U.S. DEPARTMENT OF ENERGY

UNIVERSITY of HOUSTON

Periodic Material-Based Seismic Base Isolators for Small Modular Reactors

AMM Workshop
US Department of Energy
October 17 and 18, 2016

Research Team

Y. L. Mo – University of Houston

Yu Tang – Argonne National Laboratory

Robert Kassawara – Electric Power Research Institute

K. C. Chang – National Center for Research on Earthquake Engineering, Taiwan

Project Monitoring Team

Alison Hahn (Krager) (Project Manager)

Jack Lance (Technical POC)

Project overview

Objective:

To develop a periodic foundation that can completely obstruct or change the energy pattern of the earthquake before it reaches the structure of small modular reactors (SMR).

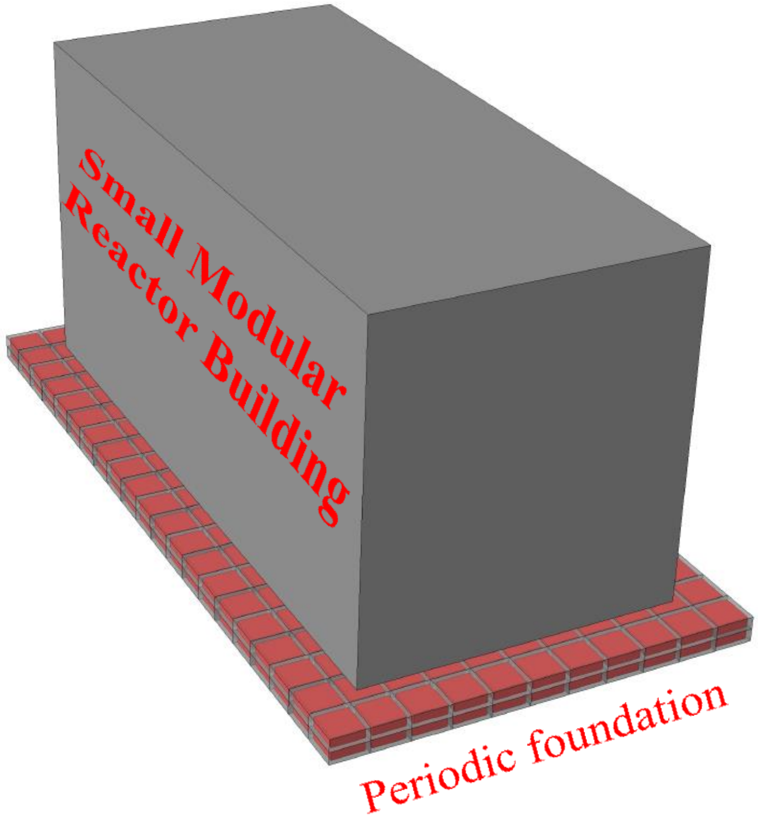
Scopes:

(1) Perform comprehensive, analytical study on periodic foundations.

(2) Design a SMR model with periodic foundations.

(3) Verify the effectiveness of periodic foundations through shake table tests.

(4) Perform finite element simulation of SMR supported by periodic foundations.

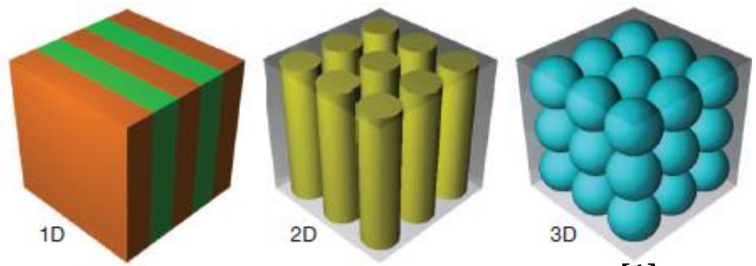


Project schedule

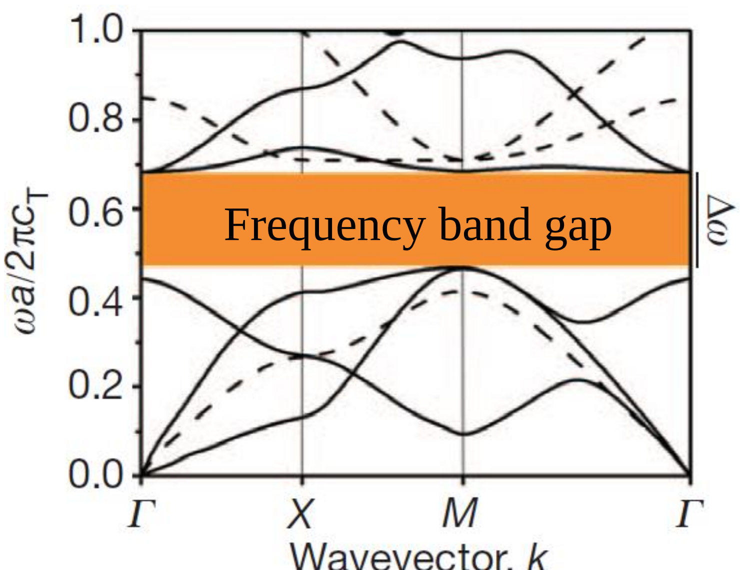
<table>
<tr><th rowspan="2">Task</th><th>2014</th><th colspan="4">2015</th><th colspan="4">2016</th><th colspan="3">2017</th></tr>
<tr><th>Oct-Dec</th><th>Jan-Mar</th><th>Apr-Jun</th><th>Jul-Sep</th><th>Oct-Dec</th><th>Jan-Mar</th><th>Apr-Jun</th><th>Jul-Sep</th><th>Oct-Dec</th><th>Jan-Mar</th><th>Apr-Jun</th><th>Jul-Sep</th></tr>
<tr><td>1</td><td colspan="3">Review of previous work and literature</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td></td><td colspan="4">Theoretical study on periodic foundations</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td></td><td></td><td colspan="5">Design of periodic foundations</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td></td><td></td><td></td><td></td><td colspan="7">Experimental study of periodic foundations</td><td></td></tr>
<tr><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="6">Experimental data analysis and numerical simulation of periodic foundations</td></tr>
<tr><td>6</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Preparation of final report</td></tr>
</table>

Basic concept

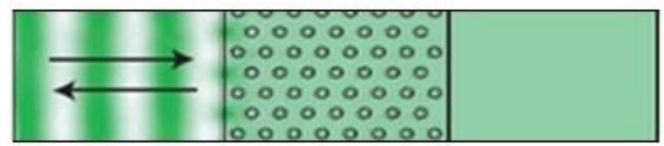
Phononic crystal is a novel composite developed in solid-state-physics



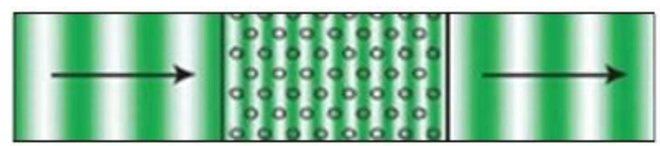
Types of phononic crystal [1]



Typical dispersion curve [1]



Wave propagation with frequency within the frequency band gap



Wave propagation with frequency outside of the frequency band gap

Wave Propagation [2]

[1] Maldovan, M. (2013). Sound and heat revolutions in phononics. *Nature*, *503*(7475), 209-217.
[2] Thomas, E. L., Gorishnyy, T., & Maldovan, M. (2006). Phononics: Colloidal crystals go hypersonic. *Nature materials*, *5*(10), 773-774.

Calculating dispersion curve

The governing equation of motion for a continuum body with isotropic elastic material

$$\rho(\mathbf{r})\frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla\left\{\left[\lambda(\mathbf{r})+2\mu(\mathbf{r})\right]\left(\nabla\cdot\mathbf{u}\right)\right\} - \nabla\times\left[\mu(\mathbf{r})\nabla\times\mathbf{u}\right] \qquad \text{Eq. 1}$$

Where: **r** is coordinate vector; $\rho(\mathbf{r})$ is the density

u(**r**) is displacement vector; λ(**r**) and μ(**r**) are the Lamé constant

The priodic boundary condition equation:

$$\mathbf{u}(\mathbf{r}+\mathbf{a},t) = e^{i\mathbf{K}\cdot\mathbf{a}}\mathbf{u}(\mathbf{r},t) \qquad \text{Eq. 2}$$

Where: **K** is the wave vector

a is unit cell size

Substituting Eq. 2 to the governing equation Eq.1, the wave equation can be transferred into a Eigen value problem as follow:

$$\left(\boldsymbol{\Omega}(\mathbf{K}) - \omega^2\mathbf{M}\right).\mathbf{u} = 0 \qquad \text{Eq. 3}$$

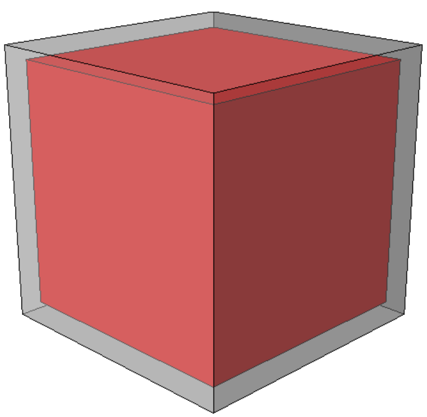
Calculating dispersion curve

Eigen value problem:

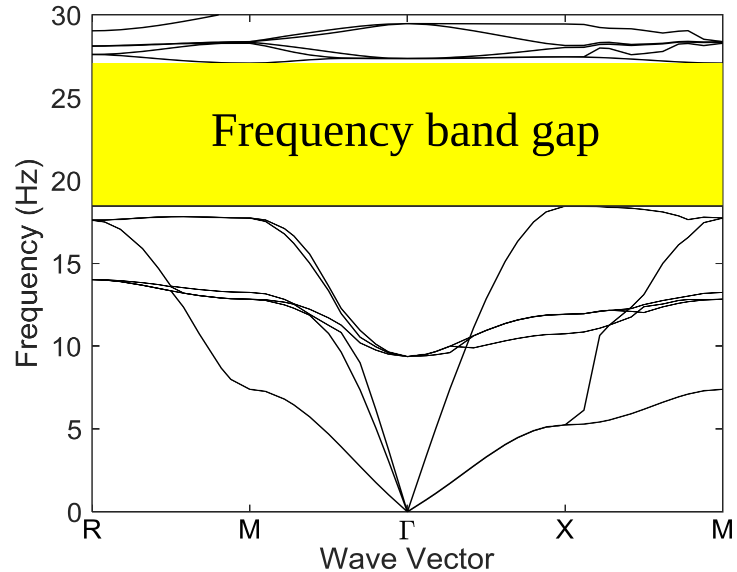
$$\left(\mathbf{\Omega}(\mathbf{K}) - \omega^2 \mathbf{M}\right).\mathbf{u} = 0$$

Where: $\mathbf{\Omega}$ is the stiffness matrix
$\mathbf{M}$ is the mass matrix

For each wave vector (**K**) a series of corresponding frequencies (ω) can be obtained.



