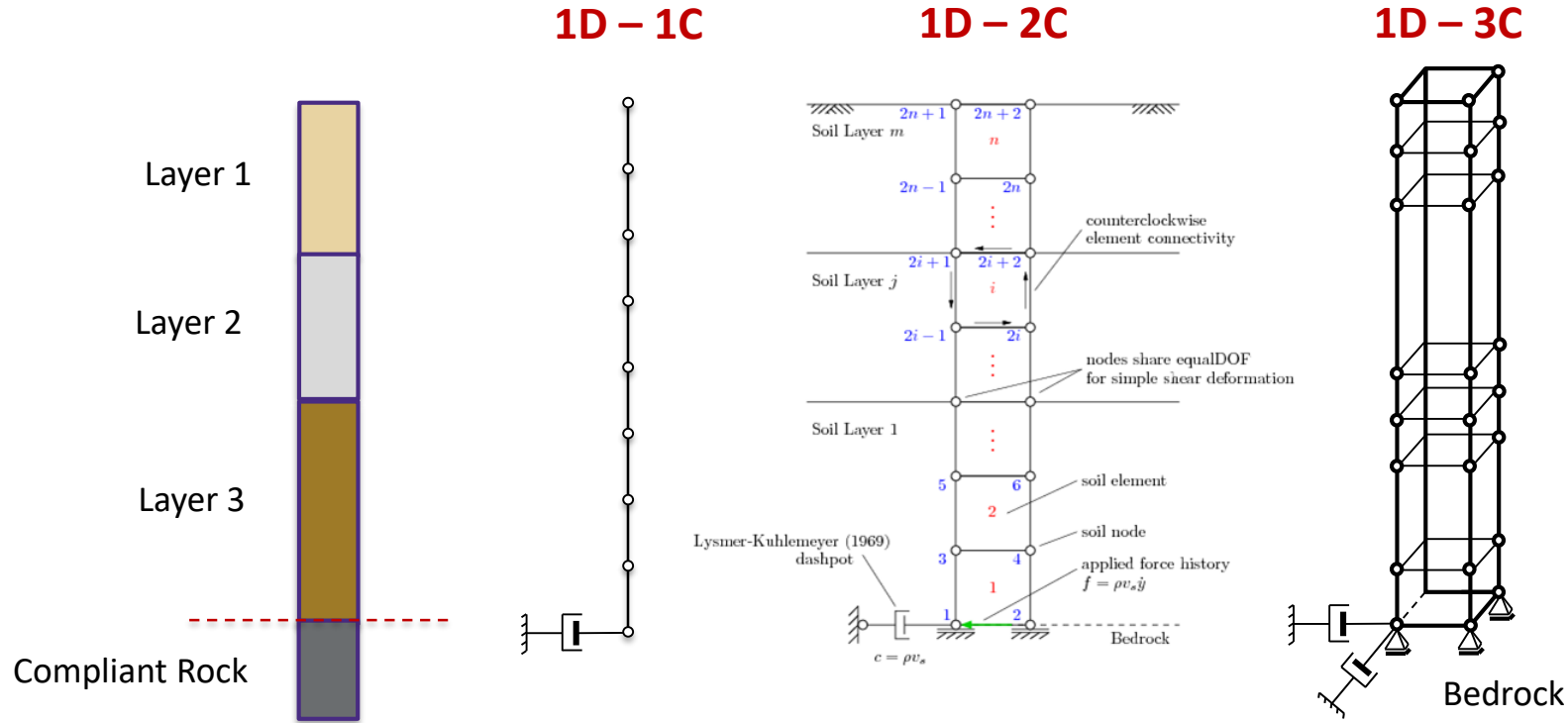
Problem Statement

Free Field Analysis



Free-Field Analysis

Numerical solution



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**



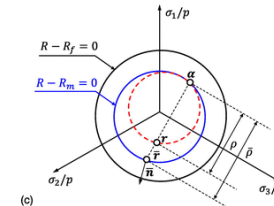
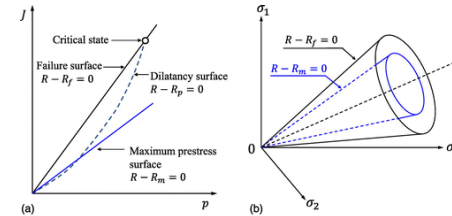
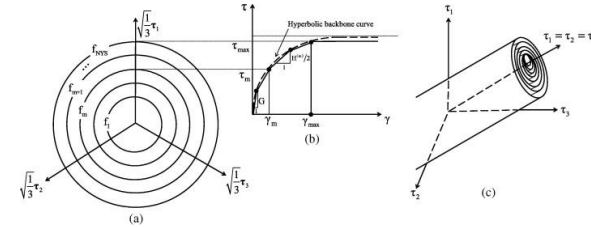
Constitutive Models

> Formulation

- Kinematic Hardening
 - > Nested surfaces
 - Prevost, Elgamal
 - > Bounding surfaces
 - Dafalias, Borja & Amies
 - Manzari-Dafalias, PM4Sand

> Implementation

- Explicit
- Implicit
- Consistent tangent operator



Constitutive Models

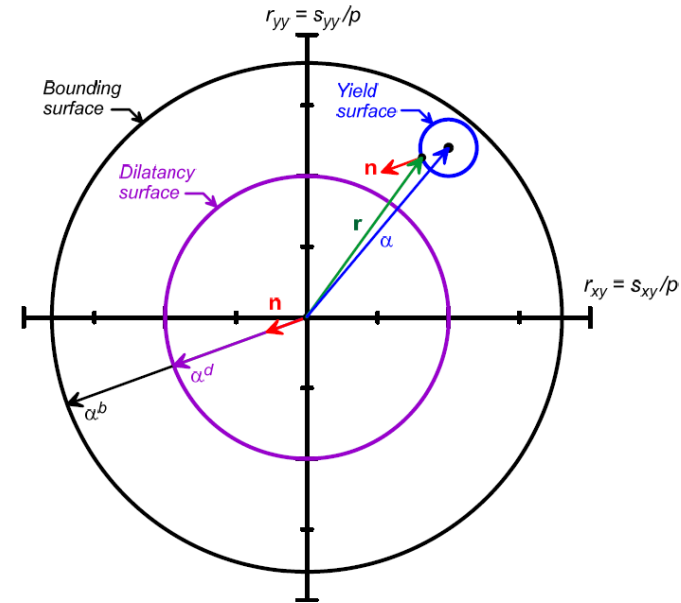
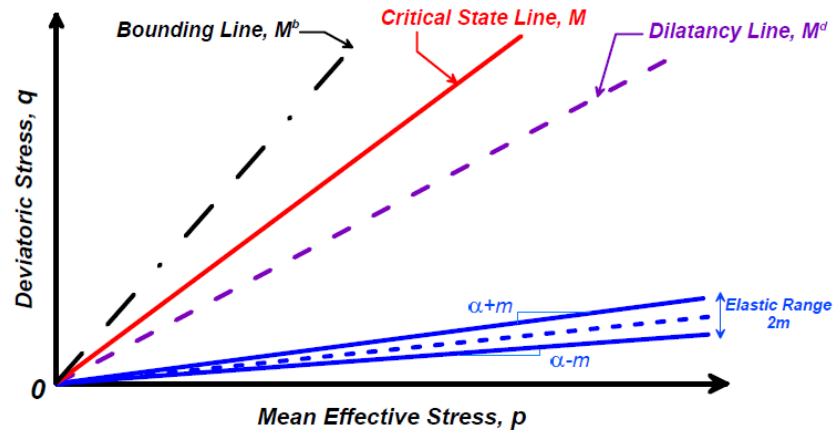
PM4Sand Model Description

- > **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 (D_r)
 - Shear modulus coefficient G_0
 - Contraction rate parameter h_{po}
- > **And 21 optional secondary parameters.**



PM4Sand - Model Description

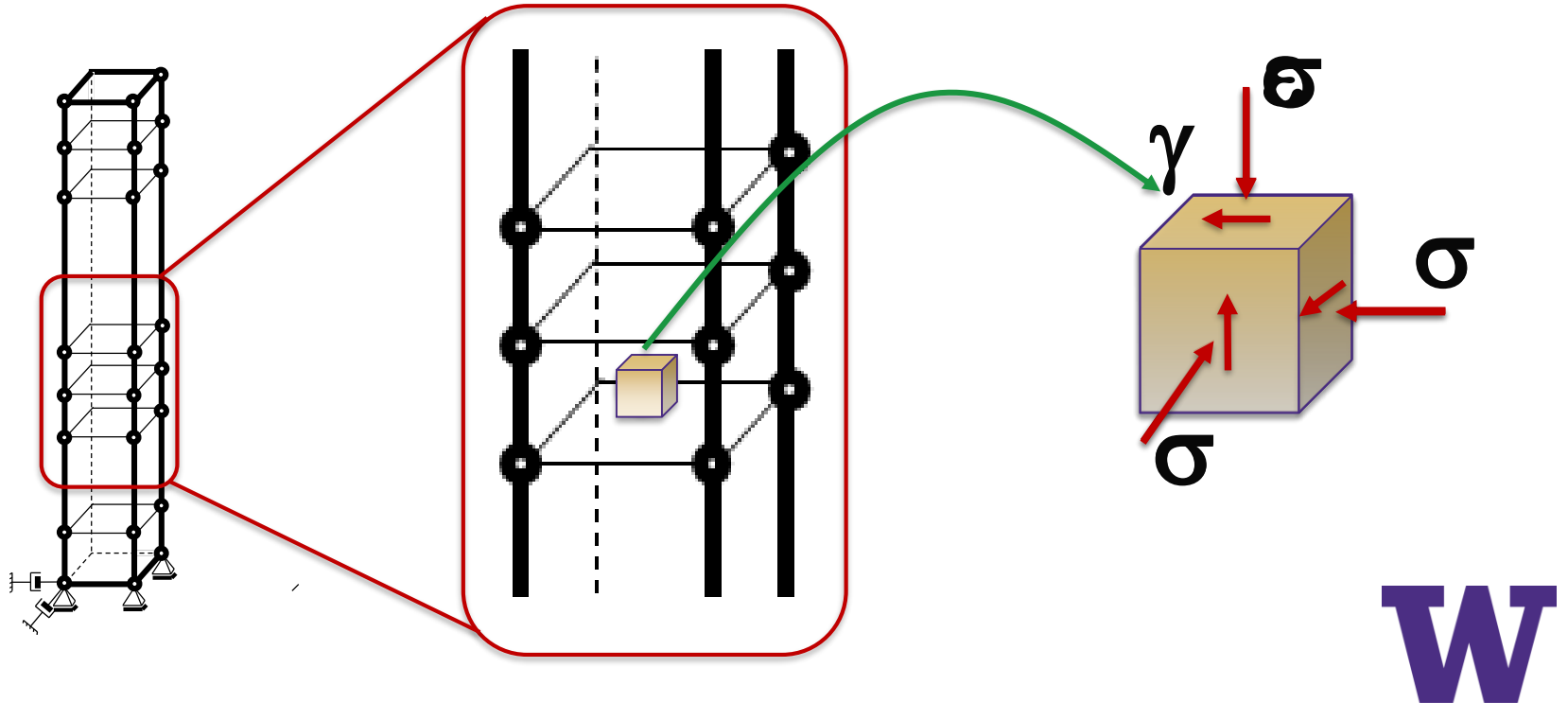
Surfaces (Yield, Bounding, Dilatancy, Critical)



