# Chapter 5

# Nonlinear Analysis Steps

## 5.1 Free Field 1D

**Elastic Material** The Real-ESSI input files for elastic example are available HERE. The compressed package of input files is HERE.

The Modeling parameters are listed.

- Elastic Material Properties
  - Mass Density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1

**Elastoplastic Material** The Real-ESSI input files for elastoplastic material example are available HERE. The compressed package of input files is HERE.

The Modeling parameters are listed.

- von-Mises nonlinear hardening material model
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1
  - von Mises radius, $k$, 60 kPa
  - nonlinear kinematic hardening rate, $H_a$, 30 MPa
  - nonlinear kinematic hardening rate, $C_r$, 25
  - isotropic hardening rate, $K_{iso}$, 0 Pa

Figure 5.1: Simulation Model

The illustration results of the simulation is shown in Fig. 5.1. As shown in the results, outside the DRM layer, there is no outgoing waves.

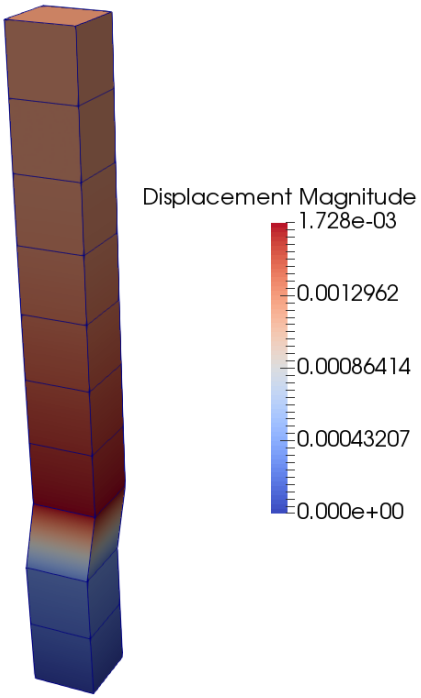


Figure 5.2: Simulation Model

The time series of simulation results is shown in Fig. 5.3.

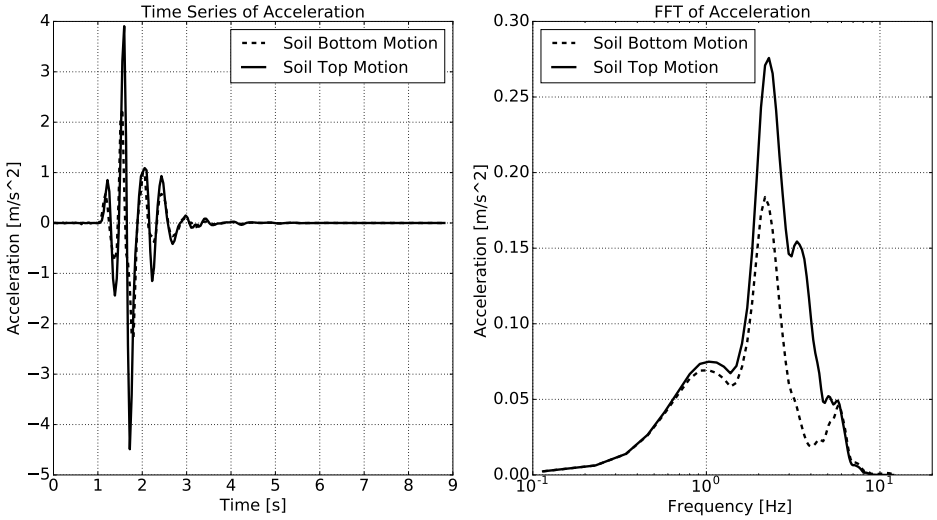


Figure 5.3: Simulation Results: Acceleration Time Series

The response spectrum of motion is shown in Fig. 5.4.

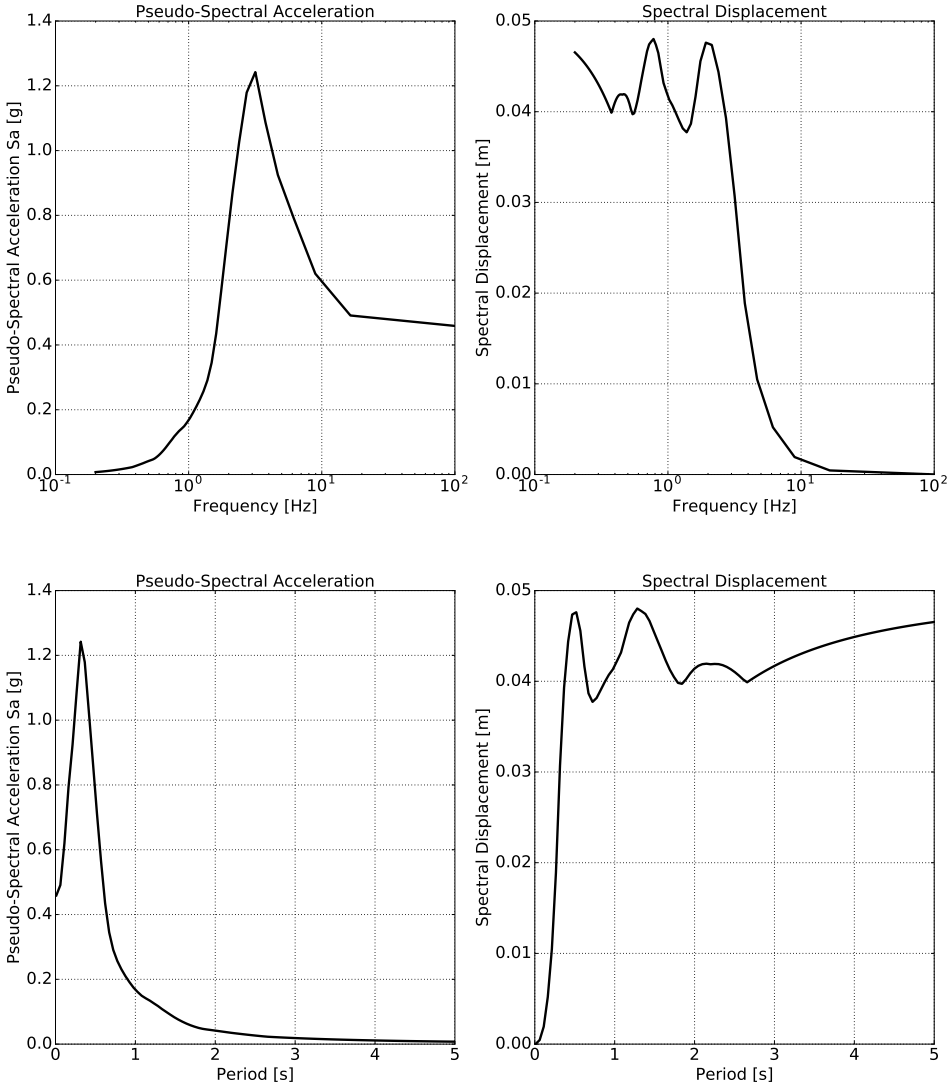


Figure 5.4: Simulation Results: Response Spectrum at Soil Top

## 5.2 Free Field 3D

**Elastic Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- Elastic Material Properties
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 5 minutes.