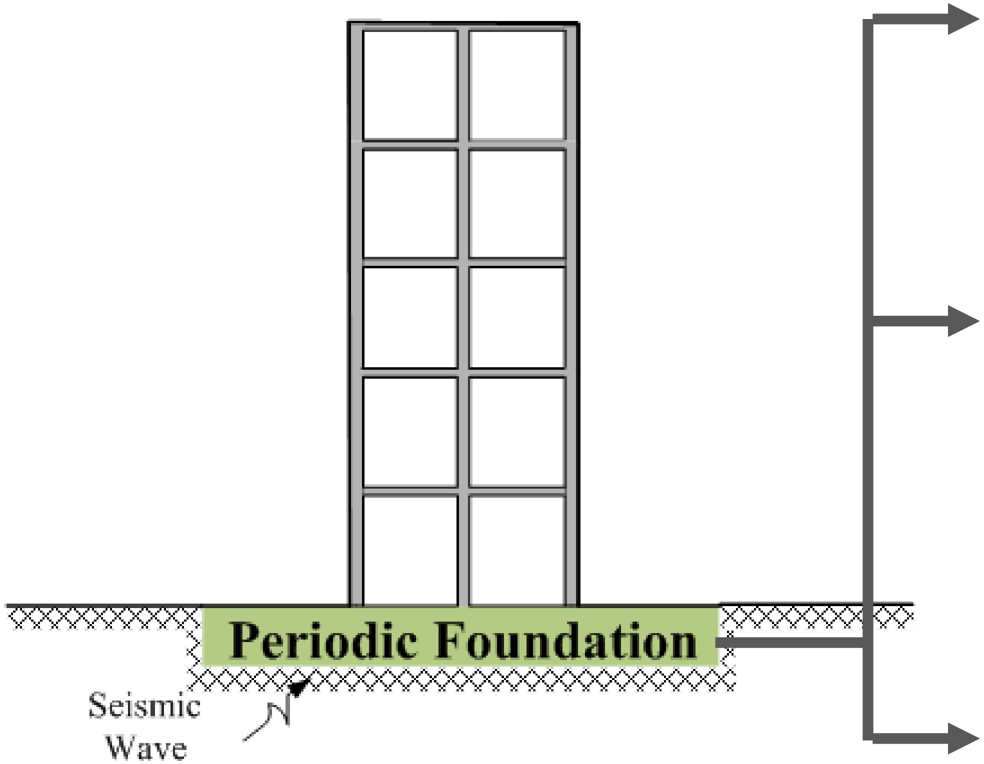
Typical unit cell of 3D two-component periodic foundation

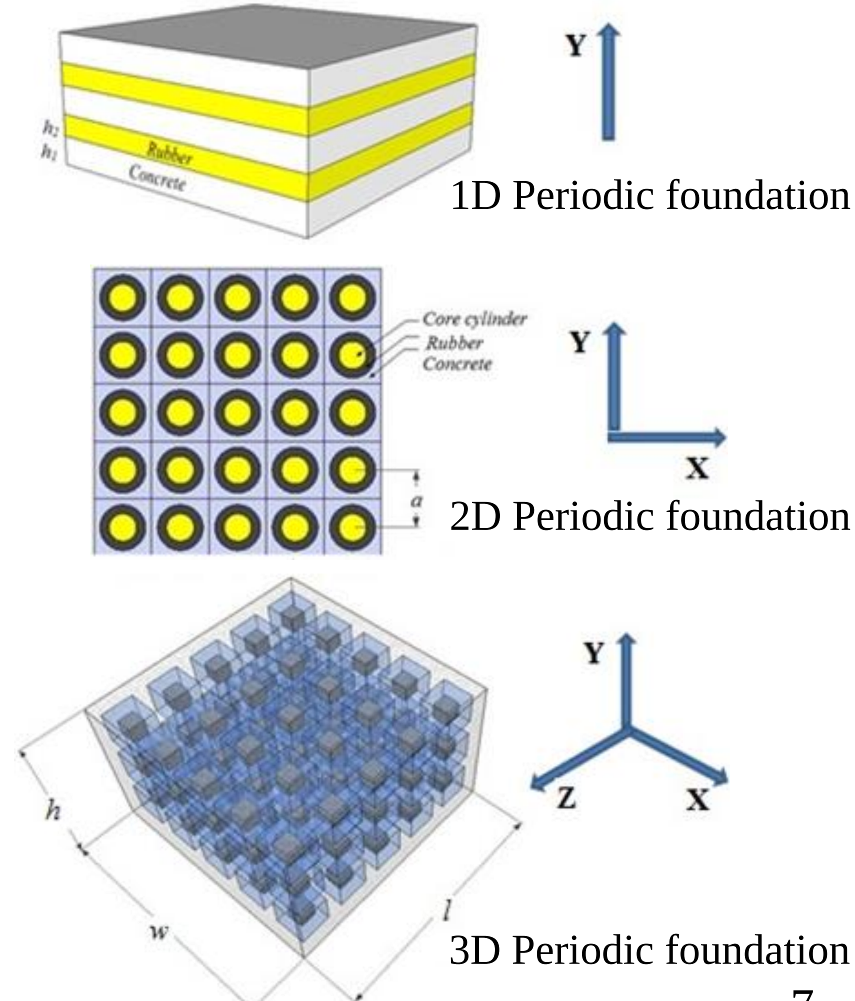


Typical dispersion curve for 3D two-component unit cell

Application of phononic crystals

In civil engineering field

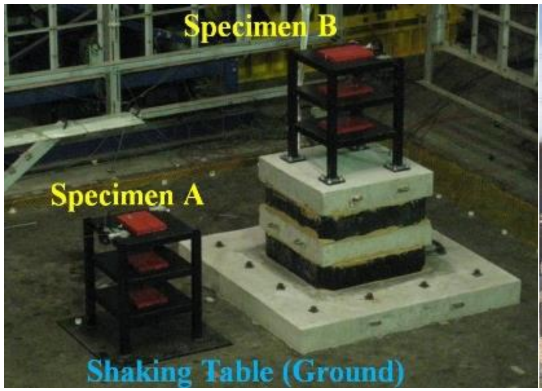


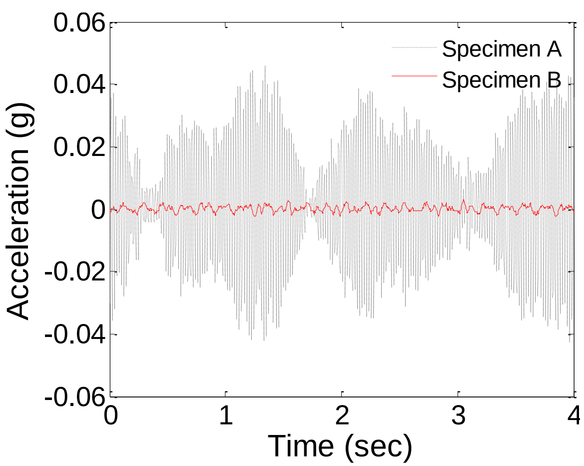


DOE Technical Report, Project No. 3219, 2014.

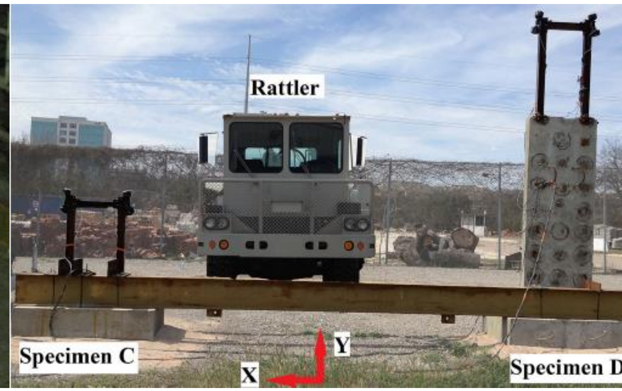
Experimental study on periodic foundations

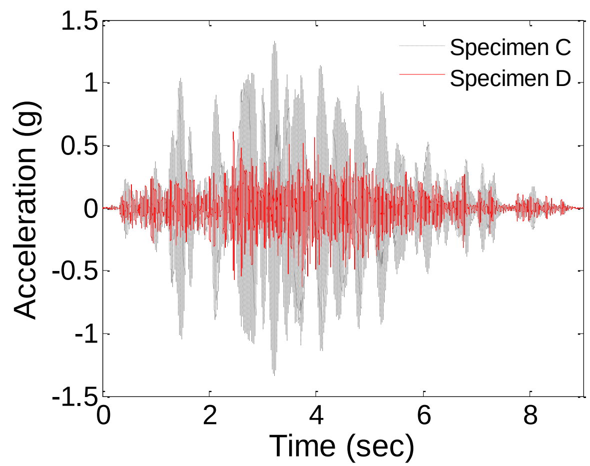
1D Periodic foundation[1]



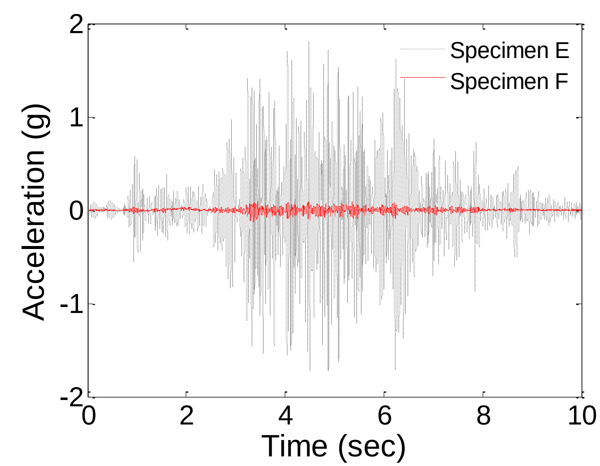


2D Periodic foundation[2]





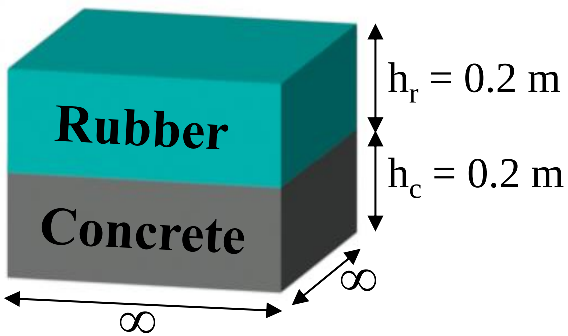
3D Periodic foundation[3]

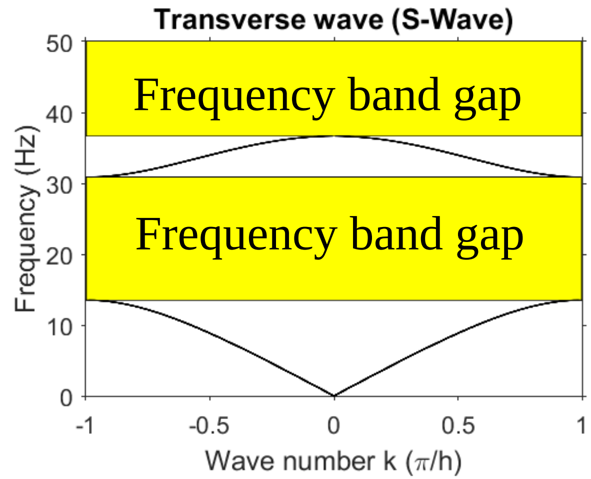


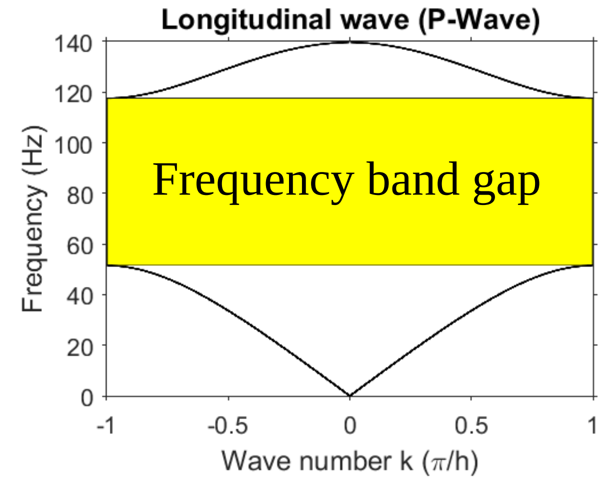
[1] Xiang et al. (2012). Periodic materials-based vibration attenuation in layered foundations: experimental validation. *Smart materials and structures*, 21, 1-10.
[2] Yan et al. (2014). Seismic isolation of two dimensional periodic foundations. *Journal of Applied Physics*, 116(4).
[3] Yan et al. (2015). Three dimensional periodic foundations for base seismic isolation. *Smart Materials and Structures*, 24(7), 075006.