$$f = \sqrt{(r-a):(r-a)} - \sqrt{1/2}m = 0$$

Model Validation

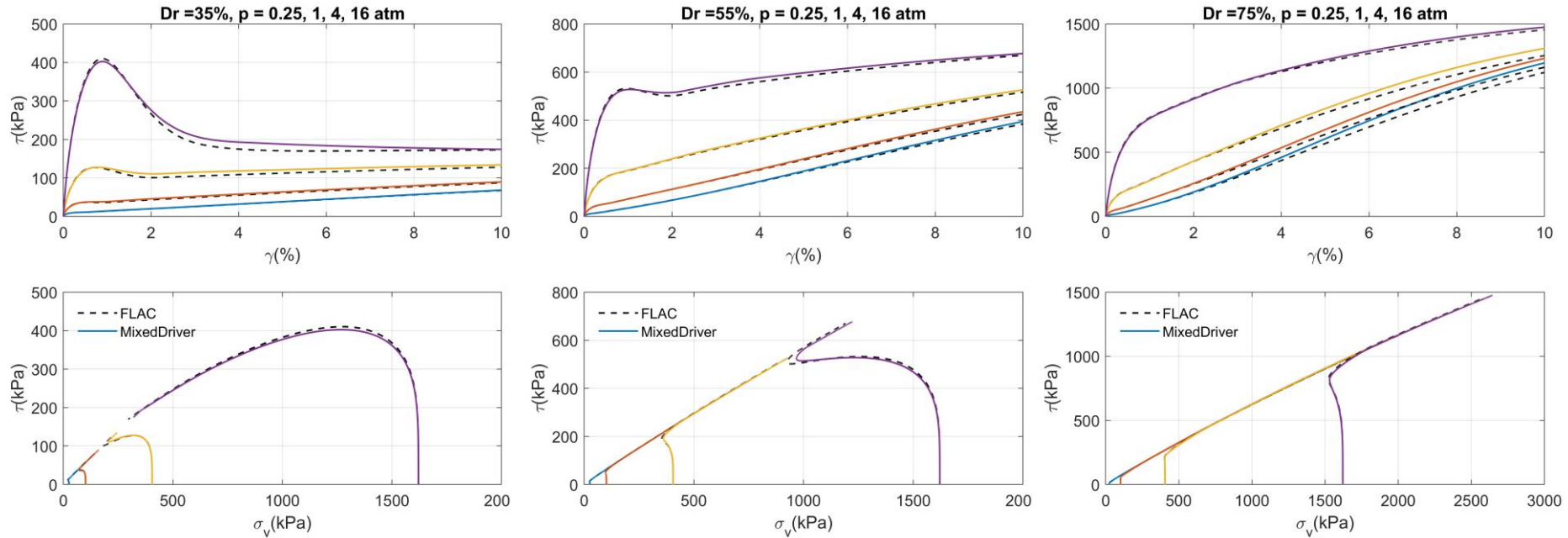
Element test - Mixed Driver



Model Validation

Element test using MixedDriver

Monotonic tests



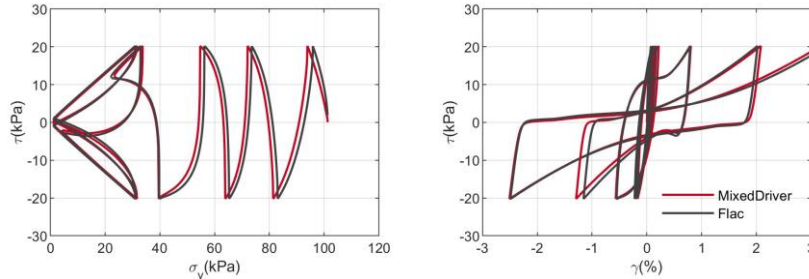
Undrained monotonic DSS loading responses for $DR = 35, 55$, and 75% with initial confining pressures of 0.25, 1, 4 and 16 atm, $K_0 = 1.0$



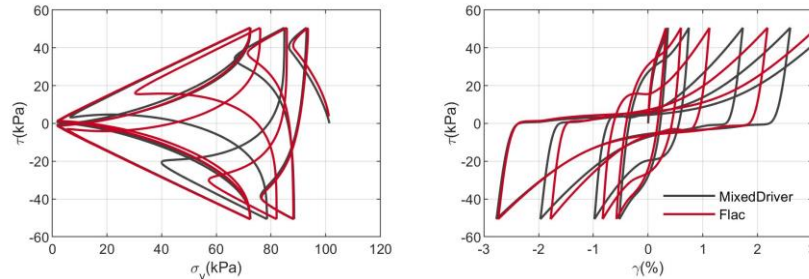
Model Validation

Element test using MixedDriver

Cyclic tests



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



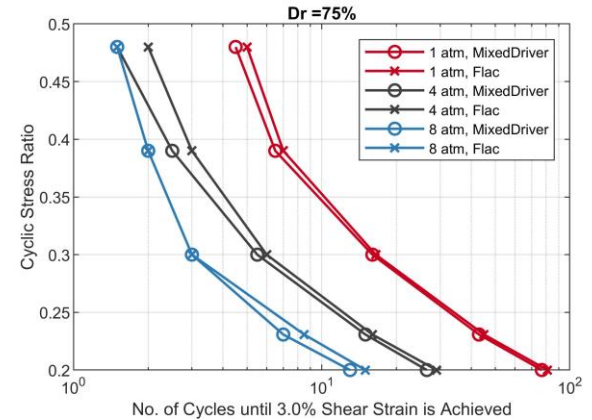
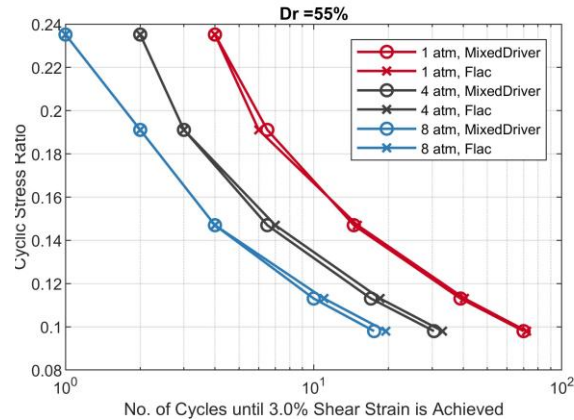
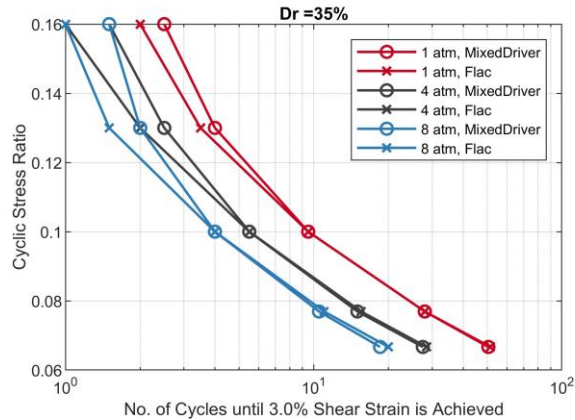
Undrained cyclic DSS loading responses for DR = 75% with initial confining pressure of 1 atm, using $C_D = 0.16$