**von-Mises Armstrong-Frederick Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- von-Mises nonlinear hardening material model
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1
  - von Mises radius, $k$, 60 kPa
  - nonlinear kinematic hardening rate, $H_a$, 30 MPa
  - nonlinear kinematic hardening rate, $C_r$, 25
  - isotropic hardening rate, $K_{iso}$, 0 Pa

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 17 minutes.

**von-Mises G/Gmax Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- von-Mises G/Gmax material model
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1
  - Total number of shear modulus 9
  - G over Gmax, 1,0.995,0.966,0.873,0.787,0.467,0.320,0.109,0.063
  - Shear strain gamma, 0,1E-6,1E-5,5E-5,1E-4, 0.0005, 0.001, 0.005, 0.01

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 565 minutes.

**Drucker-Prager G/Gmax Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- Drucker-Prager G/Gmax material model
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1
  - Initial confining stress, $p_0$, 100 kPa
  - Reference pressure, $p_{refer}$, 100 kPa
  - Pressure exponential, $n$, 0.5
  - Cohesion, $n$, 1 kPa
  - Total number of Shear Modulus 9
  - G over Gmax, 1,0.995,0.966,0.873,0.787,0.467,0.320,0.109,0.063
  - Shear strain gamma, 0,1E-6,1E-5,5E-5,1E-4, 0.0005, 0.001, 0.005, 0.01

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 565 minutes.

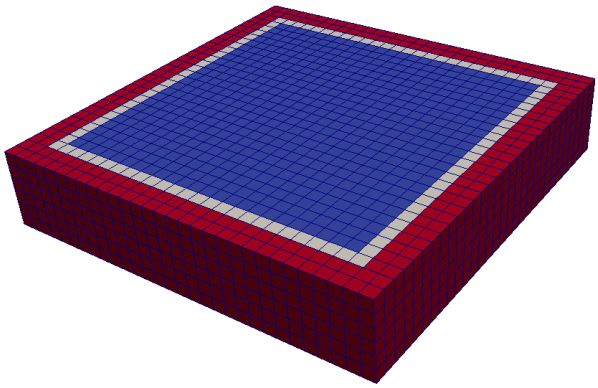

Figure 5.5: Simulation Model

The illustration results of the simulation is shown in Fig. 3.12. As shown in the results, outside the DRM layer, there is no outgoing waves.

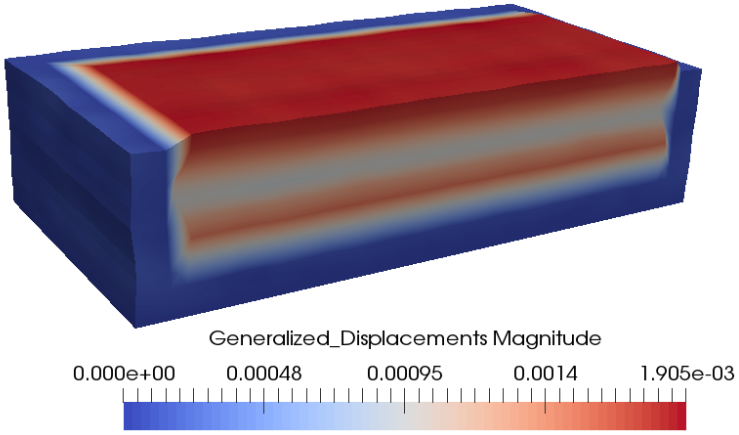


Figure 5.6: Simulation Model

The node tags of critical points for postprocessing are shown in Fig.5.12.

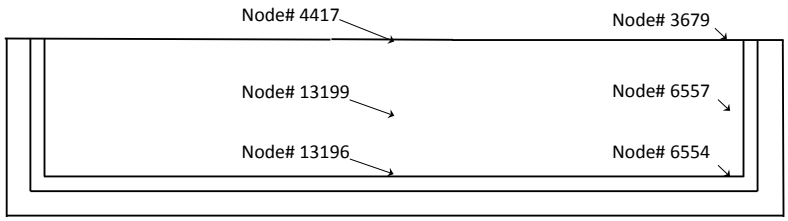


Figure 5.7: Critical Points of Simulation Model

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 871 minutes.

The time series of simulation results is shown in Fig. 5.8.

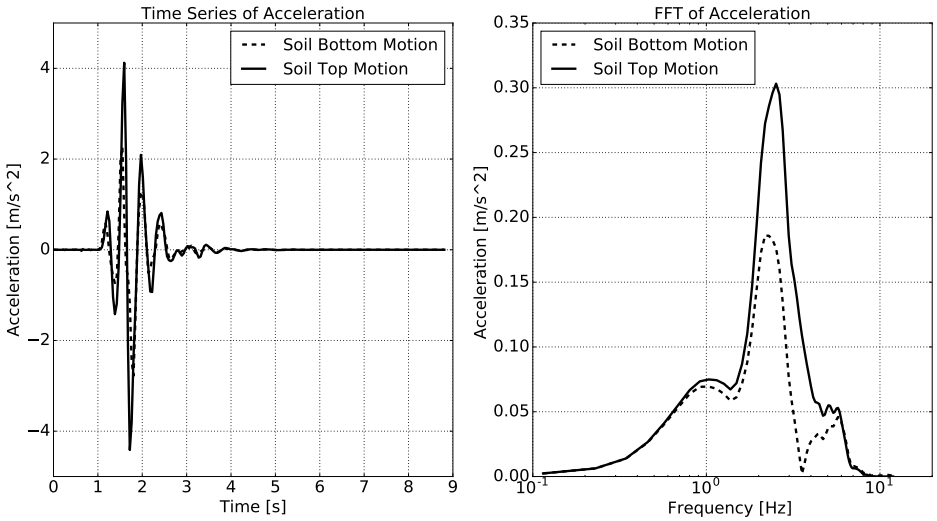


Figure 5.8: Simulation Results: Acceleration Time Series

The response spectrum of motion is shown in Fig. 5.9.