Theoretical study on periodic foundations

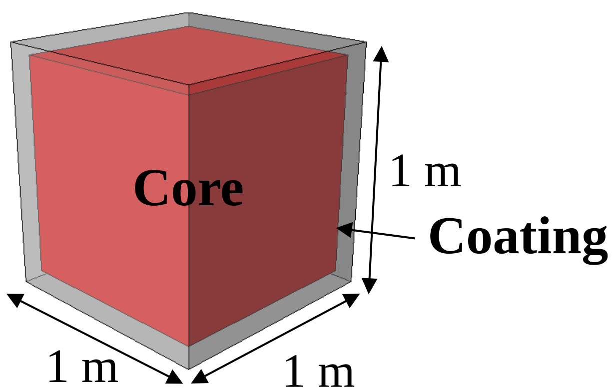
1D periodic foundation



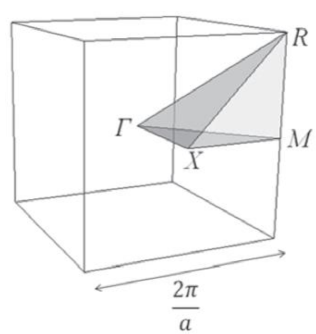


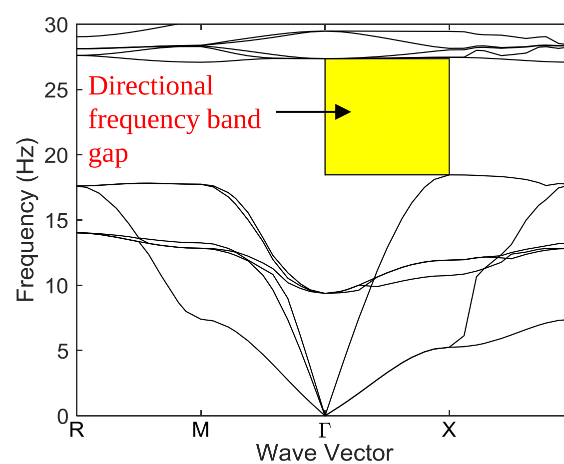


3D periodic foundation



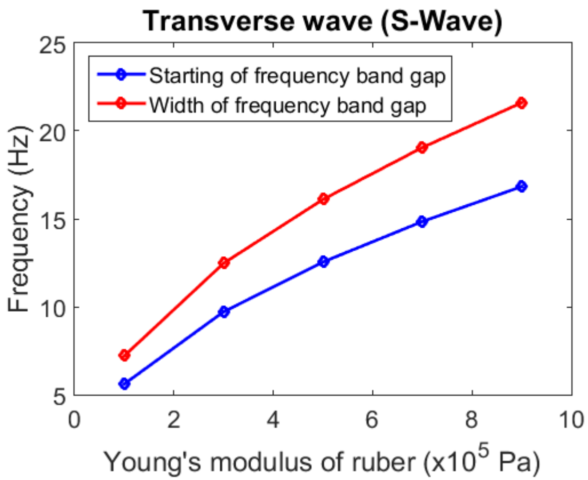
First irreducible Brillouin zone

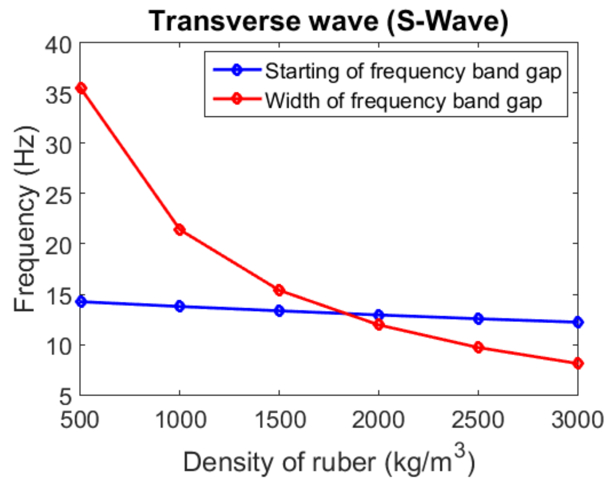


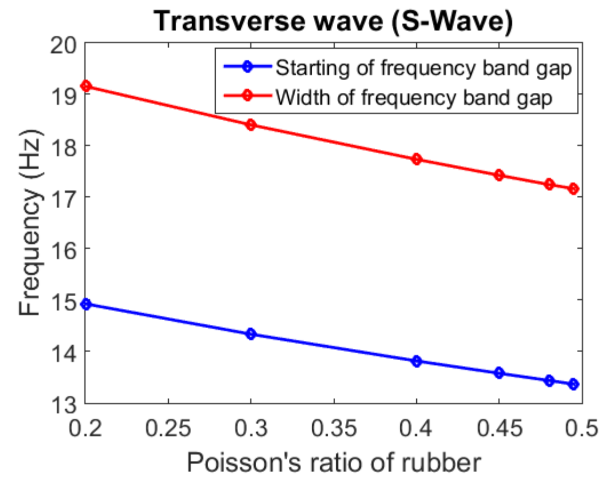


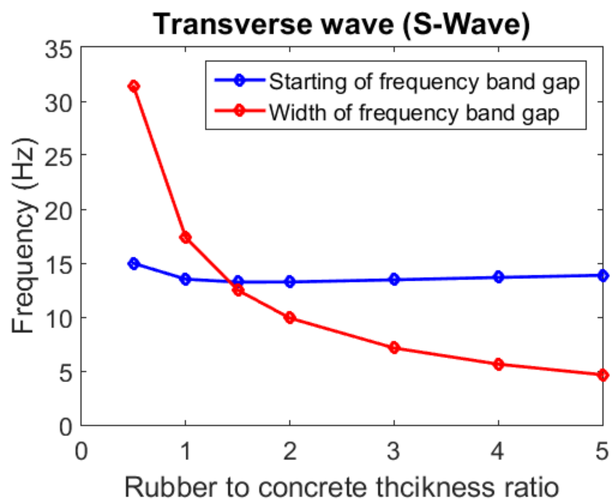
Parametric study of 1D periodic foundation

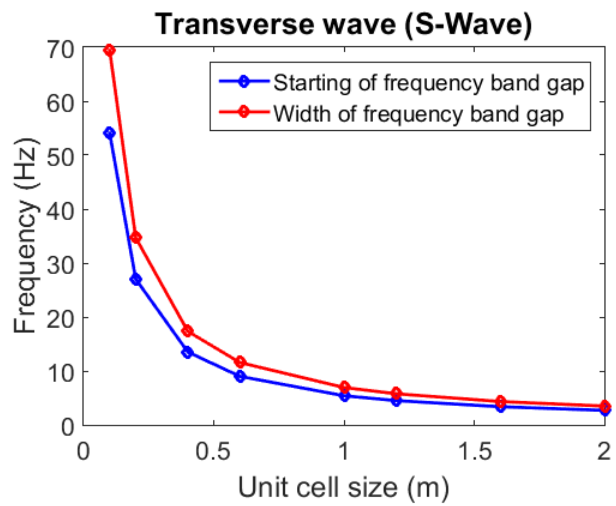
Effect of material and geometric properties on the first frequency band gap







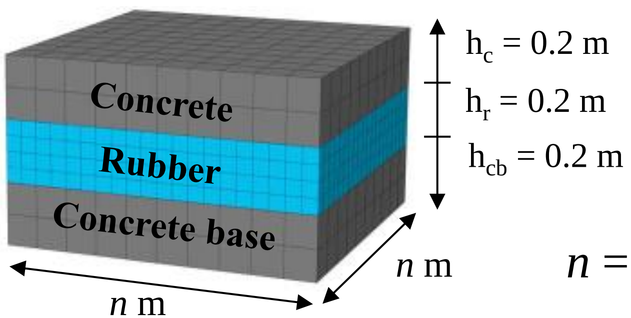




Parametric study of 1D periodic foundation

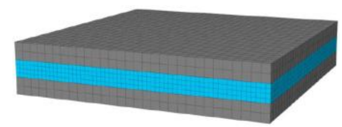
Effect of cross section size

Consider 1 unit cell on concrete base

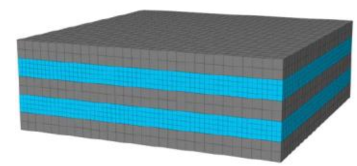


$n = 1, 2, 3$

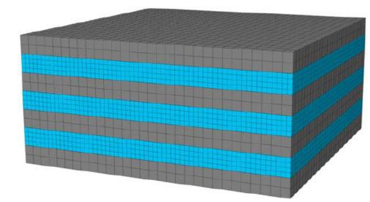
Effect of number of unit cells



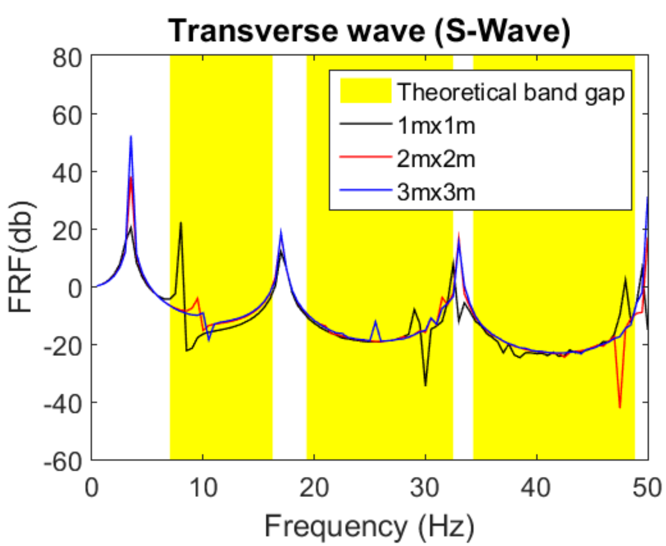
1 unit cell

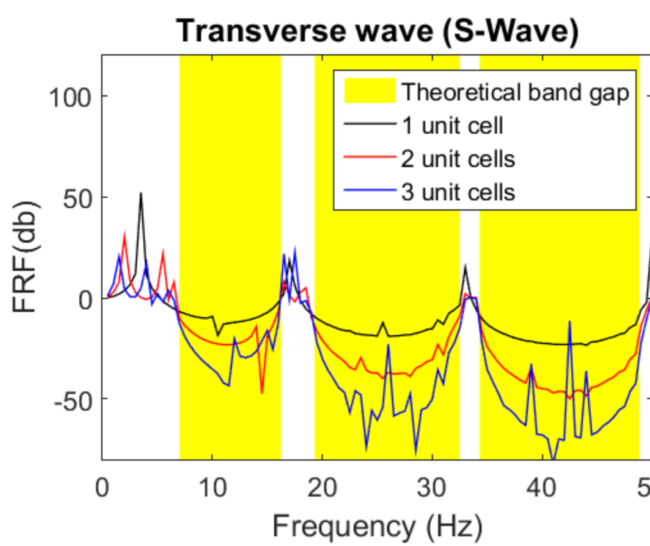


2 unit cells



3 unit cells





Frequency response:

$$FRF = 20\log(\delta_{out} / \delta_{inp})$$

where:

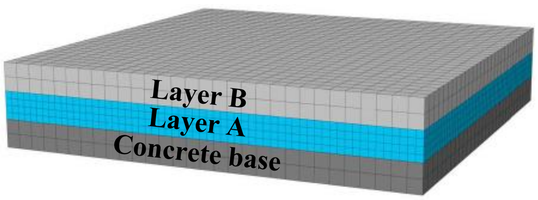
δ_{out} = amplitude of output disp

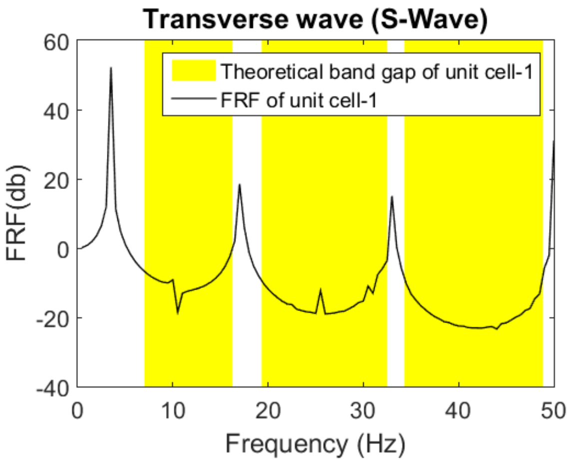
δ_{inp} = amplitude of input disp

Parametric study of 1D periodic foundation

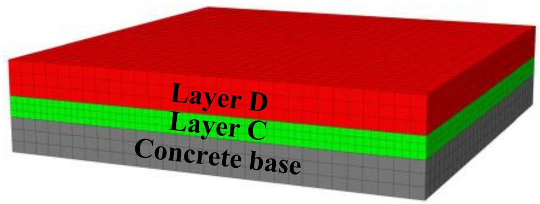
Effect of combined unit cells

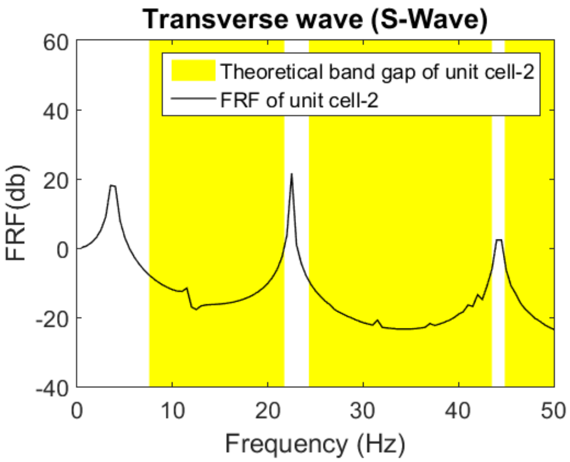
Unit cell-1



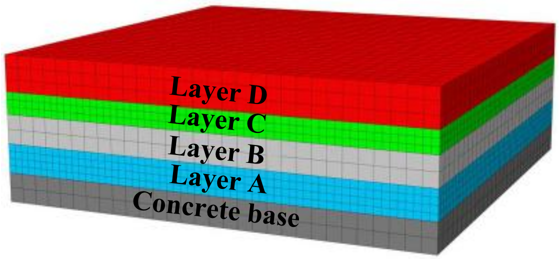


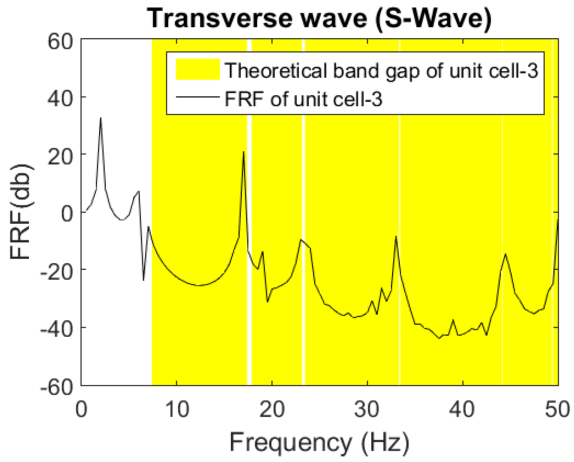
Unit cell-2





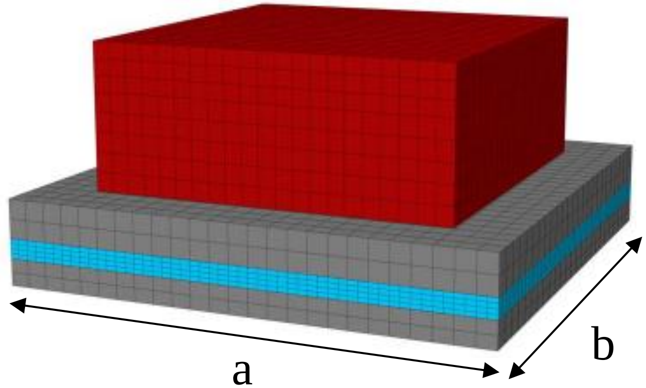
Unit cell-3

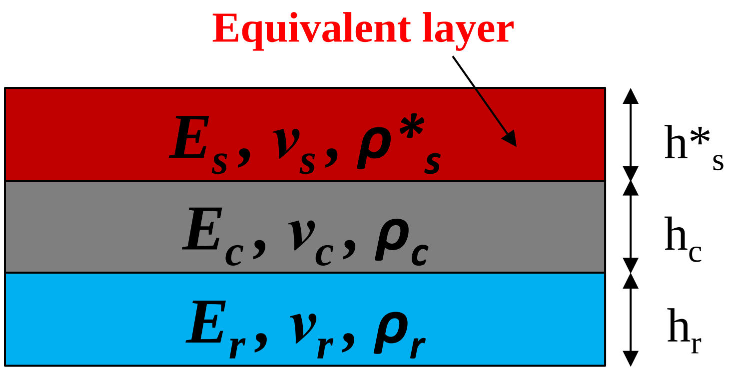




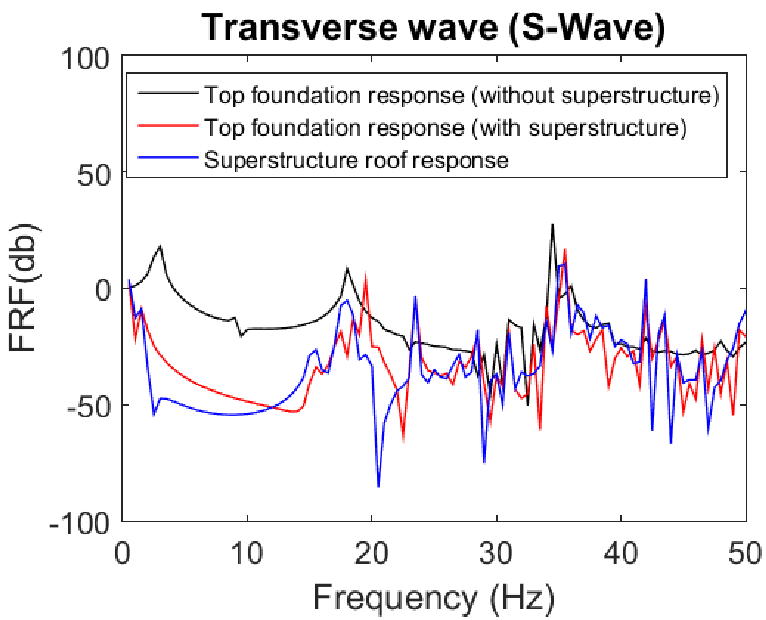
Parametric study of 1D periodic foundation

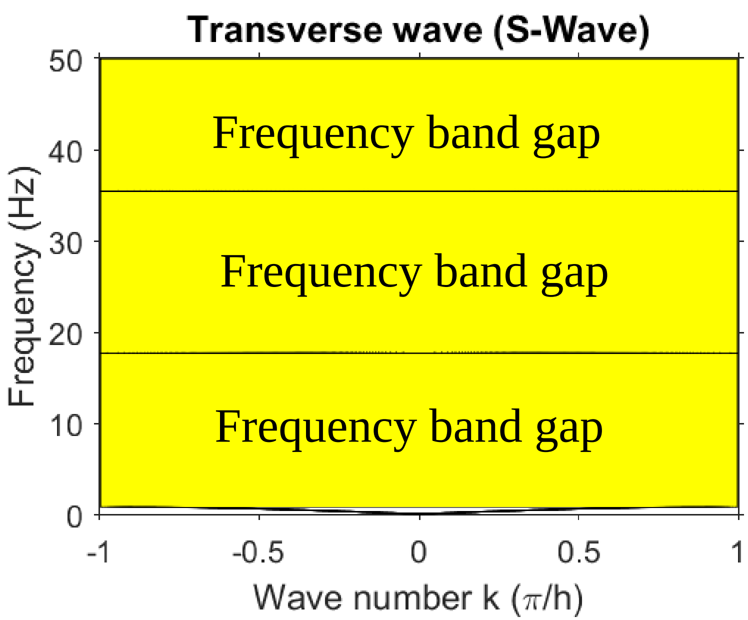
Effect of superstructure





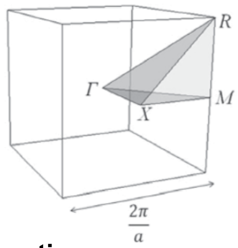
Where: $\rho^*_s = \frac{W_{superstructure}}{a \times b \times h^*_s}$

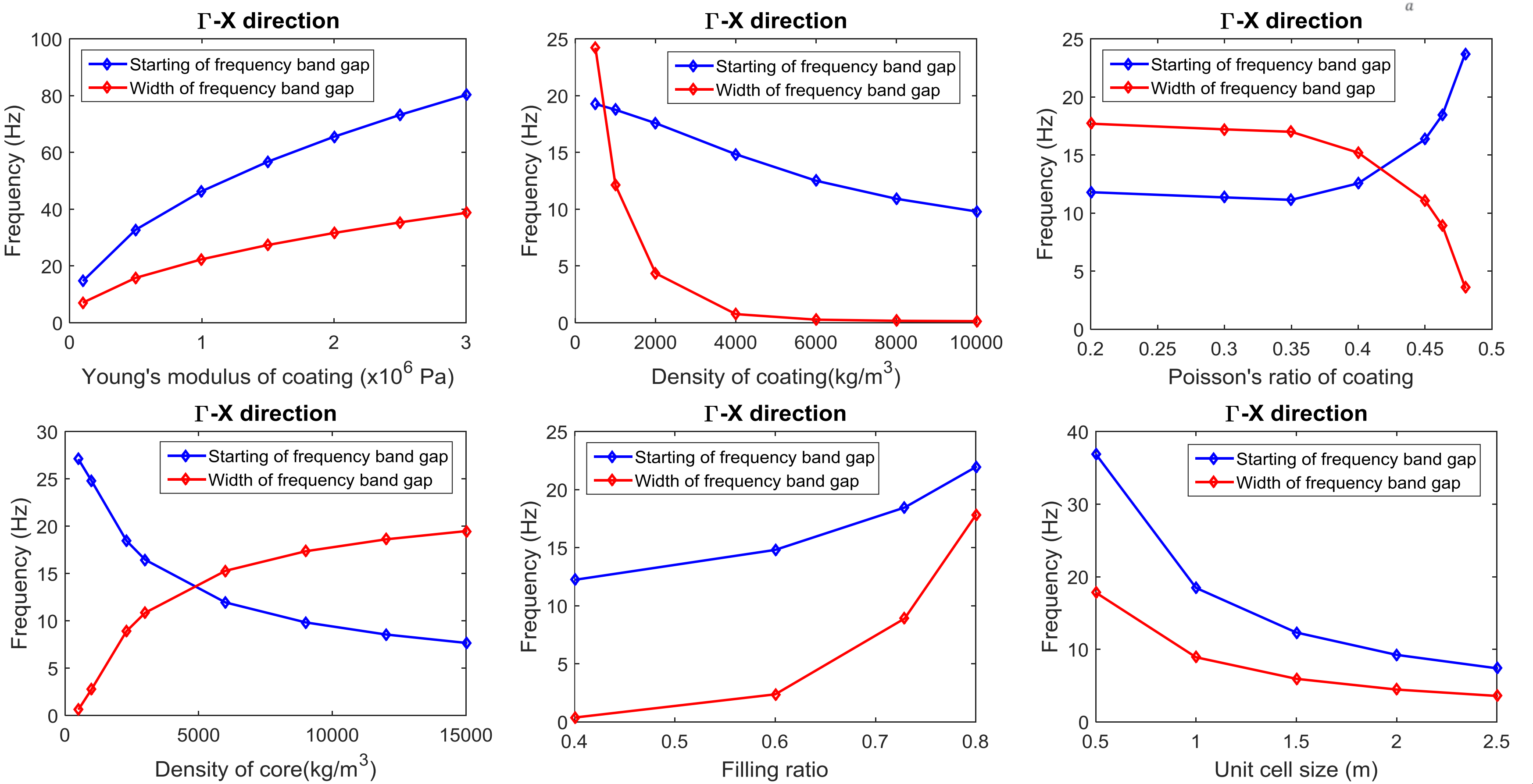




Parametric study of 3D periodic foundation

Effect of material and geometric properties on the first directional frequency band gap





Design guidelines of 1D and 3D periodic foundations

1D periodic foundation

Starting of frequency band gap (S-Wave) = $13.51F_1(E_r)F_2(\rho_r)F_3(\nu_r)F_4(\rho_c)F_5(S)F_6(r)$

Width of frequency band gap (S-Wave) = $17.36G_1(E_r)G_2(\rho_r)G_3(\nu_r)G_4(\rho_c)G_5(S)G_6(r)$

Starting of frequency band gap (P-Wave) = $51.5H_1(E_r)H_2(\rho_r)H_3(\nu_r)H_4(\rho_c)H_5(S)H_6(r)$

Width of frequency band gap (P-Wave) = $66.1I_1(E_r)I_2(\rho_r)I_3(\nu_r)I_4(\rho_c)I_5(S)I_6(r)$

3D periodic foundation

Starting of directional frequency band gap = $18.46J_1(E_r)J_2(\rho_r)J_3(\nu_r)J_4(\rho_c)J_5(S)J_6(f_r)$

Width of directional frequency band gap = $8.9K_1(E_r)K_2(\rho_r)K_3(\nu_r)K_4(\rho_c)K_5(S)K_6(f_r)$

The equations are function of:

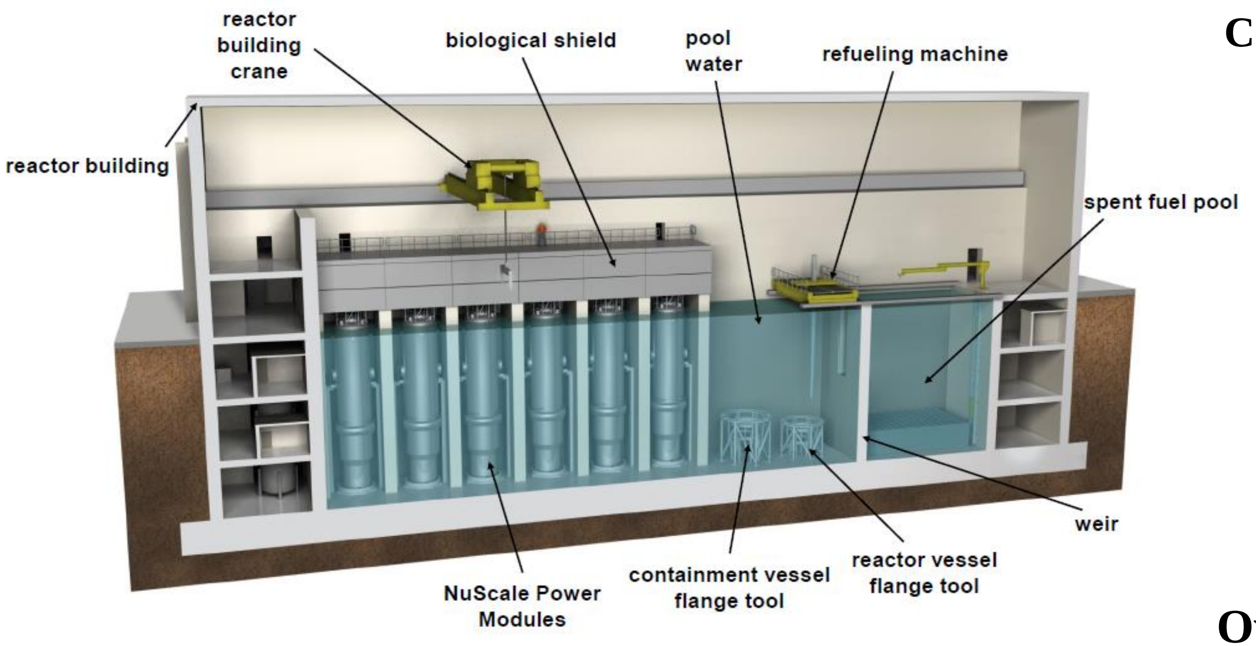
E_r : Young’s modulus of rubber
ρ_r : Density of rubber
ν_r : Poisson’s ratio of rubber
ρ_c : Density of concrete
S : Unit cell size (S)
f_r : Filling ratio

Task 3: Design of periodic foundations

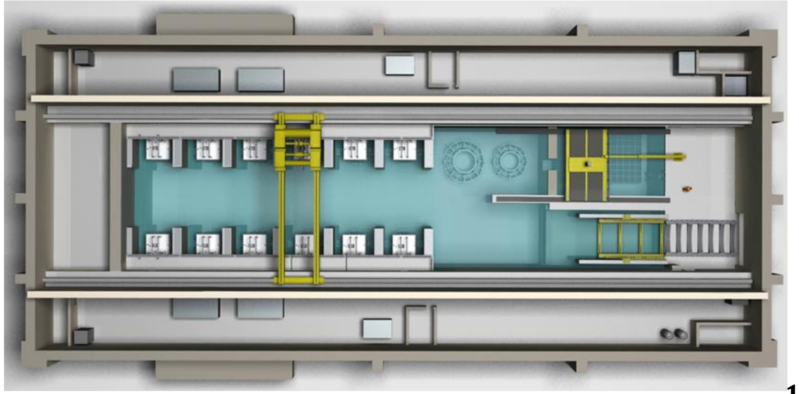
Small modular reactor (SMR) building

Cutaway elevation view

Courtesy of NuScale Power



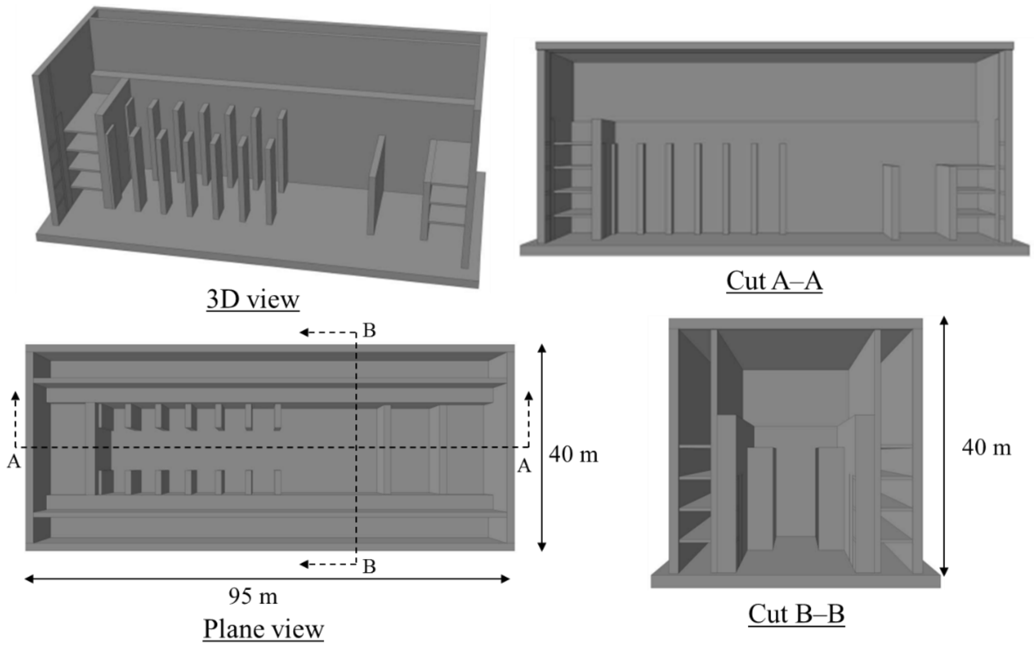
Overhead plan view



NuScale Power™

SMR building

Finite element model of representative of NuScale's SMR Building



Material Properties:

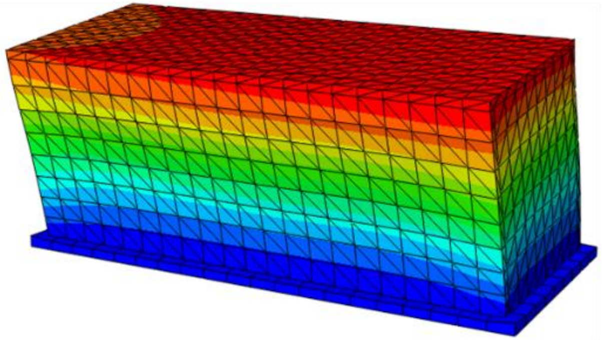
- Reinforced concrete (E_s = 31400 MPa, ρ = 2300 kg/m^3, ν = 0.2)

Mass of non-structural components:

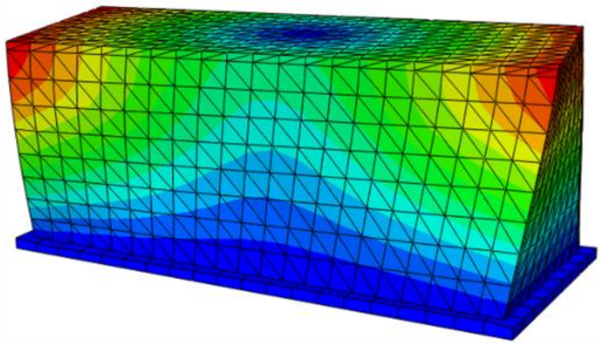
- Water in reactor pool = 5.09 million gallon = 19.28×10^6 kg
- Small modular reactors (12 units) = $12\times(8\times10^5)$= 9.6×10^6 kg
- Crane and utilities = 8×10^5 kg

SMR building

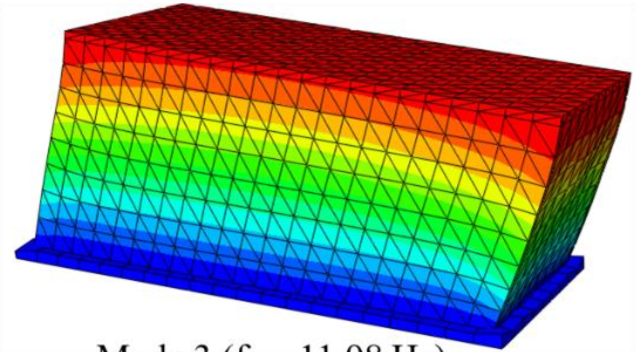
Mode shapes and natural frequencies of SMR building



Mode 1 (f_n = 6.77 Hz)



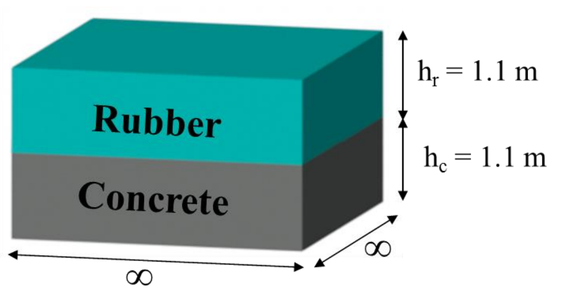
Mode 2 (f_n = 11.14 Hz)

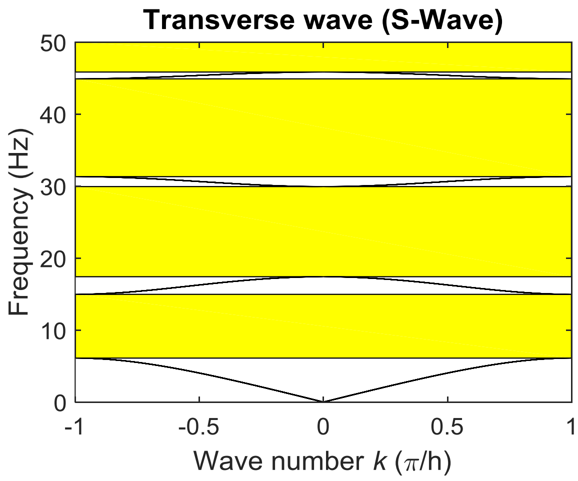


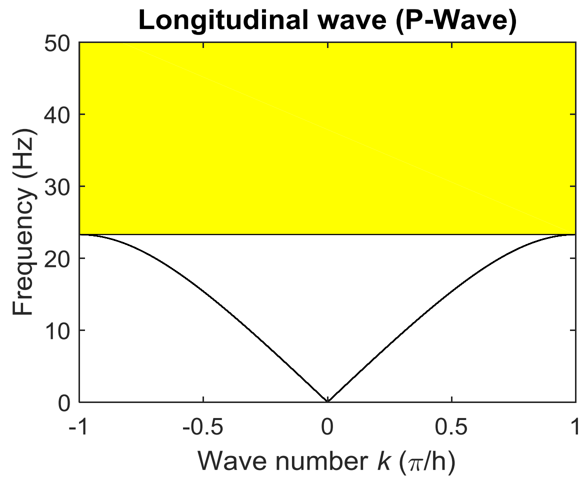
Mode 3 (f_n = 11.98 Hz)