Model Validation

Element test using MixedDriver

Effect of K_0



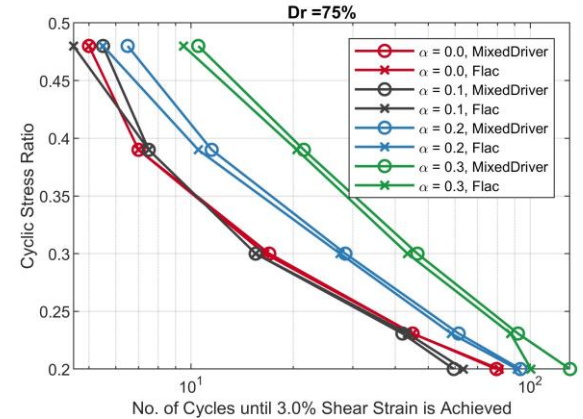
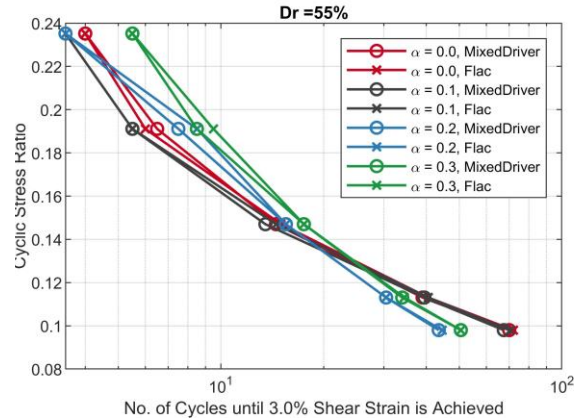
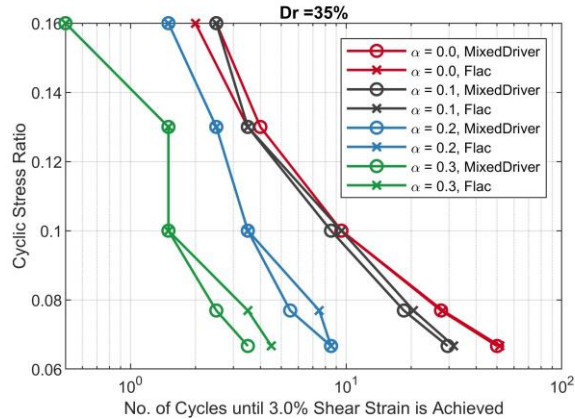
Cyclic stress ratios vs. number of cycles to reach 3% shear strain for $D_R = 35, 55$ and 75% with vertical consolidation stresses of 1, 4 and 8 atm. $K_0 = 0.5$



Model Validation

Element test using MixedDriver

Effect of $K\alpha$



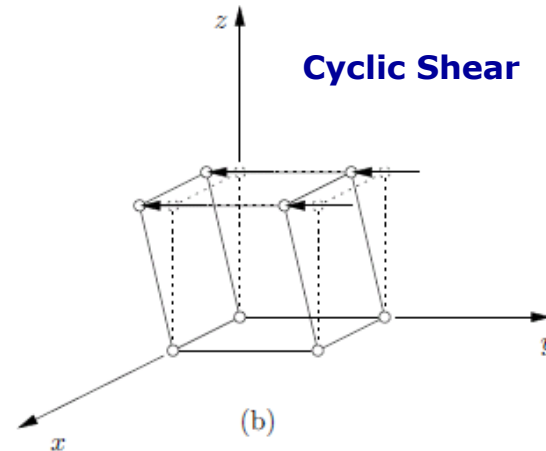
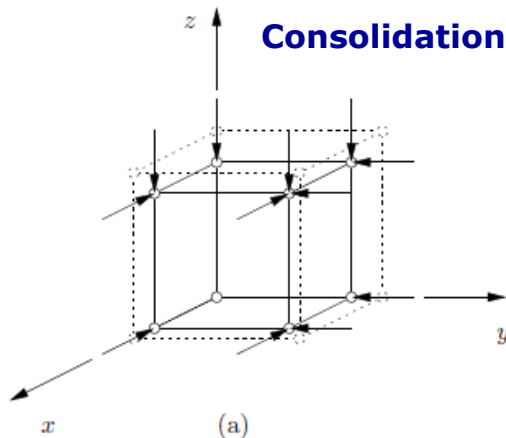
Cyclic stress ratios vs. number of cycles to reach 3% shear strain for $D_r = 35, 55$ and 75% with vertical consolidation stress of 1 atm and initial static shear stress ratios of 0.0, 0.1, 0.2, and 0.3. $K_0 = 0.5$



Validation

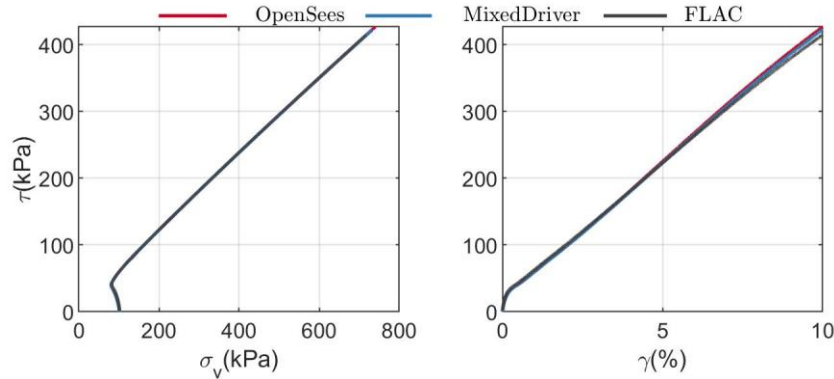
Element test in FE framework (OpenSees)

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

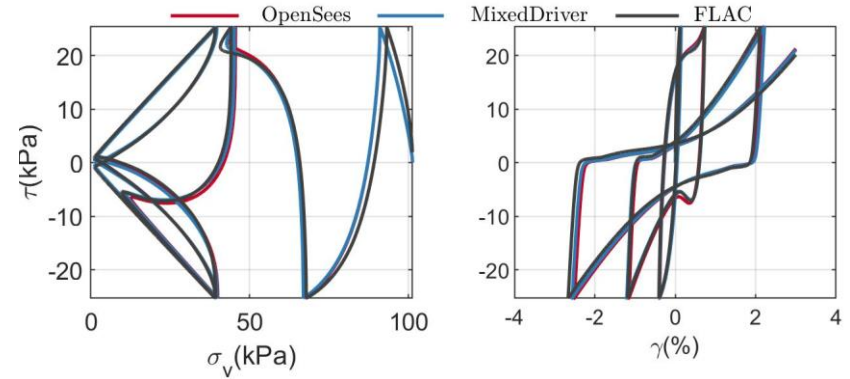


Validation

Element test in OpenSees



Undrained monotonic DSS loading responses for DR = 55% with initial vertical stress 1atm and $K_0 = 0.5$



Undrained cyclic DSS loading responses for DR = 55% with initial vertical stress 1atm and $K_0 = 0.5$



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

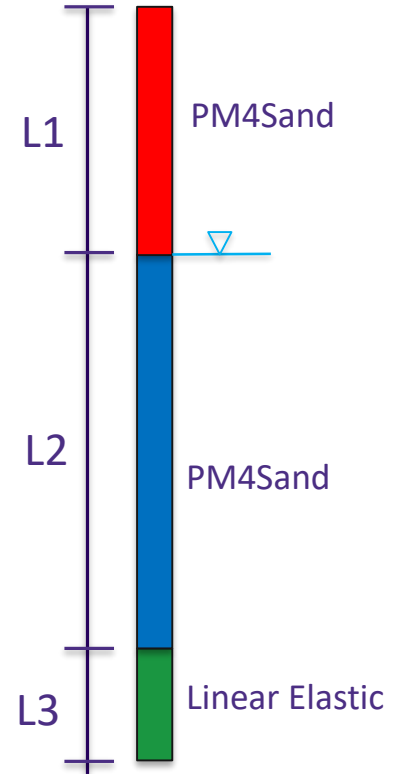
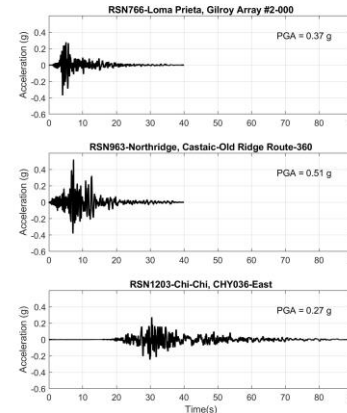
L3 : Linear elastic layer (1.0m)