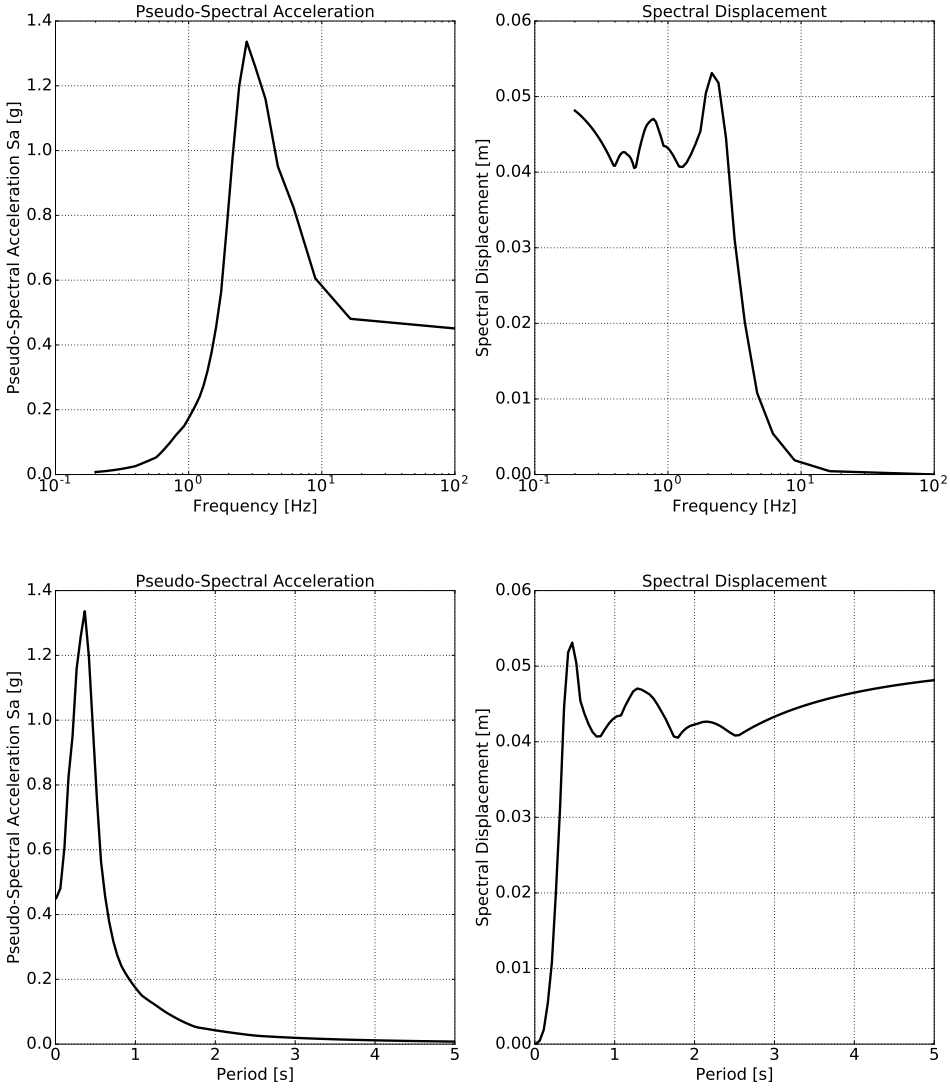


Figure 5.9: Simulation Results: Response Spectrum at Soil Top

## 5.3 Soil-Foundation Interaction 3D

**Elastic Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- Elastic Material Properties
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 13 minutes.

**von-Mises Armstrong-Frederick Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- von-Mises nonlinear hardening material model
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1
  - von Mises radius, $k$, 60 kPa
  - nonlinear kinematic hardening rate, $H_a$, 30 MPa
  - nonlinear kinematic hardening rate, $C_r$, 25
  - isotropic hardening rate, $K_{iso}$, 0 Pa

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 36 minutes.

**von-Mises G/Gmax Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- von-Mises G/Gmax material model
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1
  - Total number of shear modulus 9
  - G over Gmax, 1,0.995,0.966,0.873,0.787,0.467,0.320,0.109,0.063
  - Shear strain gamma, 0,1E-6,1E-5,5E-5,1E-4, 0.0005, 0.001, 0.005, 0.01

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 726 minutes.

**Drucker-Prager G/Gmax Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- Drucker-Prager G/Gmax material model
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1
  - Initial confining stress, $p_0$, 100 kPa
  - Reference pressure, $p_{refer}$, 100 kPa
  - Pressure exponential, $n$, 0.5
  - Cohesion, $n$, 1 kPa
  - Total number of Shear Modulus 9
  - G over Gmax, 1,0.995,0.966,0.873,0.787,0.467,0.320,0.109,0.063
  - Shear strain gamma, 0,1E-6,1E-5,5E-5,1E-4, 0.0005, 0.001, 0.005, 0.01

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 1252 minutes.

**Contact Elements** The compressed package of input files is HERE.
The Modeling parameters are listed.

- Elastic Material Properties
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 24 minutes.

**Both Elastoplastic Material and Contact Elements** The compressed package of input files is HERE.
SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 41 minutes.

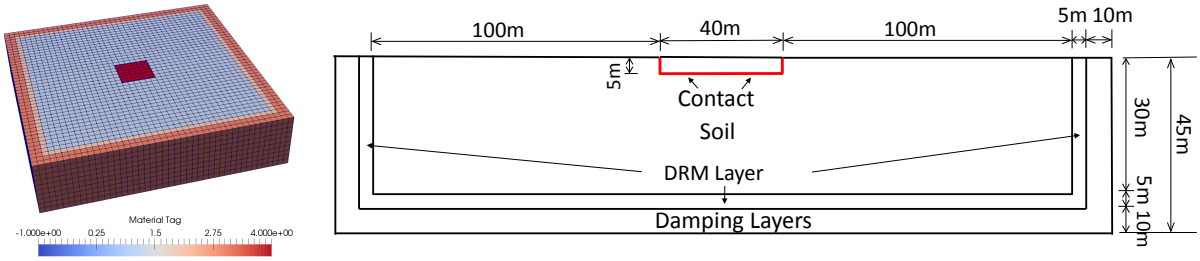


Figure 5.10: Simulation Model

The illustration results of the simulation is shown in Fig. 5.14. As shown in the results, outside the DRM layer, there is no outgoing waves.