Design of 1D periodic foundation

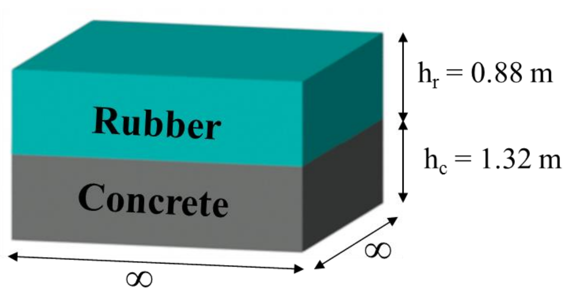
Unit cell 1

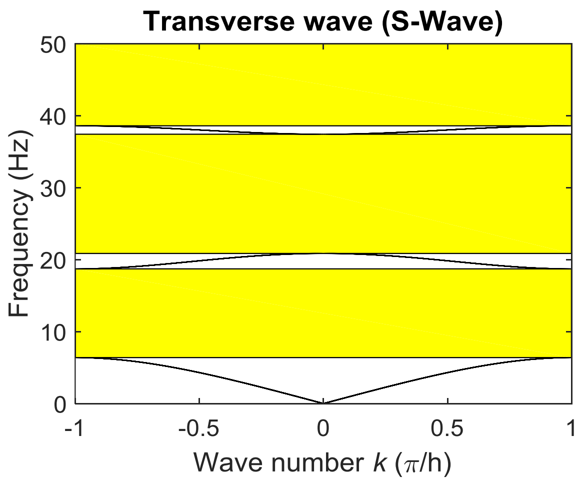


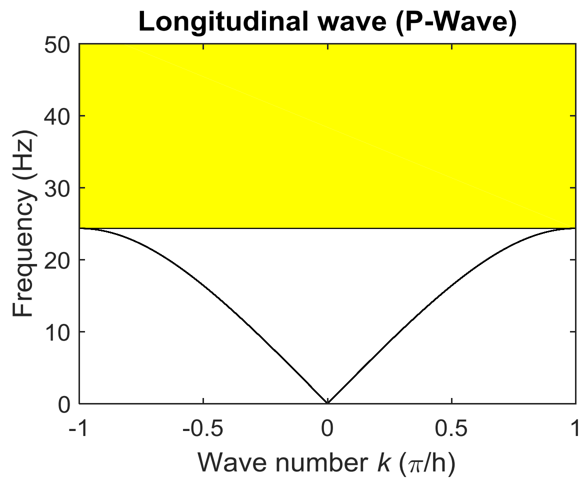




Unit cell 2

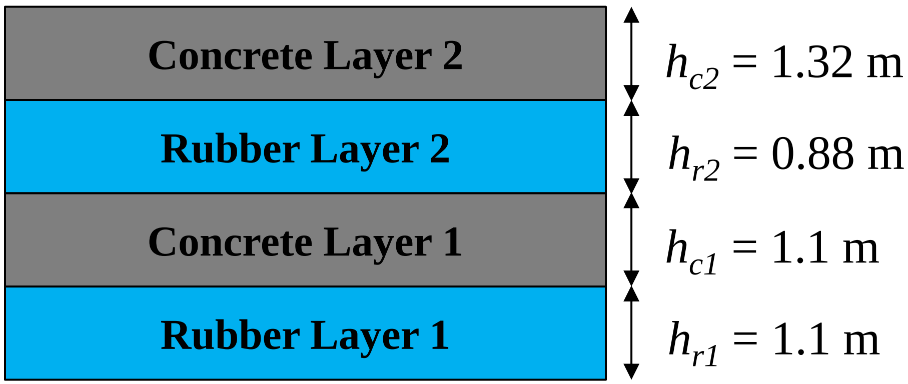




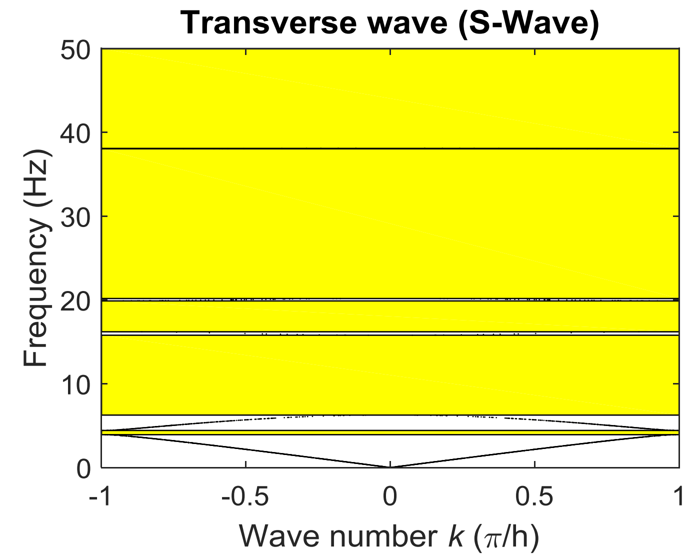


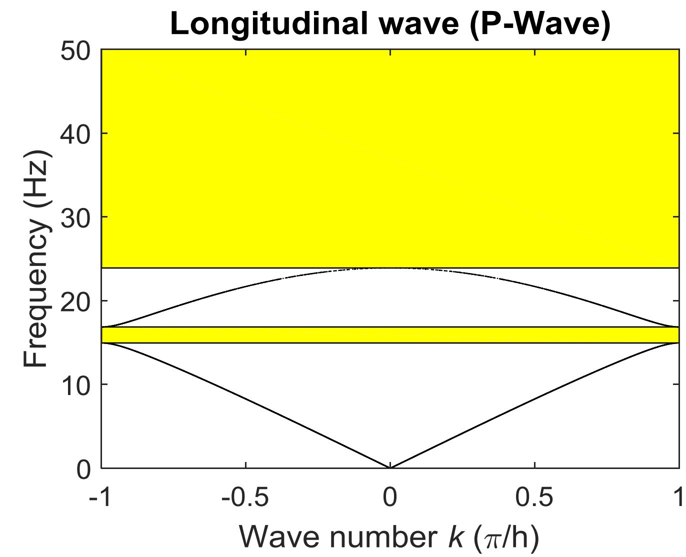
Design of 1D periodic foundation

Combined unit cell

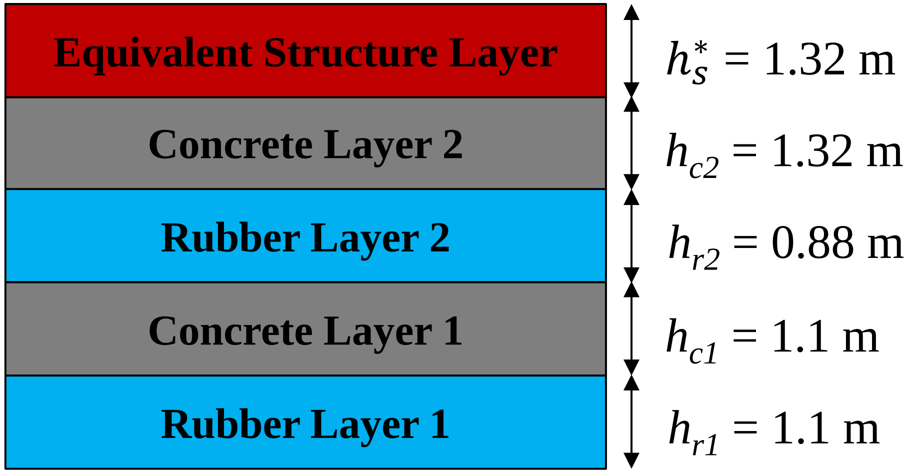


Material	Young's Modulus (MPa)	Density (kg/m^3)	Poisson's Ratio
Concrete	31400	2300	0.2
Rubber	3.49	1100	0.463

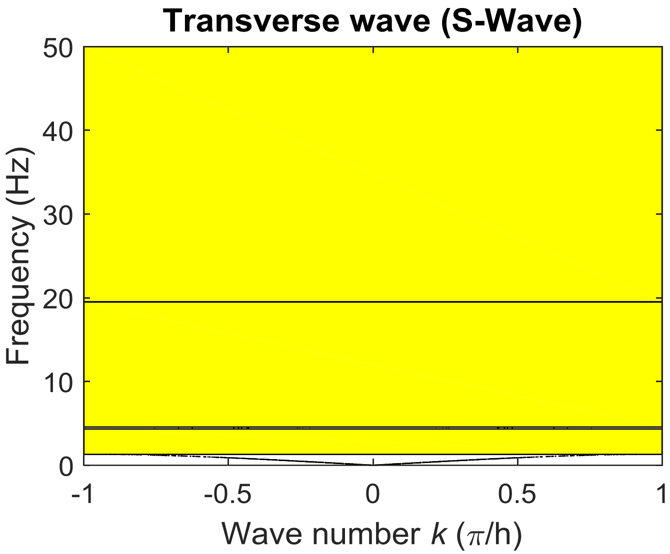


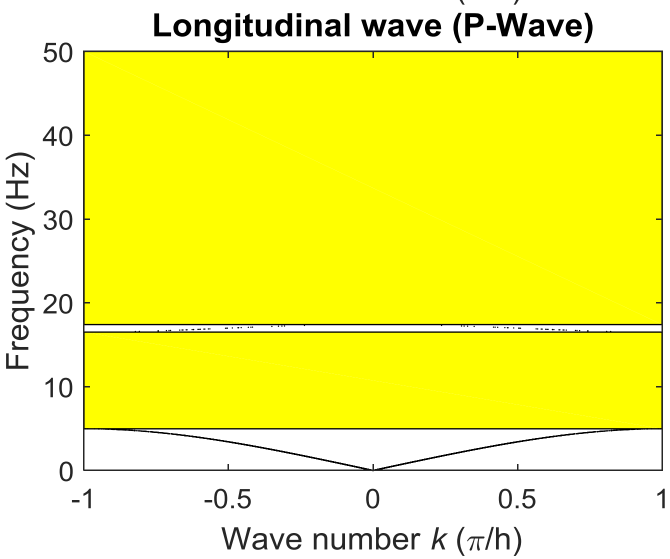


Design of 1D periodic foundation
(Combined unit cell with equivalent structure layer)



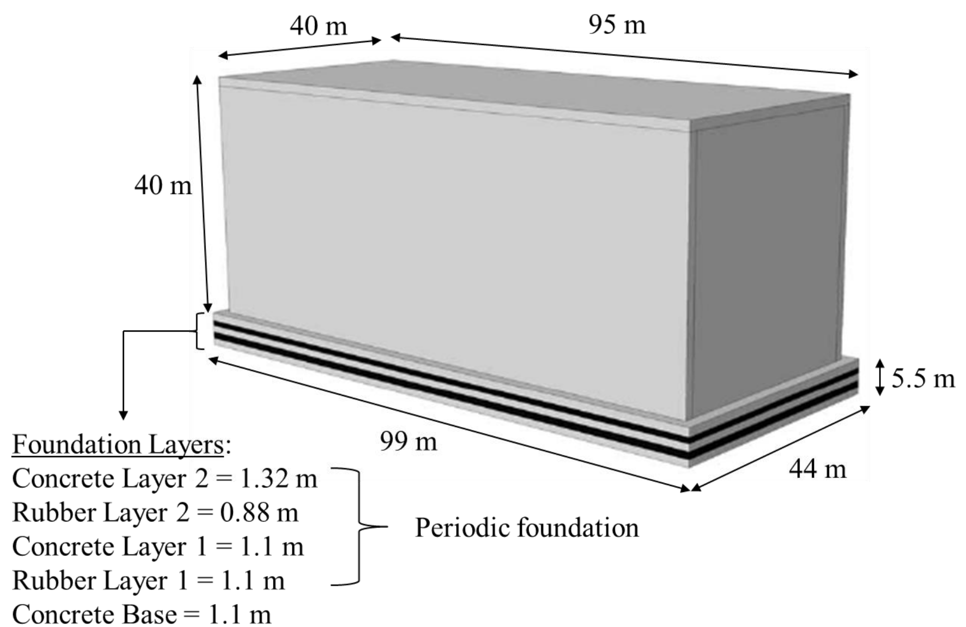
Material	Young's Modulus (Pa)	Density (kg/m^3)	Poisson's Ratio
Concrete	3.14×10^{10}	2300	0.2
Rubber	3.49×10^{6}	1100	0.463
Equivalent Super Strc	3.14×10^{10}	24247.2	0.2



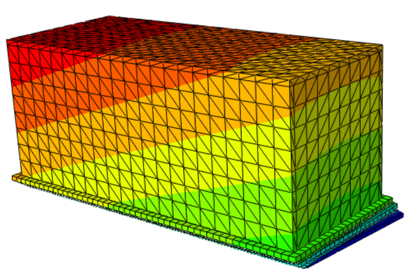


Design of 1D periodic foundation

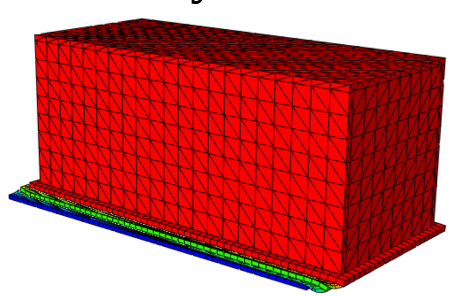
Designed 1D periodic foundation supporting SMR building



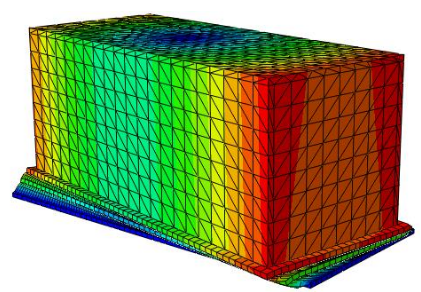
Natural frequencies of structure system



Mode 1 (f_n = 0.59 Hz)



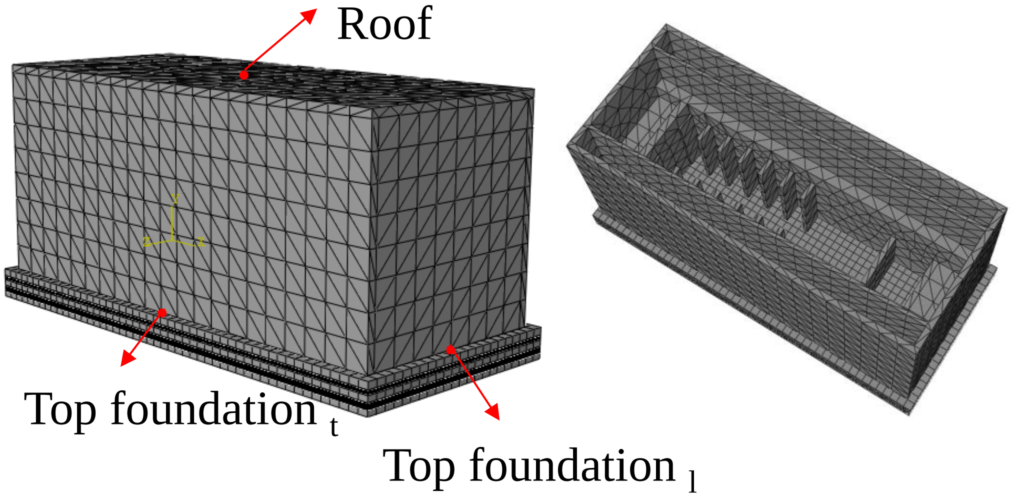
Mode 2 (f_n = 0.63 Hz)