Motions

M1 : Gilroy

M2 : Northridge

M3 : Chi-chi

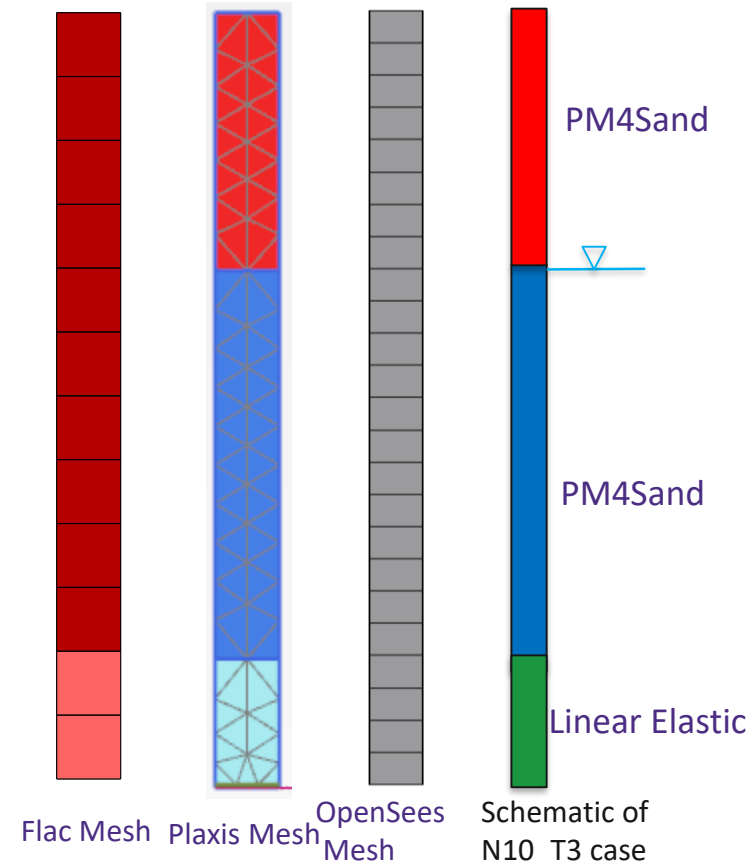


Schematic of
N10_T3 case

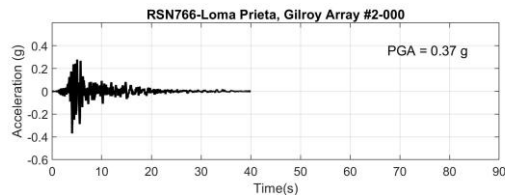


Validation: 1D analysis numerical model

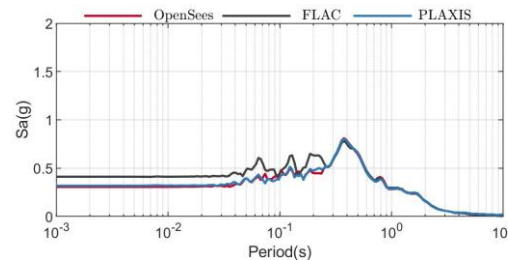
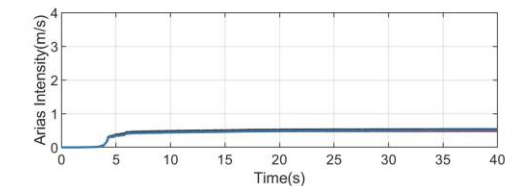
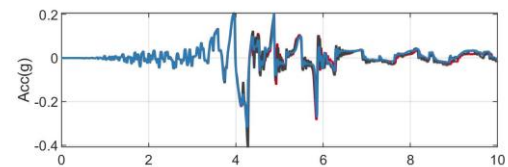
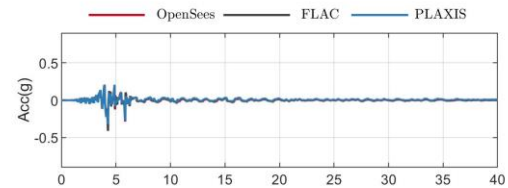
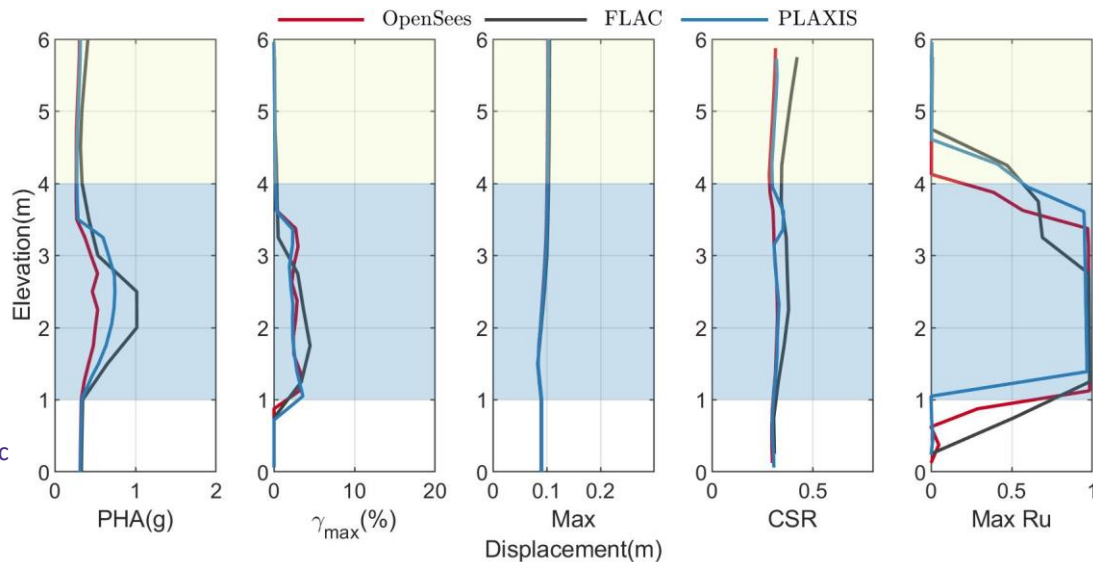
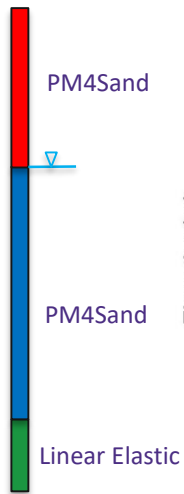
- SSPquadUP elements with size of 0.25m
- Boundary Conditions:
 - > Nodes on the bottom fixed in vertical displacement DOFs
 - > Input motion is applied using dashpot
 - > Nodes at the same elevation tied together for displacement DOFs, but not tied for the pore pressure DOF
 - > Nodes above ground water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



N10_T3



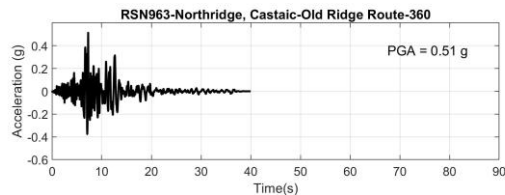
Input Motion



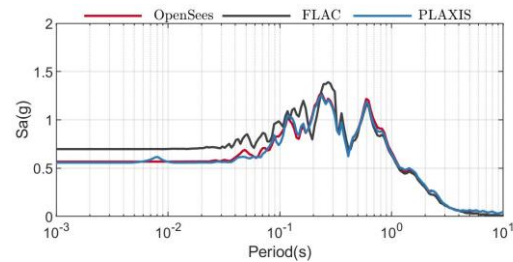
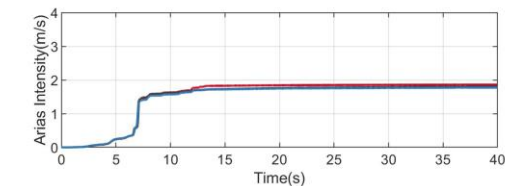
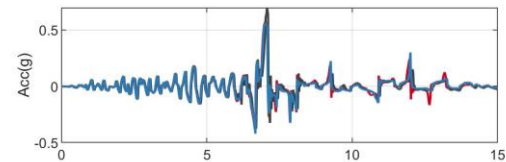
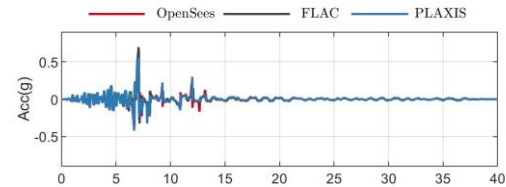
Acceleration response at surface



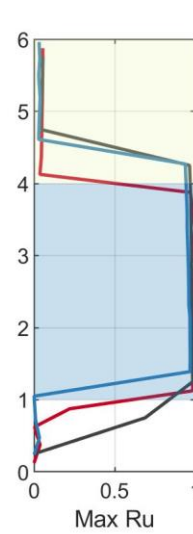
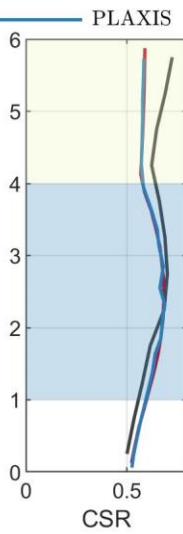
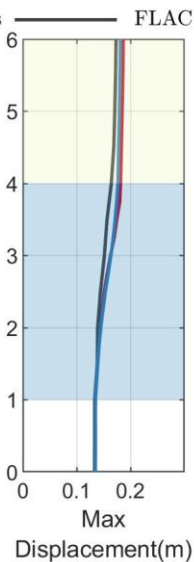
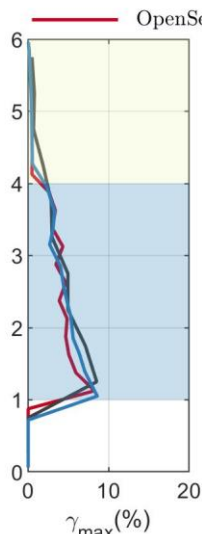
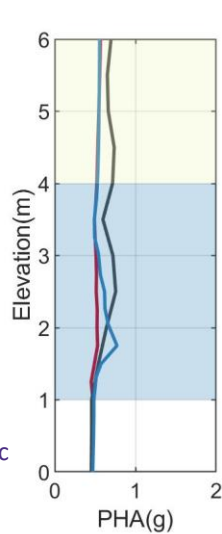
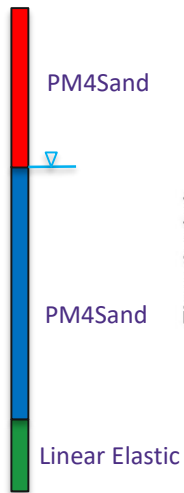
N10_T3