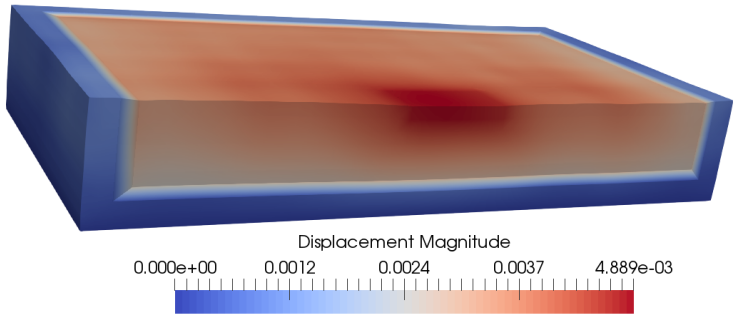


Figure 5.11: Soil Foundation Interaction Results

The node tags of critical points for postprocessing are shown in Fig.5.12.

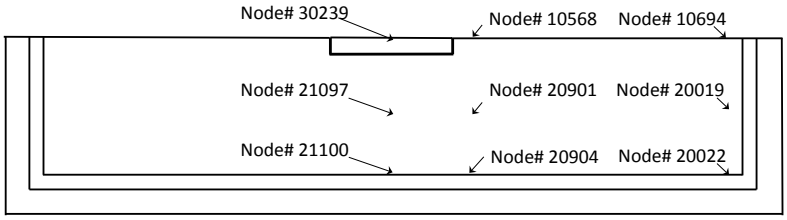


Figure 5.12: Critical Points of Simulation Model

## 5.4 Soil-Structure Interaction 3D

**Elastic Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- Elastic Material Properties
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 10 minutes.

**von-Mises Armstrong-Frederick Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- von-Mises nonlinear hardening material model
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1
  - von Mises radius, $k$, 60 kPa
  - nonlinear kinematic hardening rate, $H_a$, 30 MPa
  - nonlinear kinematic hardening rate, $C_r$, 25
  - isotropic hardening rate, $K_{iso}$, 0 Pa

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 46 minutes.

**von-Mises G/Gmax Material** The compressed package of input files is HERE.
The Modeling parameters are listed.

- von-Mises G/Gmax material model
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1
  - Total number of shear modulus 9
  - G over Gmax, 1,0.995,0.966,0.873,0.787,0.467,0.320,0.109,0.063
  - Shear strain gamma, 0,1E-6,1E-5,5E-5,1E-4, 0.0005, 0.001, 0.005, 0.01

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 755 minutes.

**Drucker-Prager G/Gmax Material** The compressed package of input files is HERE.

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 1178 minutes.

The Modeling parameters are listed.

- Drucker-Prager G/Gmax material model
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1
  - Initial confining stress, $p_0$, 100 kPa
  - Reference pressure, $p_{refer}$, 100 kPa
  - Pressure exponential, $n$, 0.5
  - Cohesion, $n$, 1 kPa
  - Total number of Shear Modulus 9
  - G over Gmax, 1,0.995,0.966,0.873,0.787,0.467,0.320,0.109,0.063
  - Shear strain gamma, 0,1E-6,1E-5,5E-5,1E-4, 0.0005, 0.001, 0.005, 0.01

**Contact Elements** The compressed package of input files is HERE.

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 15 minutes.

**Both Elastoplastic Material and Contact Elements** The compressed package of input files is HERE.

The thickness of the shell structure is 2 meters.

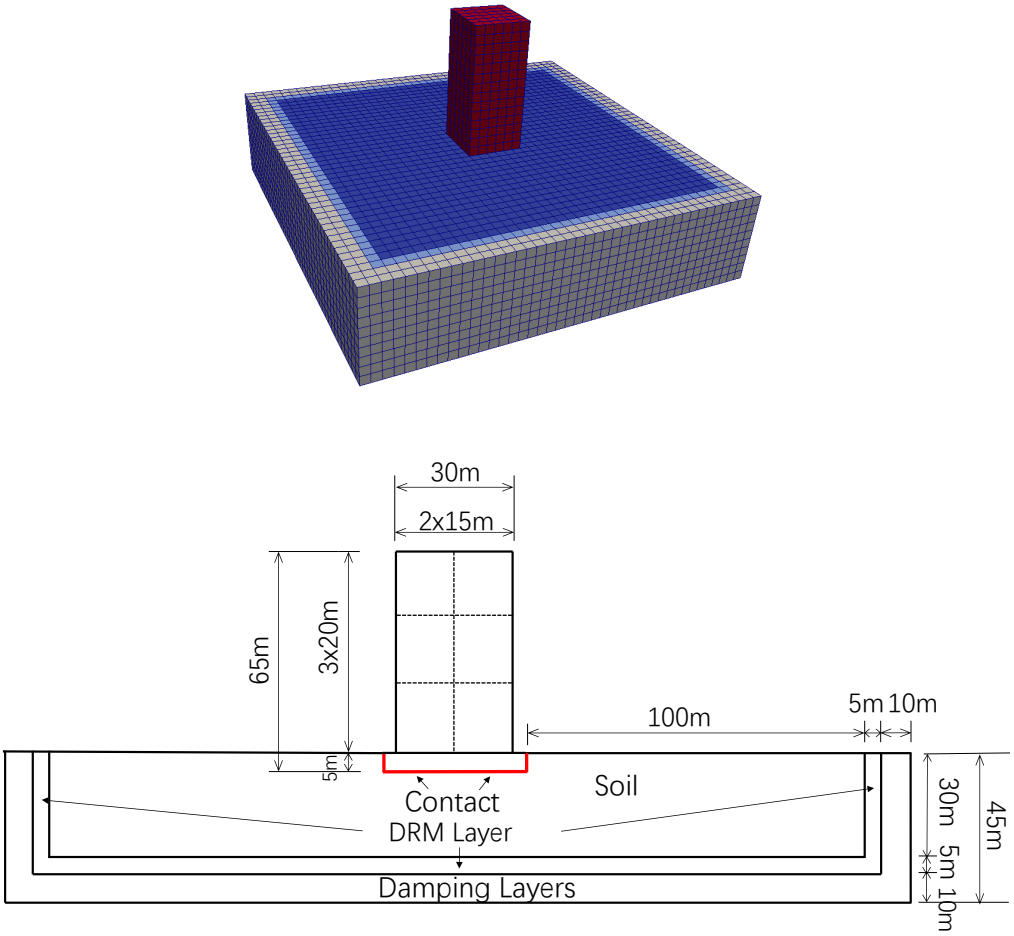


Figure 5.13: Simulation Model

The illustration results of the simulation is shown in Fig. 5.14. As shown in the results, outside the DRM layer, there is no outgoing waves.