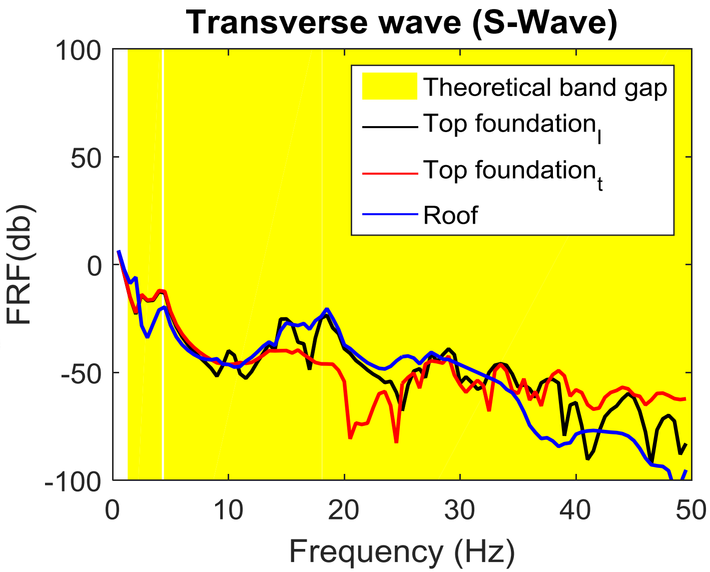


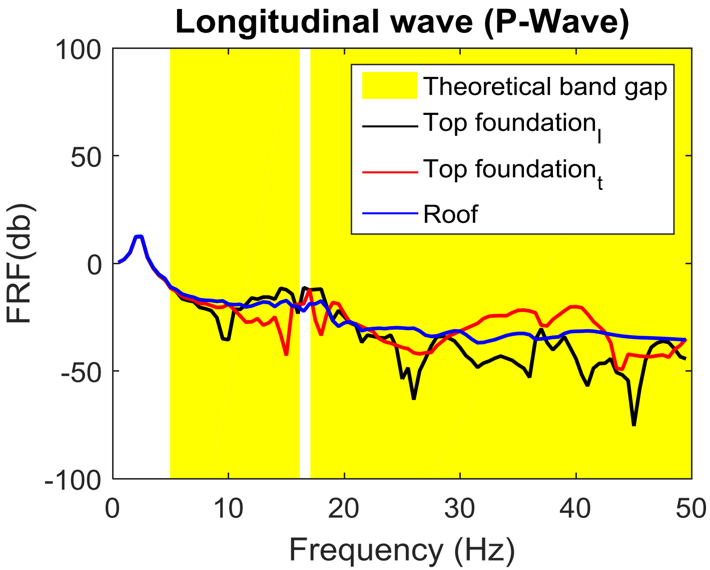
Mode 3 (f_n = 0.64 Hz)

Design of 1D periodic foundation

Frequency response function







Damping ratio:

$\xi_{concrete} = 4\ \%$

$\xi_{rubber} = 10\ \%$

Frequency response:

$$FRF = 20\log(\delta_{out} / \delta_{inp})$$

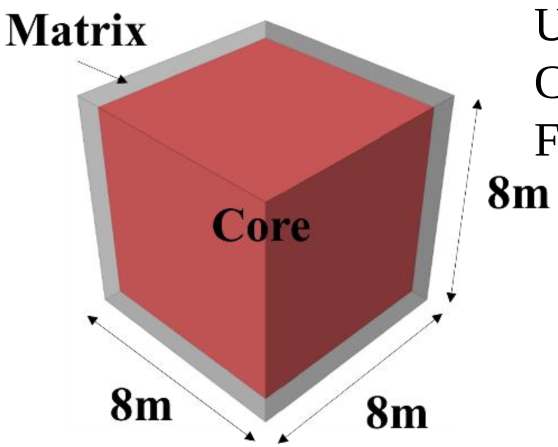
where:

δ_{out} = amplitude of output disp

δ_{inp} = amplitude of input disp

Design of 3D periodic foundation

One unit cell of 3D periodic foundation

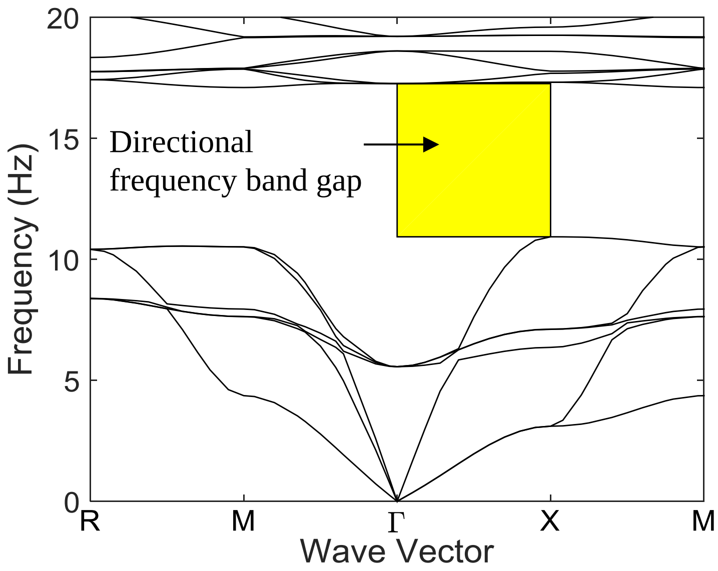


Unit cell size = 8 m
Core size = 7.2 m
Filling ratio = 0.729

Material properties

Material	Young's Modulus (MPa)	Density (kg/m^3)	Poisson's Ratio
Reinforced Concrete	31400	2300	0.2
Rubber	3.49	1100	0.463

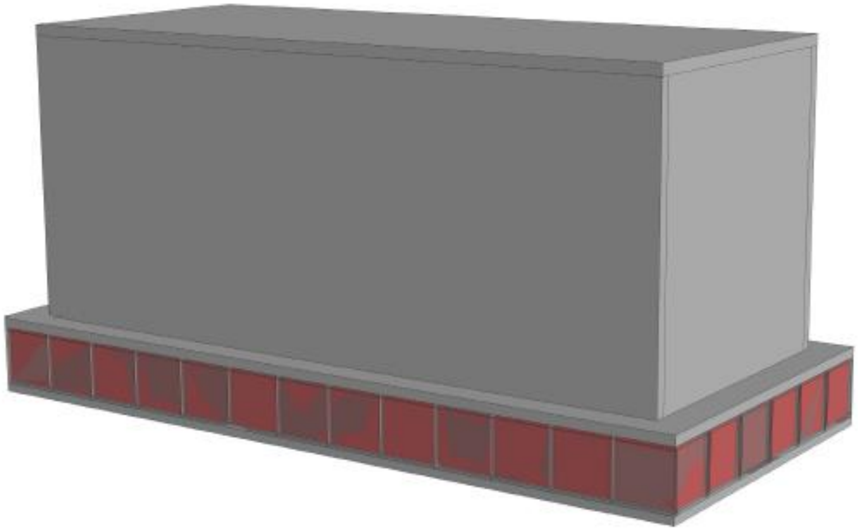
Dispersion curve for infinite number of unit cells



Starting of 1st frequency band gap = 11.18 Hz
Width of 1st frequency band gap = 5.98 Hz

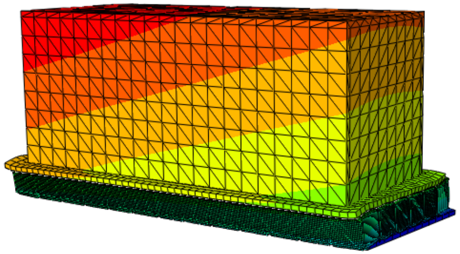
Design of 3D periodic foundation

Designed 3D periodic foundation supporting SMR building

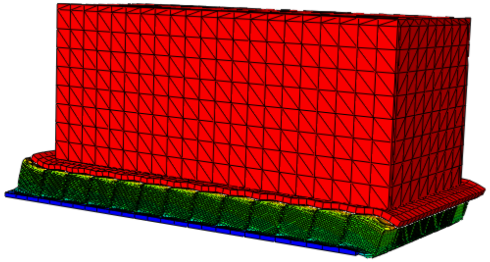


Unit cells on periodic foundation: 13 X 6 X 1

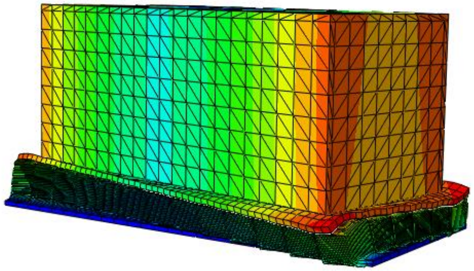
Natural frequencies of structure system



Mode 1 (f_n = 0.86 Hz)



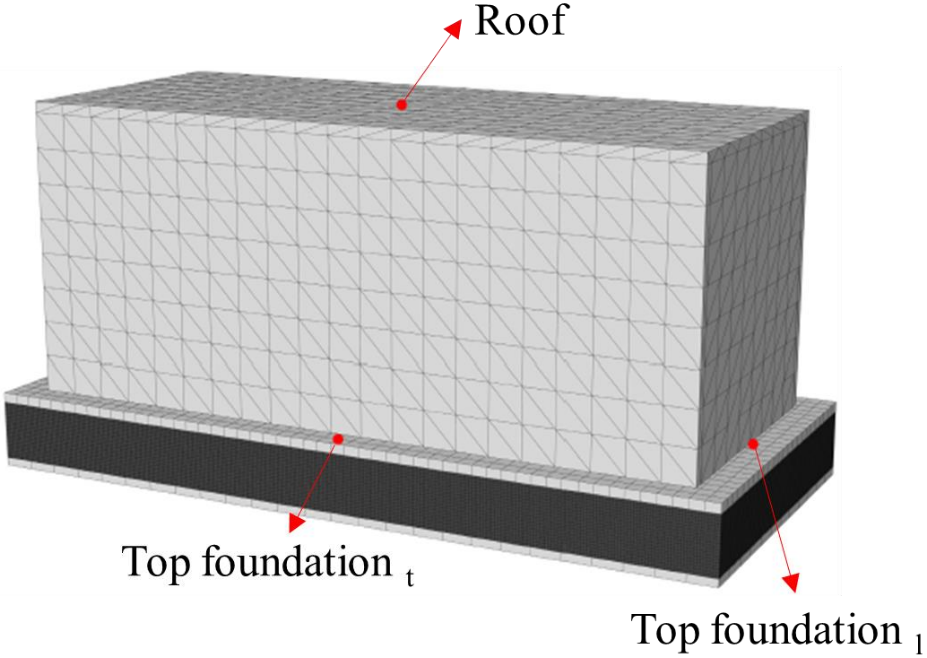
Mode 2 (f_n = 0.91 Hz)