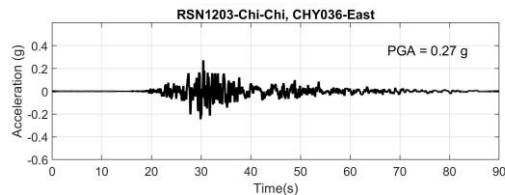
Input Motion



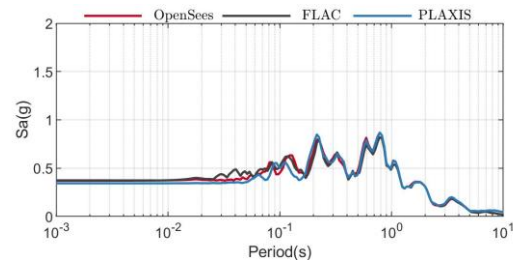
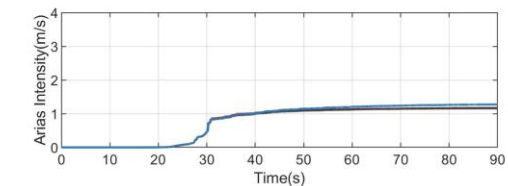
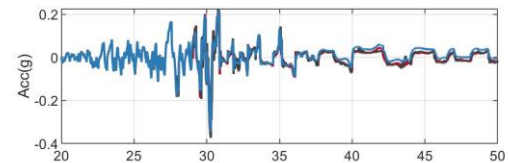
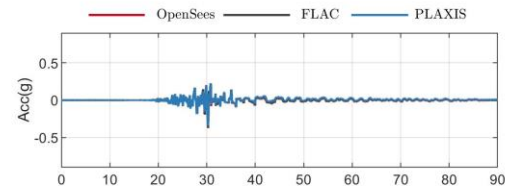
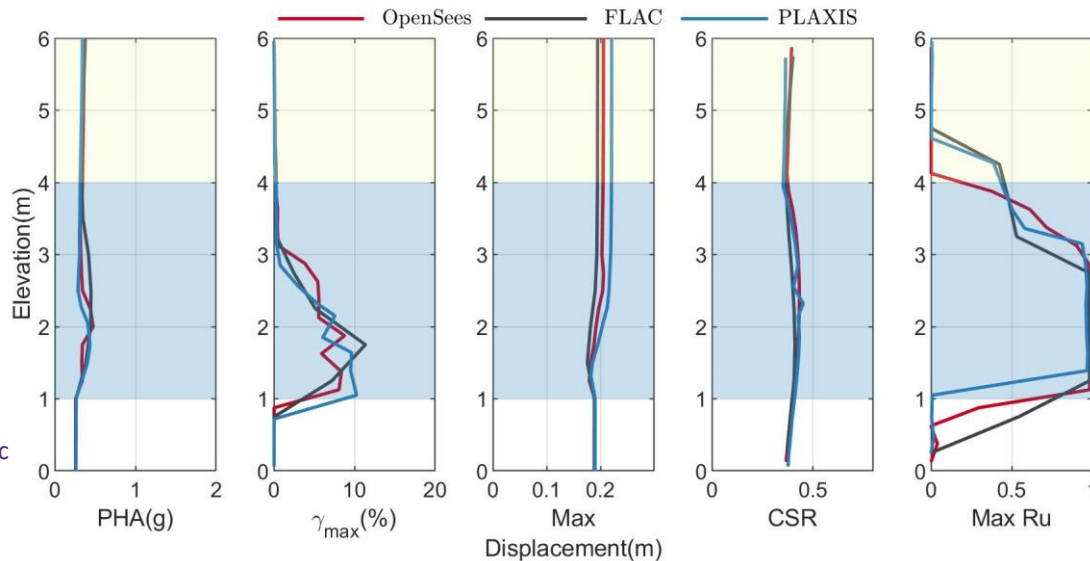
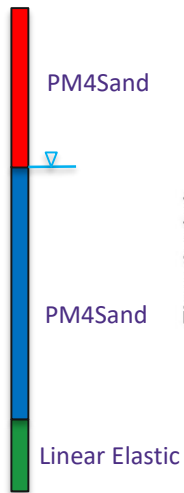
Acceleration response at surface



N10_T3



Input Motion



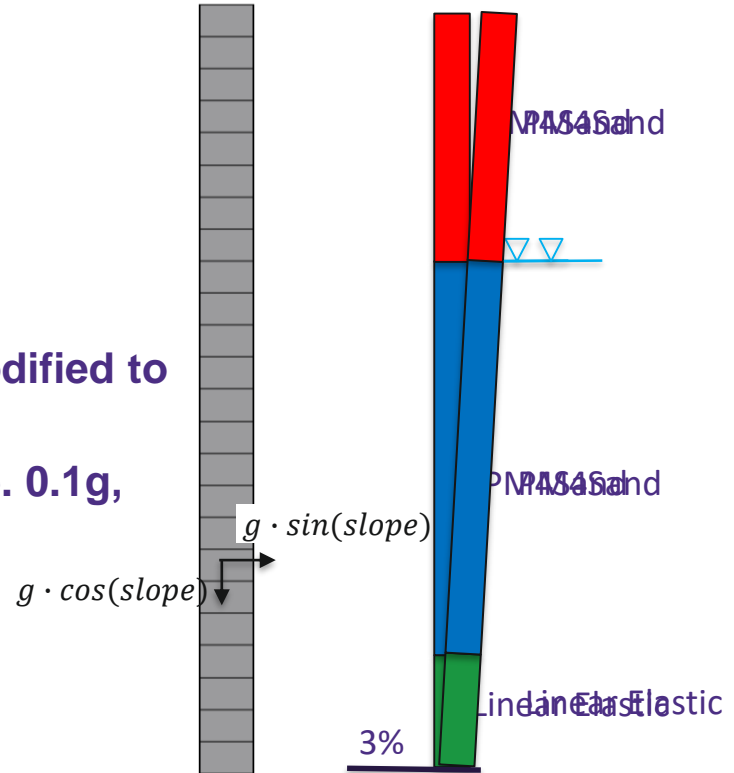
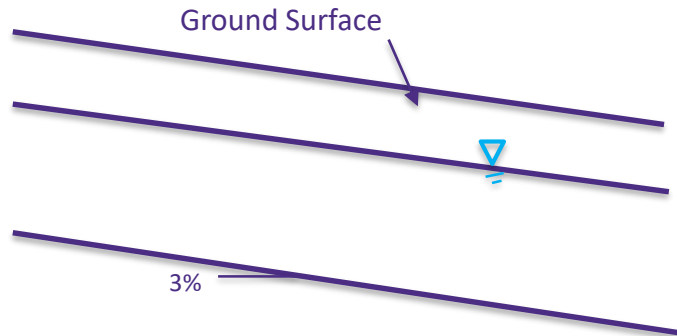
Acceleration response at surface



Validation: 1D analysis

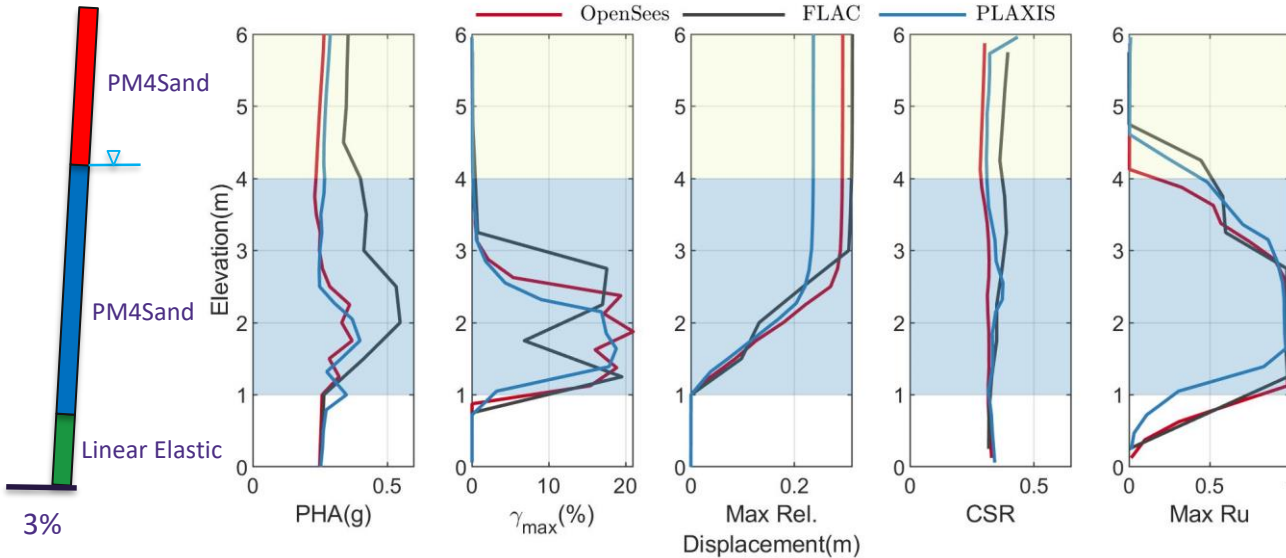
Sloping ground

- > 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.

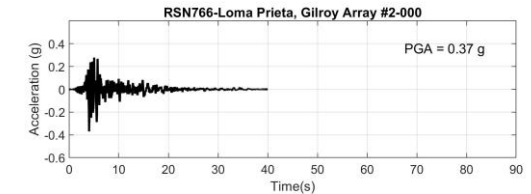


Validation: 1D analysis

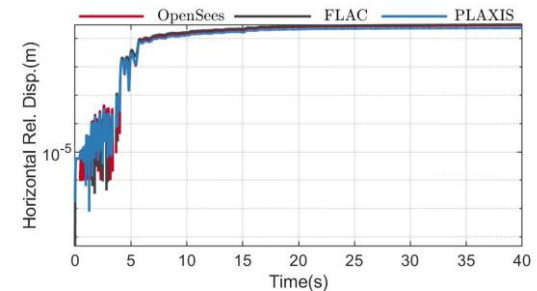
Sloping ground



Comparison of PGA, max shear strain, max horizontal displacement, cyclic stress ratio and maximum excess pore pressure ratio profile between OpenSees and Flac(Gilroy02 scaled to 0.3g).