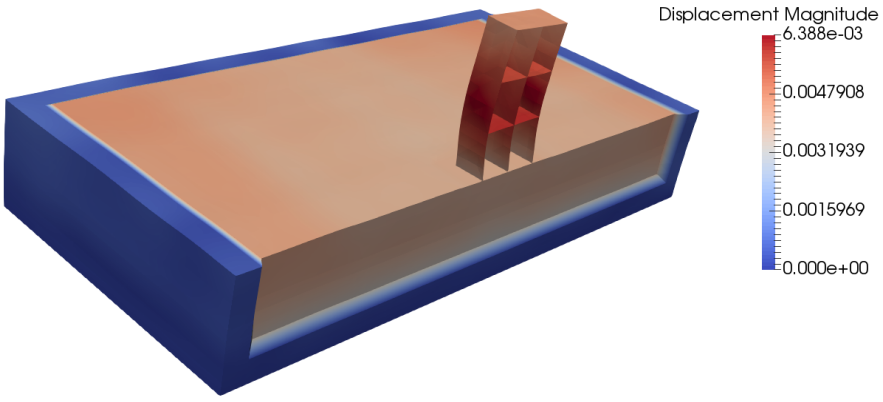


Figure 5.14: Simulation Model

The node tags of critical points for postprocessing are shown in Fig.5.15.

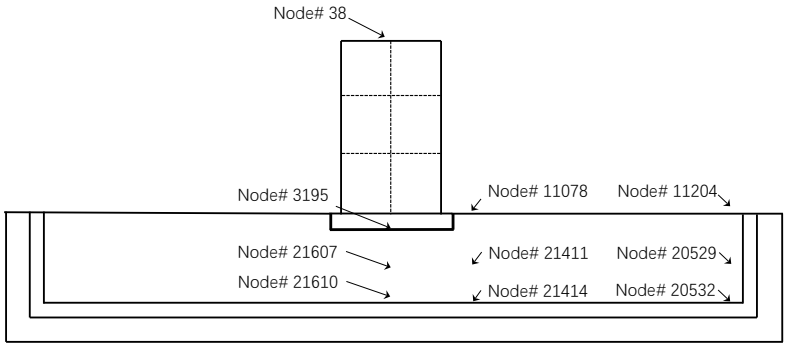


Figure 5.15: Critical Points of Simulation Model

SIMULATION TIME: With 8 cores on AWS EC2 c4.2xlarge instance, the running time for this example is 47 minutes.

**Simulation with 1D motion** The time series of simulation results is shown in Fig. 5.16.

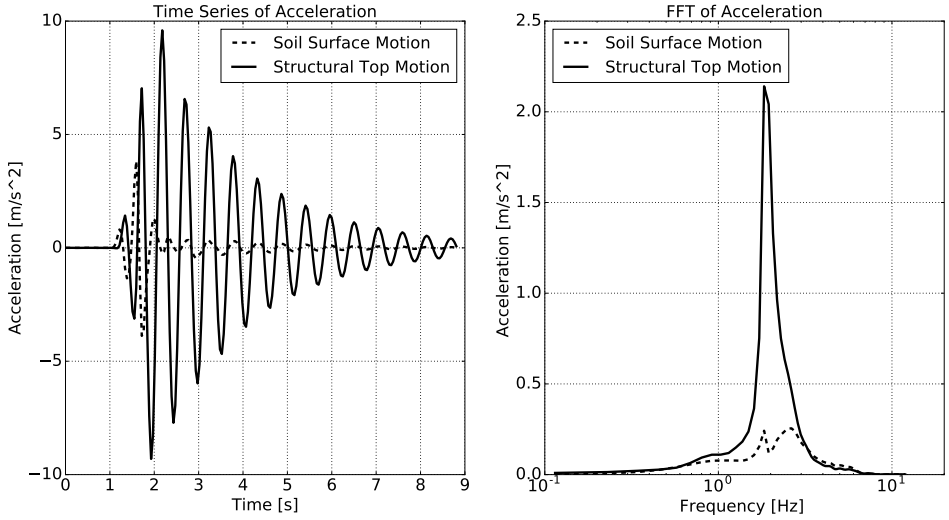


Figure 5.16: Simulation Results: Acceleration Time Series with 1D motion

The response spectrum of motion is shown in Fig. 5.17.