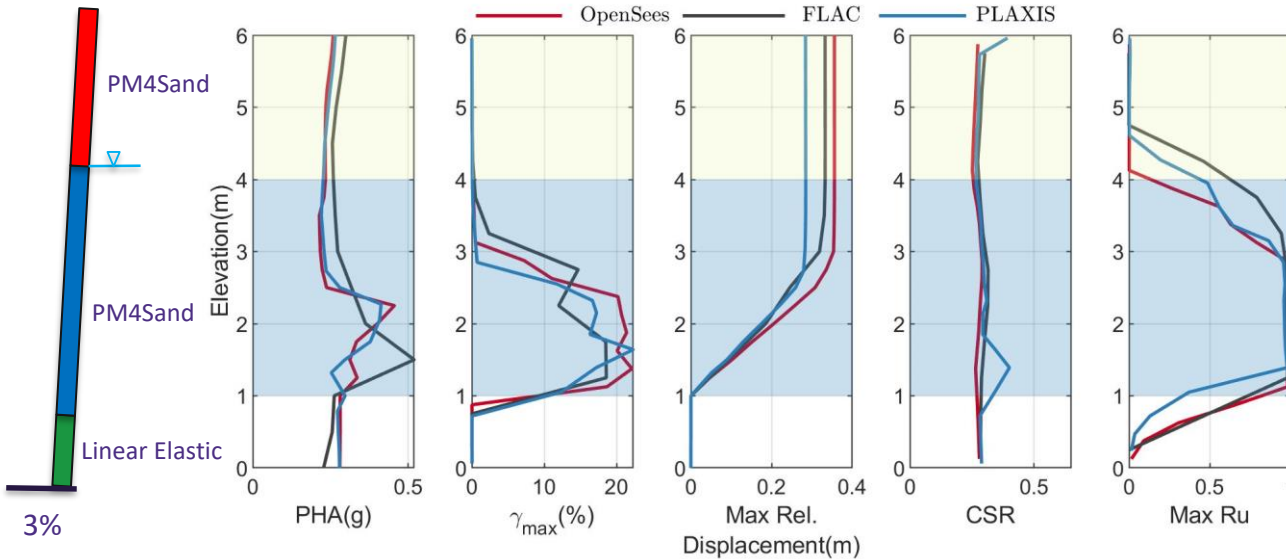
Input Motion



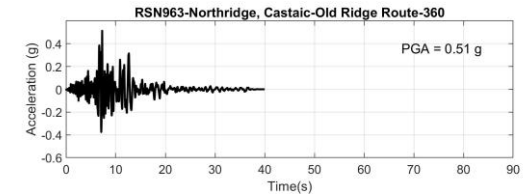
Comparison of lateral displacement at surface



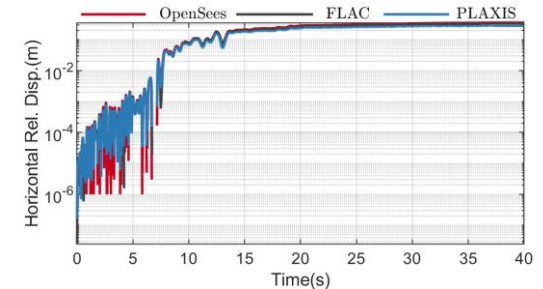
Validation: 1D analysis Sloping ground



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

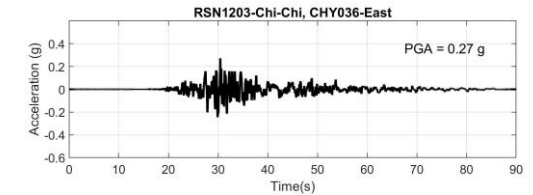
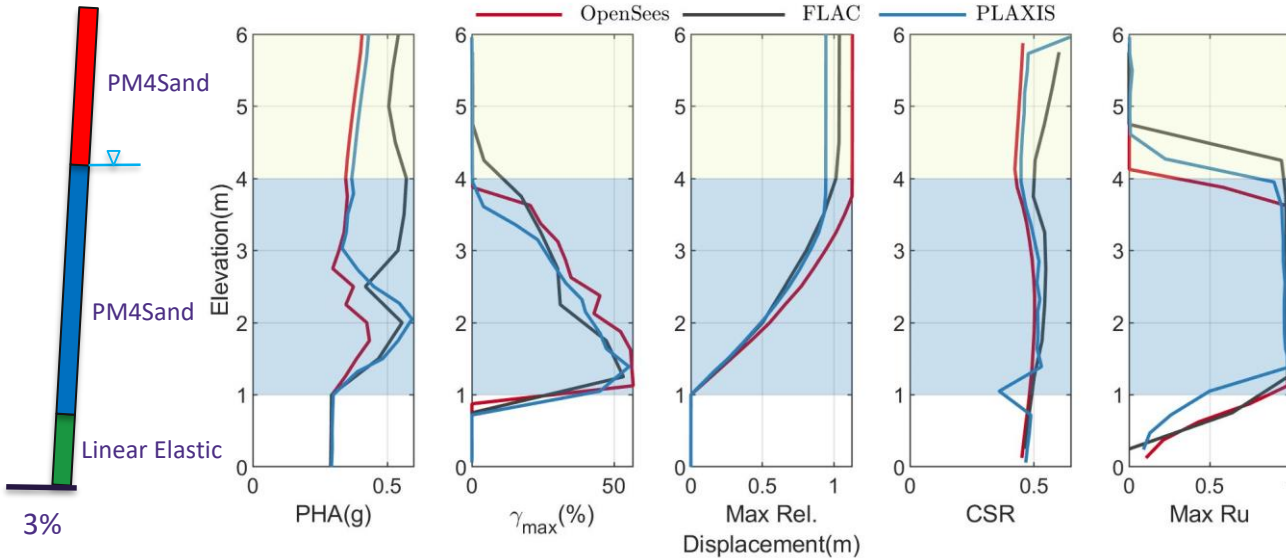


Comparison of lateral displacement at surface

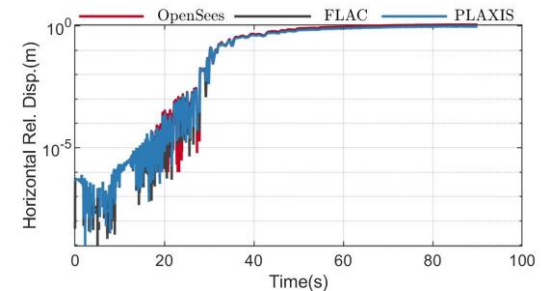


Validation: 1D analysis

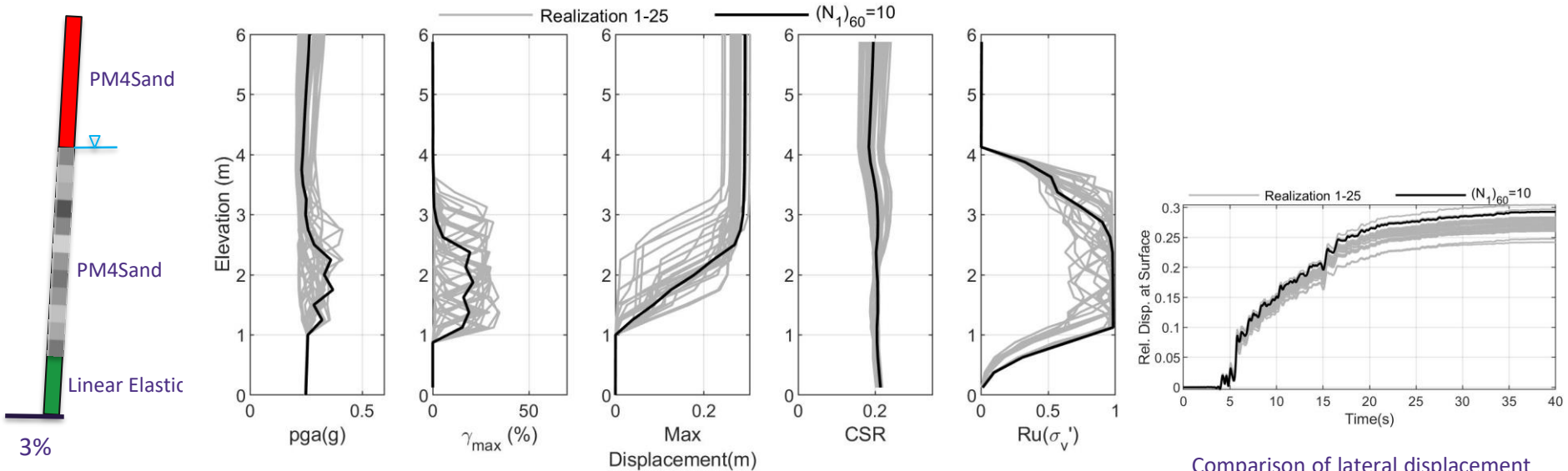
Sloping ground



Input Motion



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



Verification: 1D Analysis

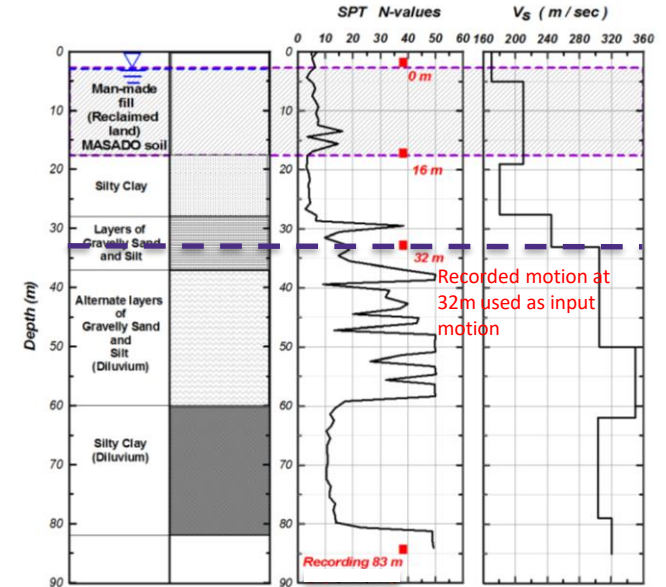
Port Island array

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))

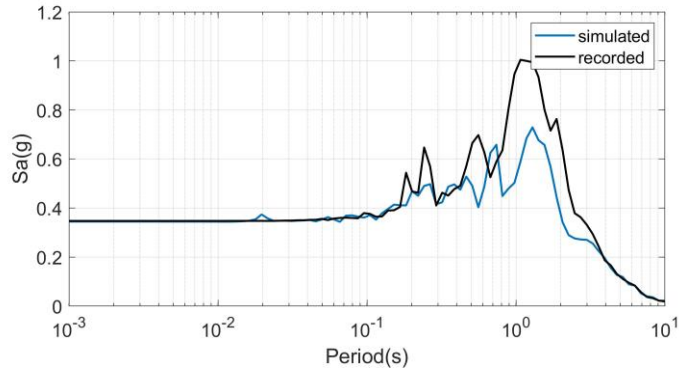
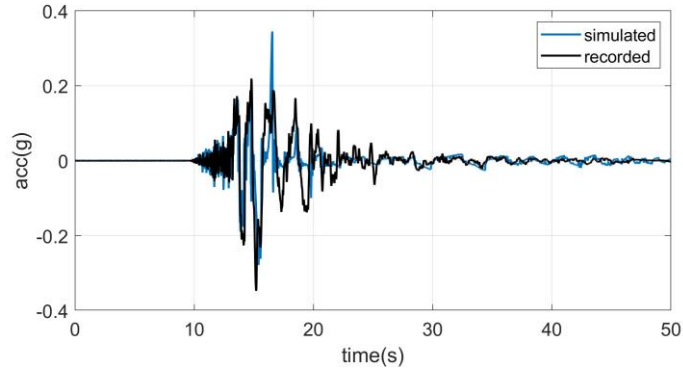
Depth(m)	Material Model	Primary Parameters		
		Dr	G0	hpo
0-3	PM4Sand	0.47	729.0	0.7
3-5	PM4Sand	0.47	729.0	0.7
5-14	PM4Sand	0.39	695.51	0.8
14-17.5	PM4Sand	0.47	507.53	0.9
		Su_rate	G0	hpo
17.5-26.5	PM4Silt	0.25	588.0	20.0
26.5-32	PM4Silt	0.75	1076.0	50.0

* All secondary input parameters are kept as default values

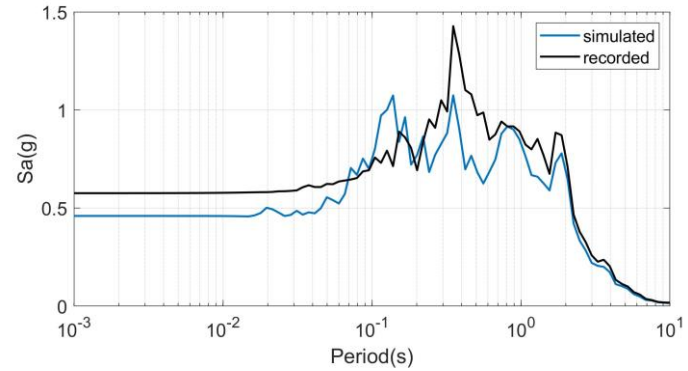
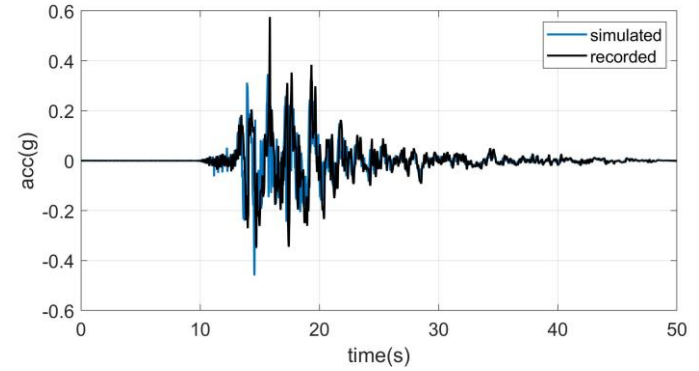


Soil profile at the Port Island site showing SPT N-values, shear wave velocities(from Ziotopoulou(2012))





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



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

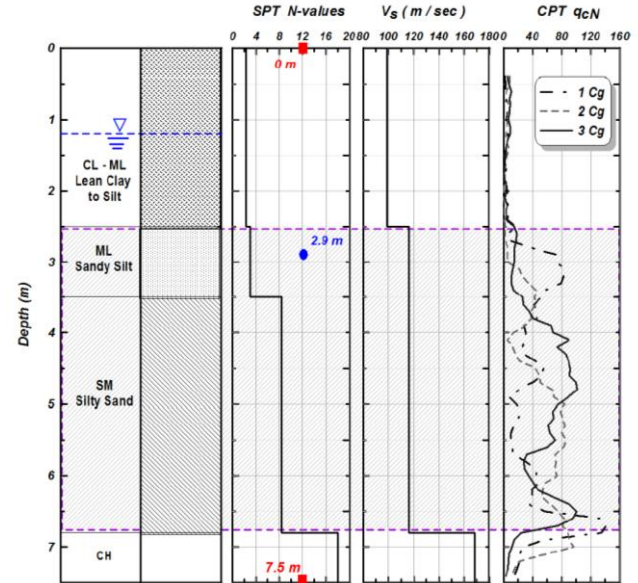


Verification: 1D analysis

WildLife Array

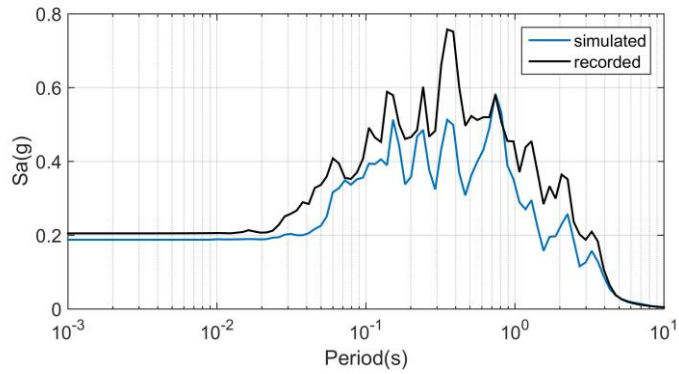
Wildlife Liquefaction array(WLA) during 1987 Superstition Hills earthquake is simulated using OpenSees. Nonliquefiable layers are modeled using PressureIndependentMultiYield material and the material properties are adopted from Sideras(2011). Liquefiable layers are modeled using PM4Sand material. PM4Sand 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

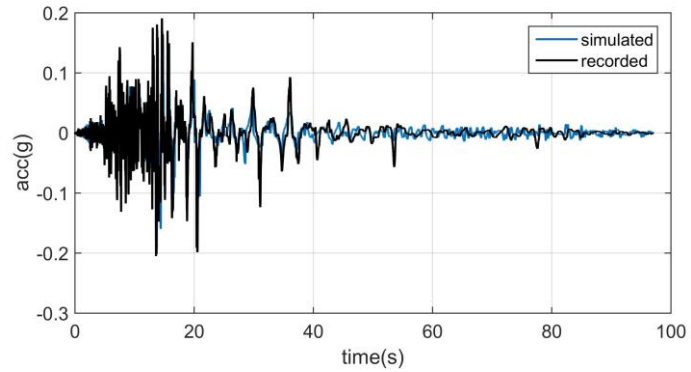


Soil profile at the WildLife site showing SPT N-values, shear wave velocities(from Ziotopoulou(2012))



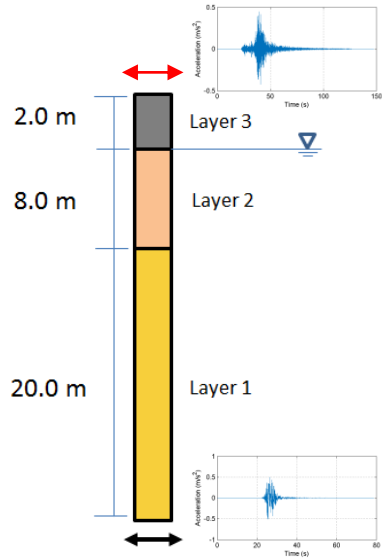


Comparison of recorded and simulated acceleration response spectra at surface



Comparison of recorded and simulated acceleration time history at surface

Resources: DesignSafe Jupyter notebooks



Workflow:

- Run OpenSees
- Postprocess results
- Create report
- Explore use of interactive plots

The screenshot displays a Jupyter notebook titled "Free Field Analysis Example" within the DesignSafe environment. The notebook is written in Python 2 and includes the following sections:

- Free Field Analysis Example**: A text block explaining the workflow for running OpenSees in DesignSafe, including postprocessing results using Python scripts, generating a LaTeX report, and creating interactive plots.
- Setup agave and start OpenSees job**: A code block showing the setup of the Agave environment and the execution of the OpenSees job. The code includes:

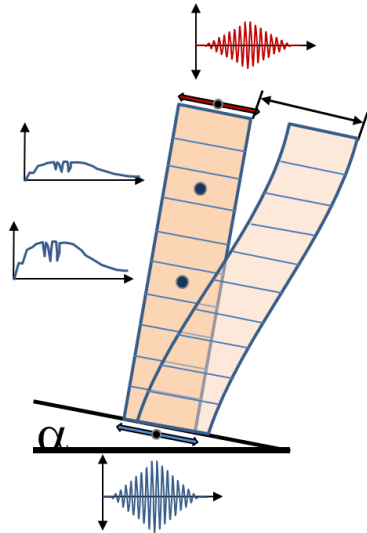

```
from agavepy.agave import Agave
ag = Agave.restore()
app_id = 'opensees-docker-2.5.0.6248ul0'
app = ag.apps.get(appId=app_id)
job_desc = {
    "job": "opensees",
    "exe": "opensees",
    "bat": "opensees.bat",
    "nod": "opensees.nod",
    "proc": "opensees.proc",
    "mem": "opensees.mem",
    "max": "opensees.max",
    "arc": "opensees.arc",
    "ret": "opensees.ret",
    "inp": "opensees.inp",
    "par": "opensees.par",
    "n1": "opensees.n1",
}
job = ag
from agavepy.agave import Agave
asrp = A
asrp.res
Out[9]: 'FINISHE'
```
- Create Interactive Plots**: A code block showing the creation of interactive plots. The code includes:


```
interactive(displot, timeStep = widgets.FloatSlider(min = 0.01, max = time[-1], step = 0.01))
```

The notebook also displays two plots:

- Displacement**: A plot showing Displacement (m) vs Time (s). The y-axis ranges from 0 to 30, and the x-axis ranges from 0 to 60. The plot shows a sharp peak around 20 seconds.
- Acceleration**: A plot showing Acceleration (m/s^2) vs Time (s). The y-axis ranges from -1 to 1, and the x-axis ranges from 0 to 60. The plot shows a sharp peak around 20 seconds.