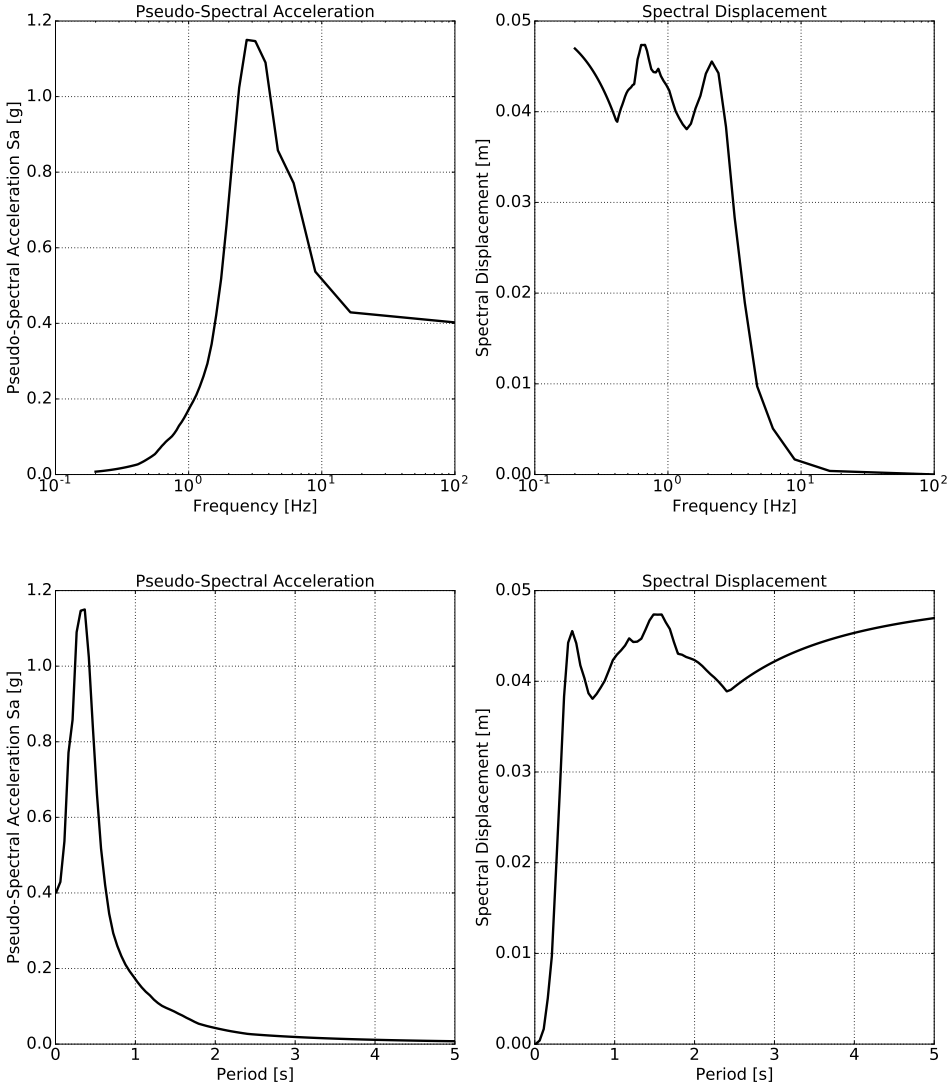


Figure 5.17: Simulation Results: Response Spectrum of Structure Top with 1D motion

**Simulation with 3 $\times$ 1D motion** The time series of simulation results is shown in Fig. 5.18.

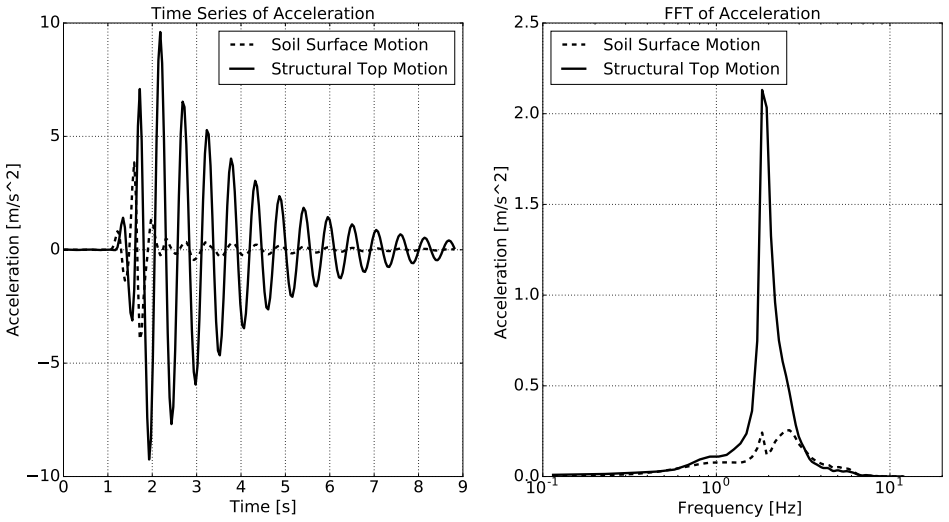


Figure 5.18: Simulation Results: Acceleration Time Series with 3D motion

The response spectrum of motion is shown in Fig. 5.19.

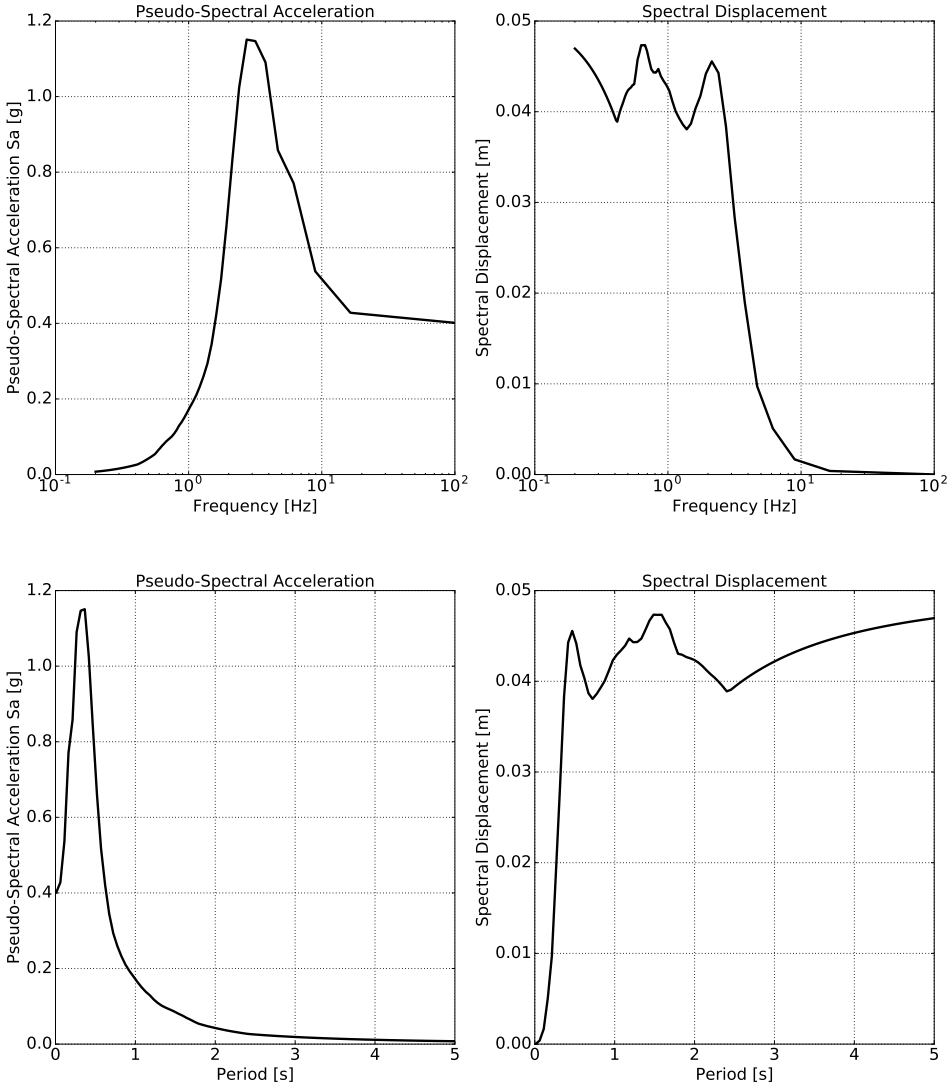


Figure 5.19: Simulation Results: Response Spectrum of Structure Top with 3D motion

## 5.5 Structure Analysis without Soil

### 5.5.1 Eigen Analysis

The Real-ESSI input files for this example are available HERE. The compressed package of input files is HERE.