Resources: SimCenter Site Response App



Site Response Tool

Soil Layers

Analysis

Height GWT Total Layers

LayerName	Thickness	Density	Vs	Material	Color
Layer 1	2	1.61	182	PM4Sand	#4e687e
Layer 2	3	2.0	180	PM4Sand	#4ca9b2
Layer 3	1	2	182	Elastic	#5adfd7
Rock	-	2	760	Elastic	#4228e5

Configure Layer properties Ground motion

PM4Sand

Dr G0 hpo Den Element size (Vertical)

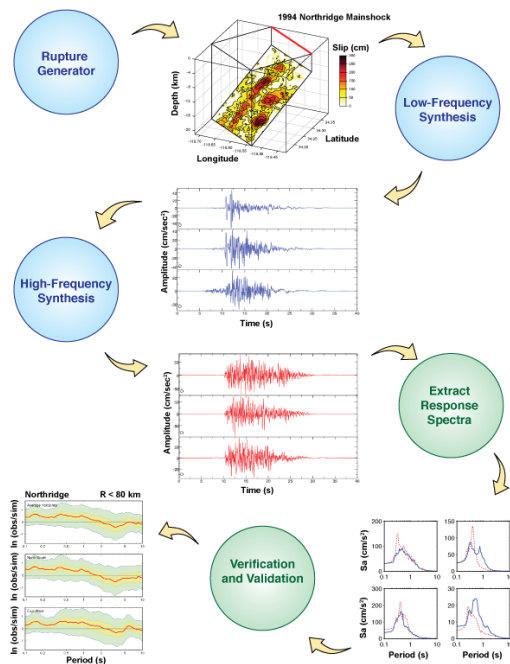
P_atm h0 emax emin nb nd

Ado z_max cz ce phic nu

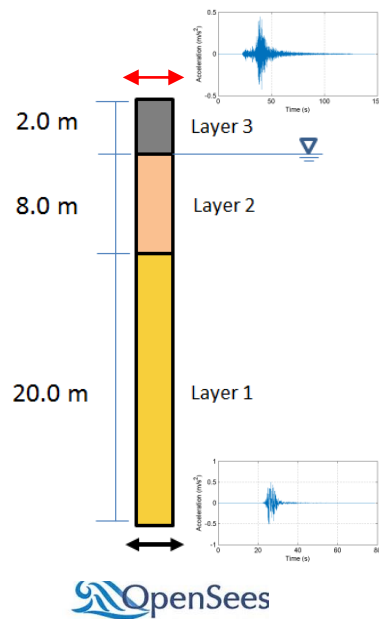
cgd cdr ckaf Q R m

Fsed_min p_sedo hPerm vPerm ubulk

Broad Band Platform Site Response module



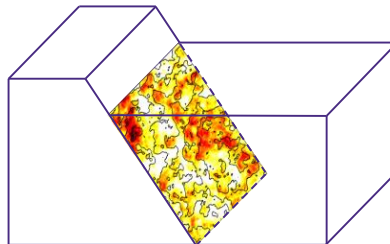
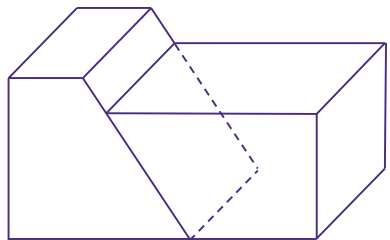
+



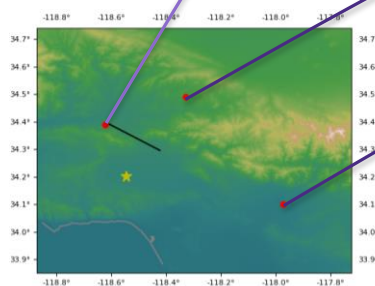
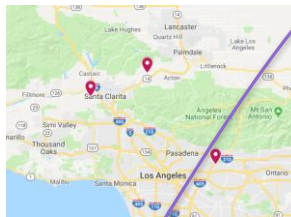
Broad Band Platform Site Response module

SC/EC
AN NSF+USGS CENTER

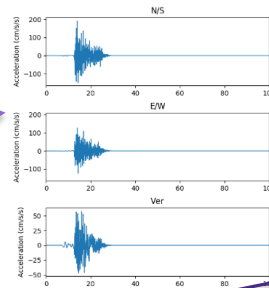
.src file



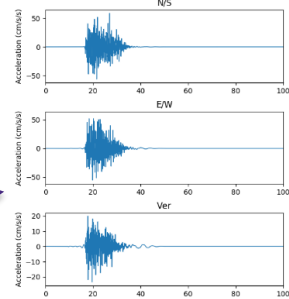
.stl file



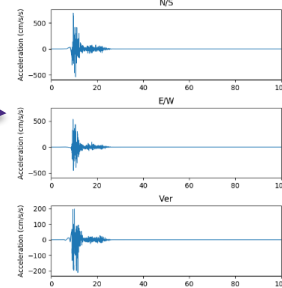
Seismograms for run 6085424, station vasq



Seismograms for run 6085424, station balp

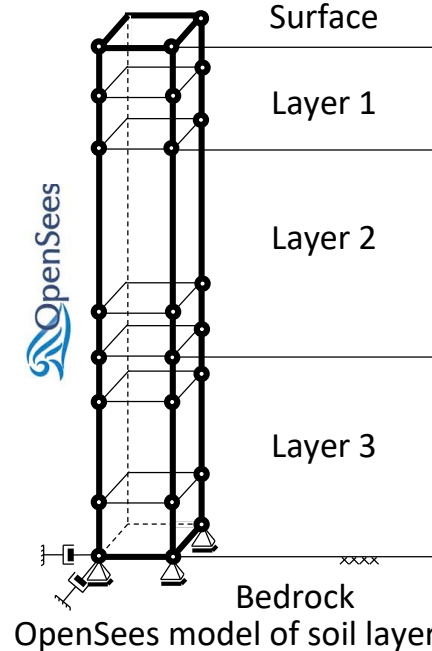
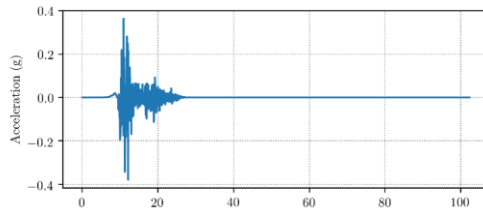
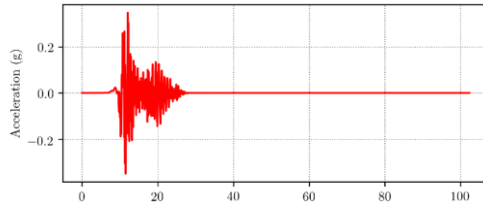


Seismograms for run 6085424, station nwhp

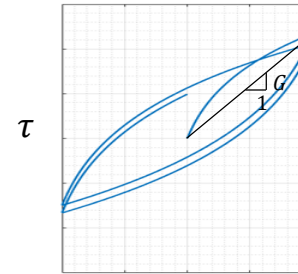


Broad Band Platform Site Response module

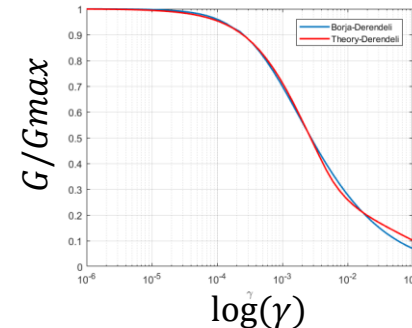
SC/EC
AN NSF+USGS CENTER



Nonlinear soil response

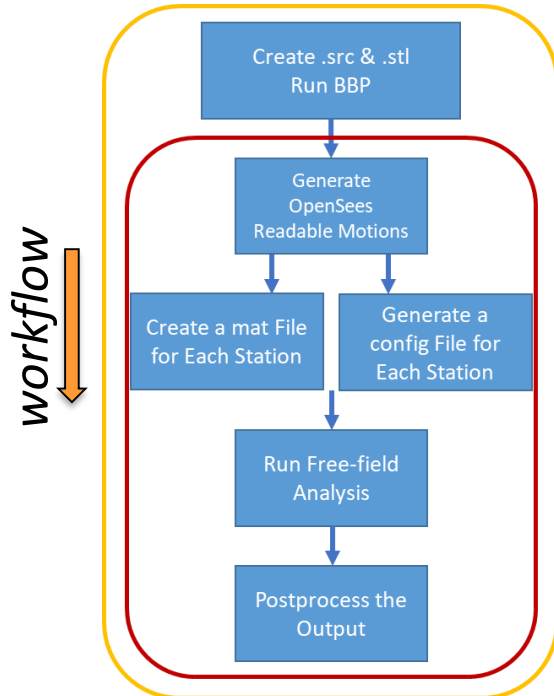


Model parameters related to
laboratory evidence

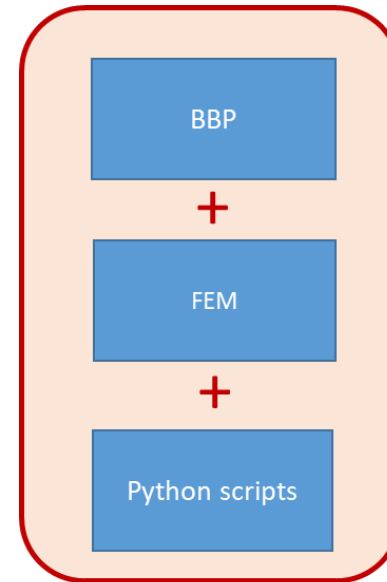


Broad Band Platform Site Response module

Bash file



Updated BBP





Thanks