The thickness of the shell structure is 2 meters. The simulation model is shown below.

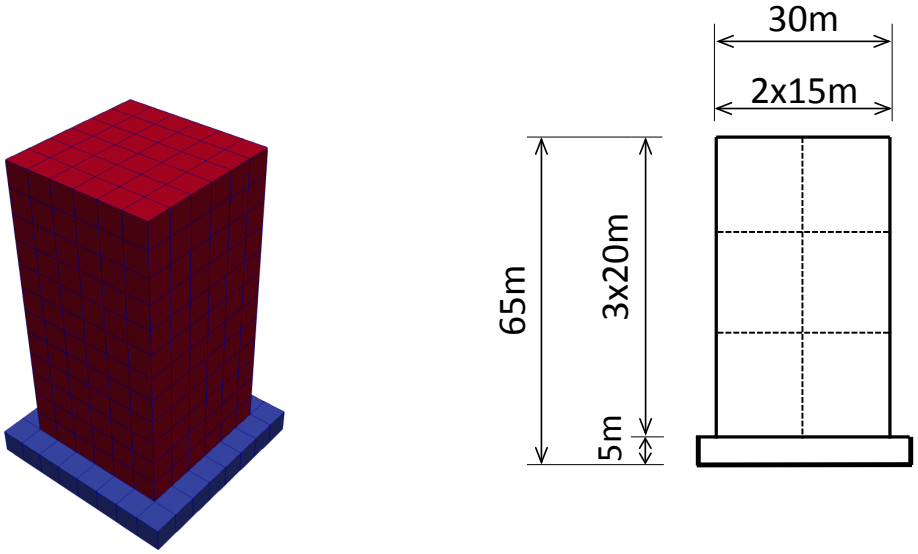


Figure 5.20: Simulation Model

The eigen results:

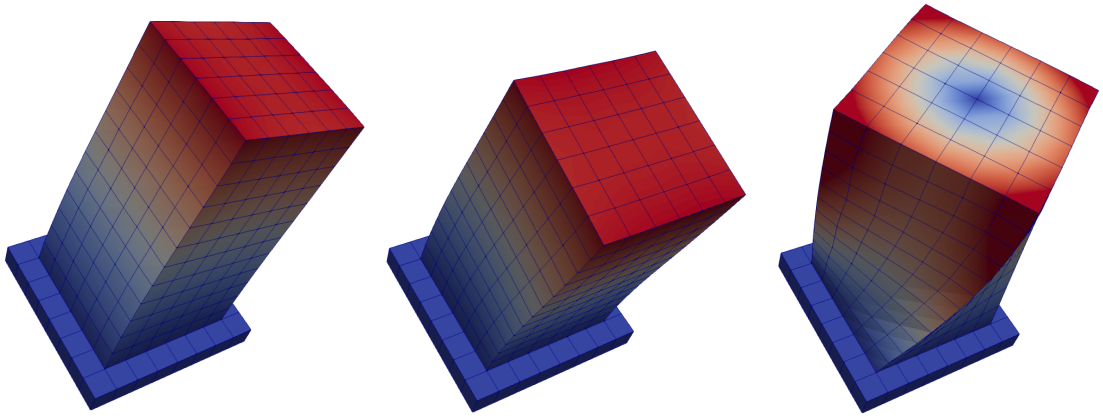

Figure 5.21: Eigen Results (Eigen Mode 1 to 3 from left to right)

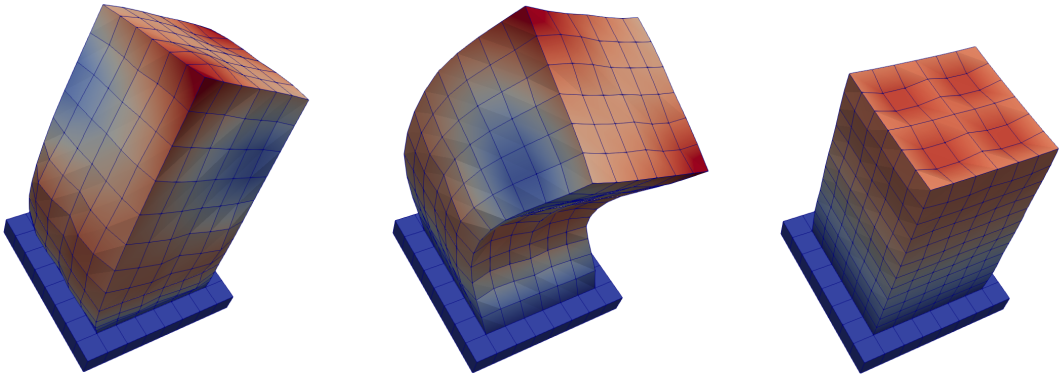

Figure 5.22: Eigen Results (Eigen Mode 4 to 6 from left to right)

### 5.5.2 Imposed Motion

The Real-ESSI input files for this example are available HERE. The compressed package of input files is HERE.

The Modeling parameters are listed.

- Elastic Material Properties
  - Mass density, $\rho$, 2000 $kg/m^3$
  - Young's modulus, $E$, 1.1 GPa
  - Poisson's ratio, $\nu$, 0.1

The thickness of the shell structure is 2 meters. The simulation model is shown below.

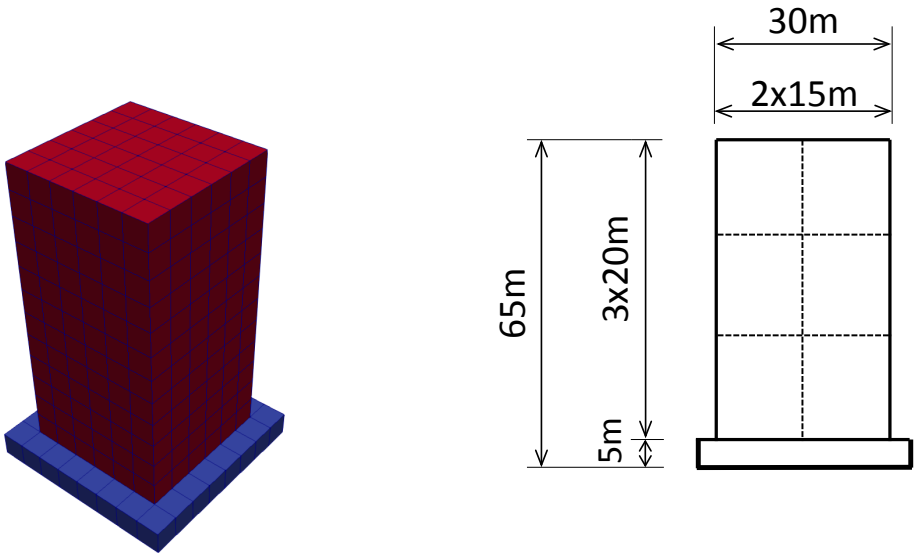


Figure 5.23: Simulation Model

The simulation results:

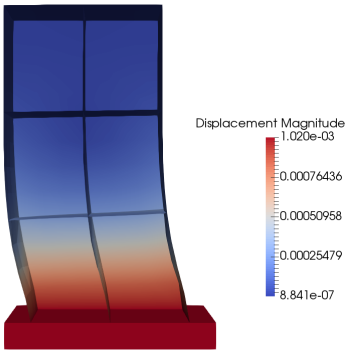


Figure 5.24: Simulation Results

The time series of simulation results is shown in Fig. 5.25.

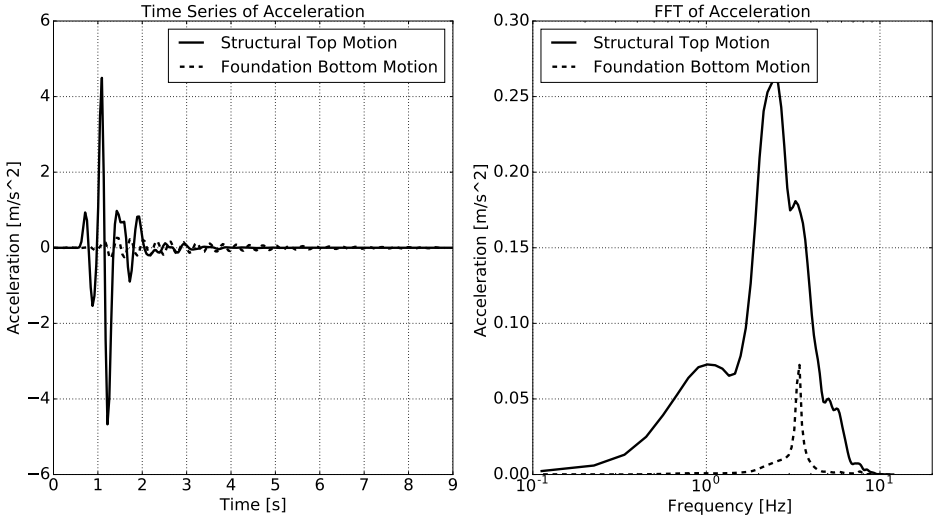


Figure 5.25: Simulation Results: Acceleration Time Series with 1D imposed motion

The response spectrum of motion is shown in Fig. 5.26.

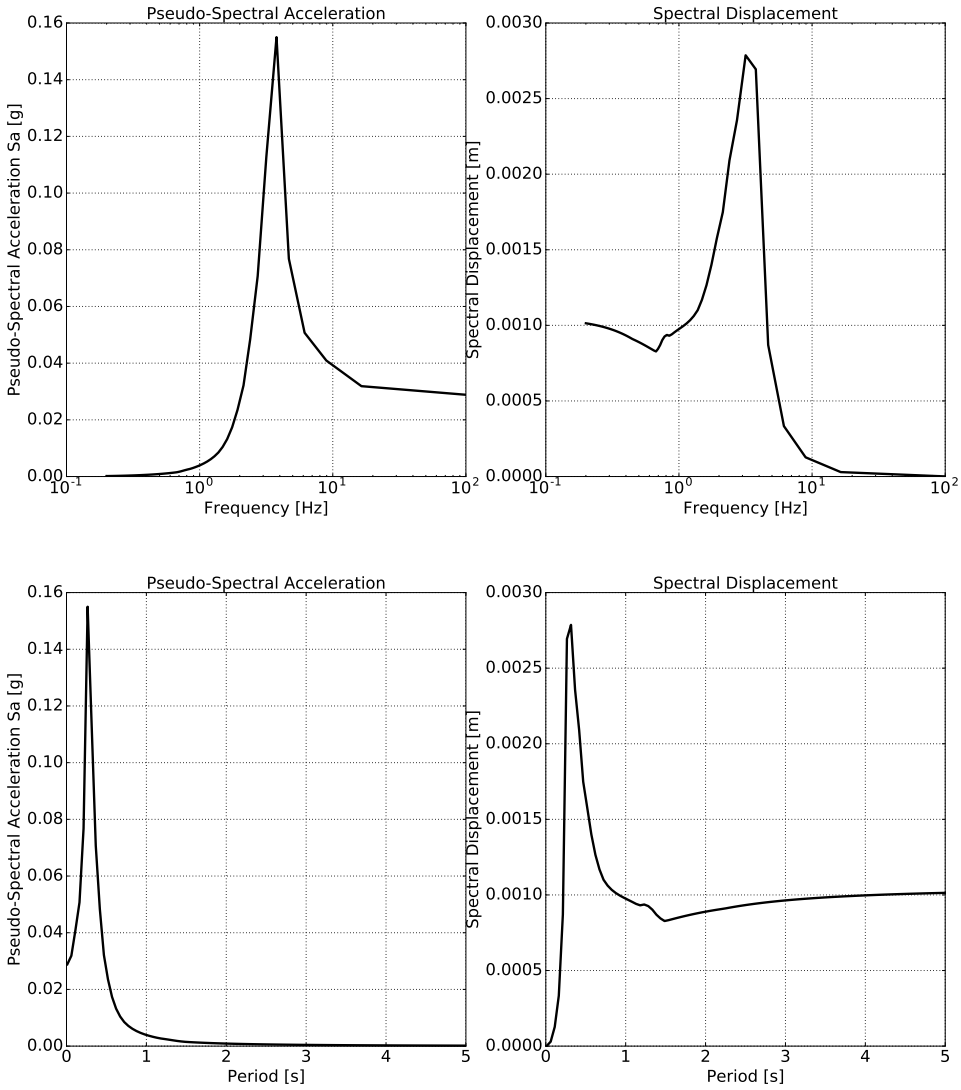


Figure 5.26: Simulation Results: Response Spectrum of Structure Top with 1D imposed motion