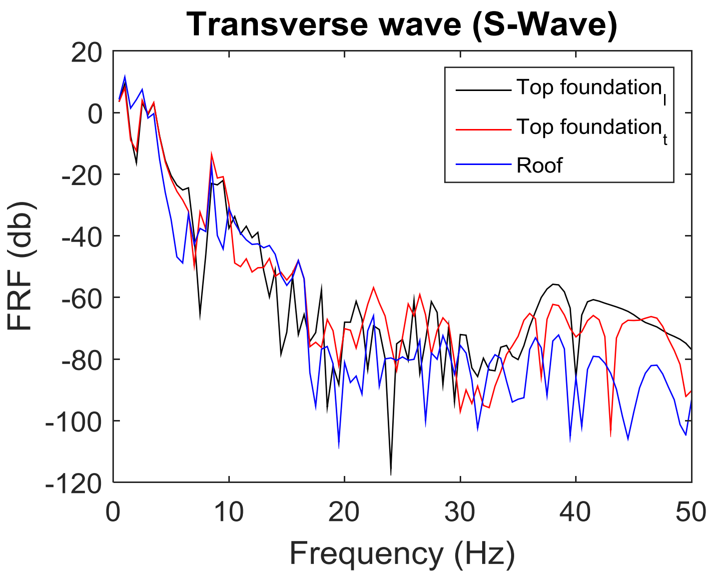


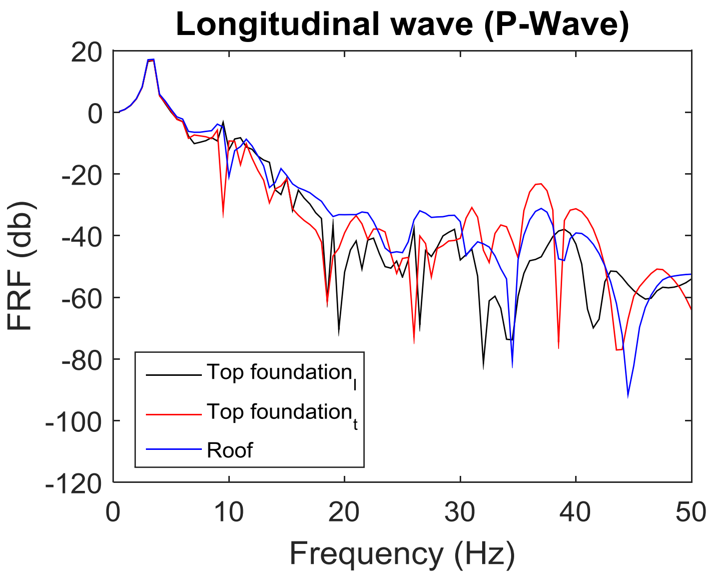
Mode 3 (f_n = 0.95 Hz)

Design of 3D periodic foundation

Frequency response function







Damping ratio:

$\xi_{concrete}$ = 4 %

ξ_{rubber} = 10 %

Frequency response:

$$FRF = 20\log(\delta_{out} / \delta_{inp})$$

where:

δ_{out} = amplitude of output disp

δ_{inp} = amplitude of input disp

Similitude requirements for dynamic models

Model type / Scaling Parameters		True ultimate strength model (1)	Models with artificial mass (2)	Gravity forces neglected / Linear elastic models (3)	Models with strain distortion (4)
Length	l_r	l_r	l_r	l_r	l_r
Time	t_r	$l_r^{1/2}$	$l_r^{1/2}$	$l_r(E/\rho)_r^{-1/2}$	$(\varepsilon_r l_r)^{1/2}$
Frequency	ω_r	$l_r^{-1/2}$	$l_r^{-1/2}$	$l_r^{-1}(E/\rho)_r^{1/2}$	$(\varepsilon_r l_r)^{-1/2}$
Velocity	v_r	$l_r^{1/2}$	$l_r^{1/2}$	$(E/\rho)_r^{1/2}$	$(\varepsilon_r l_r)^{-1/2}$
Gravitational acceleration	g_r	1	1	neglected	1
Acceleration	a_r	1	1	$l_r^{-1}(E/\rho)_r$	1
Mass density	ρ_r	E_r/l_r	**	ρ_r	$\varepsilon_r E_r l_r^{-1}$
Strain	ε_r	1	1	1	ε_r
Stress	σ_r	E_r	E_r	E_r	$E_r\varepsilon_r$
Modulus of elasticity	E_r	E_r	E_r	E_r	E_r
Specific stiffness	$(E/\rho)_r$	l_r	**	$(E/\rho)_r$	$l_r\varepsilon_r^{-1/2}$
Displacement	δ_r	l_r	l_r	l_r	$l_r\varepsilon_r$
Force	F_r	$E_r l_r^2$	$E_r l_r^2$	$E_r l_r^2$	$E_r l_r^2\varepsilon_r$
Energy	$(EN)_r$	$E_r l_r^3$	$E_r l_r^3$	$E_r l_r^3$	$E_r l_r^3\varepsilon_r^2$

To fit the shake table, the length scale is decided to be $l_r = \frac{l_m}{l_p} = \frac{1}{22}$

m = model
p = prototype

Similitude requirements for dynamic models

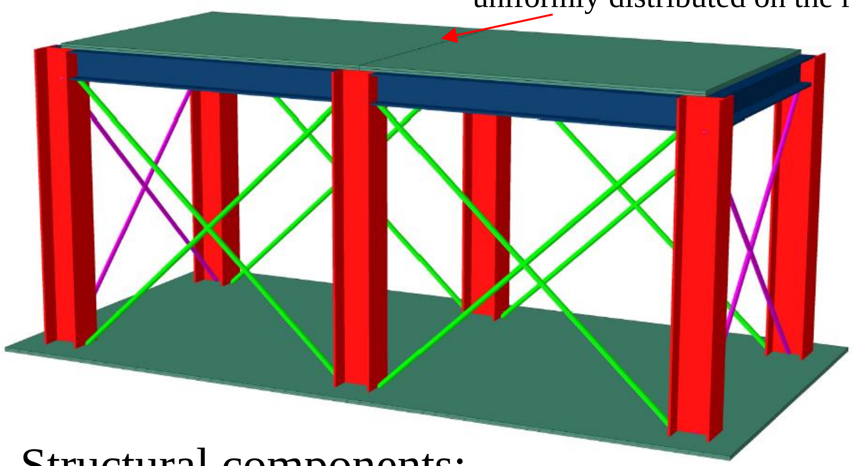
Essential scaled parameters:

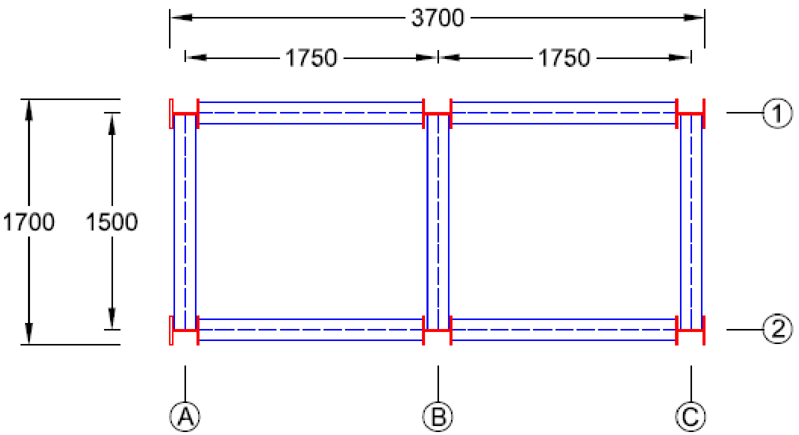
- Frequency band gaps $\frac{1}{\sqrt{l_r}} = \sqrt{22}$
- Natural frequency of periodic foundation structure system $\frac{1}{\sqrt{l_r}} = \sqrt{22}$
- Natural frequency of superstructure only $\frac{1}{\sqrt{l_r}} = \sqrt{22}$
- Duration of earthquake record $\sqrt{l_r} = \frac{1}{\sqrt{22}}$

Parameter	Prototype	Model	Required scale
Natural frequency of superstructure (Hz)	6.77	31.1	$\sqrt{22} = 4.69$
Natural frequency of 1D periodic foundation structure system (Hz)	0.59	3	$\sqrt{22} = 4.69$
First theoretical S-Wave frequency band gap of 1D periodic foundation with equivalent superstructure layer (Hz)	1.3 – 4.34	6.12 – 20.34	$\sqrt{22} = 4.69$
Natural frequency of 3D periodic foundation structure system (Hz)	0.86	4.06	$\sqrt{22} = 4.69$
First theoretical directional frequency band gap of 3D periodic foundation (Hz)	11.18 – 17.16	50.9 – 75.03	$\sqrt{22} = 4.69$
Sampling time of earthquake record (sec)	0.005	0.001066	$1/\sqrt{22} = 0.213$

Scaled SMR Building

Designed small scale SMR building

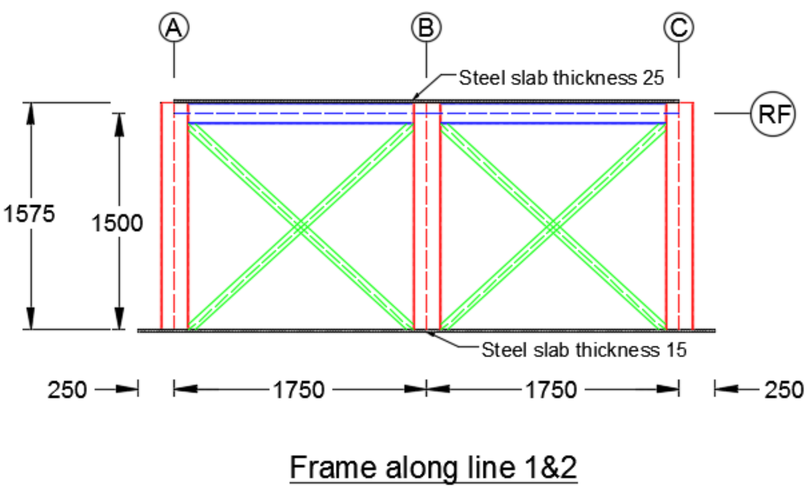




Plane view (unit: mm)

Structural components:

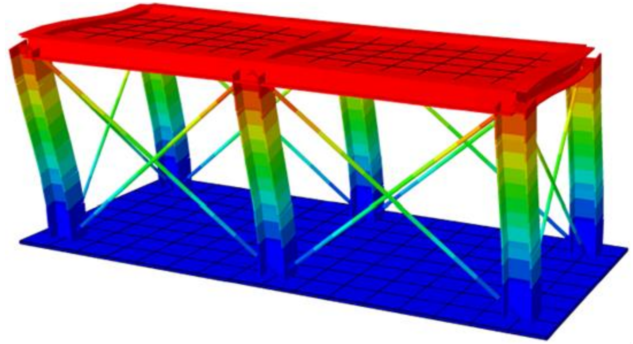
Structural component	Cross-section
Column	200X200X8X12
Beam	150X150X7X10
Longitudinal brace	65X65X6
Transverse brace	50X50X5



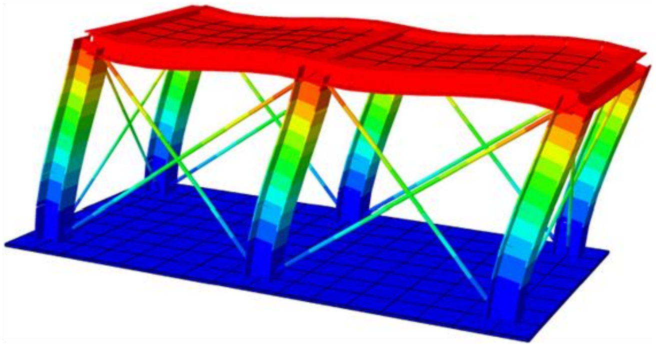
Elevation view (unit: mm)

Scaled SMR Building

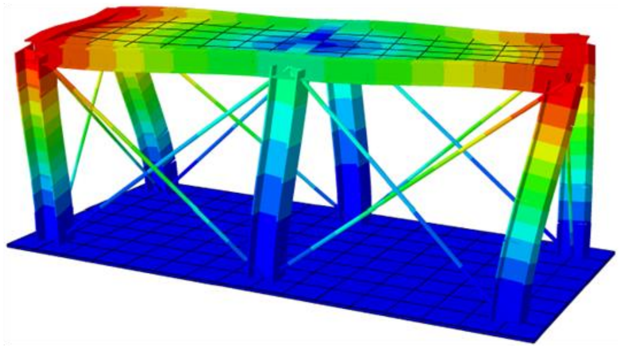
Mode shapes and natural frequencies of structure system



Mode 1 (f_n = 31.1 Hz)



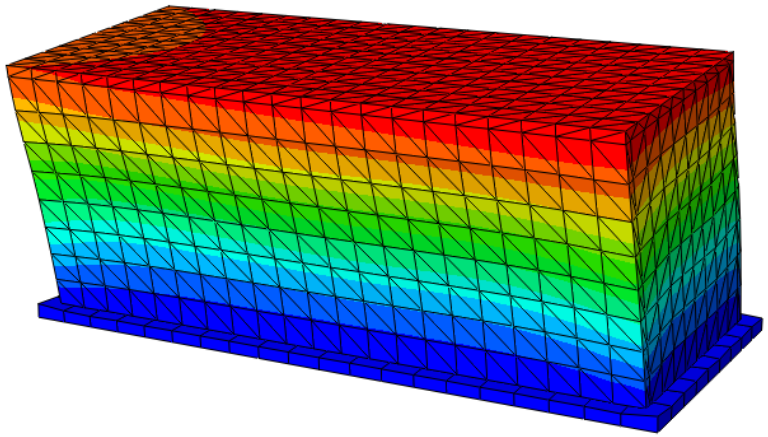
Mode 2 (f_n = 53.55 Hz)



Mode 3 (f_n = 56.73 Hz)

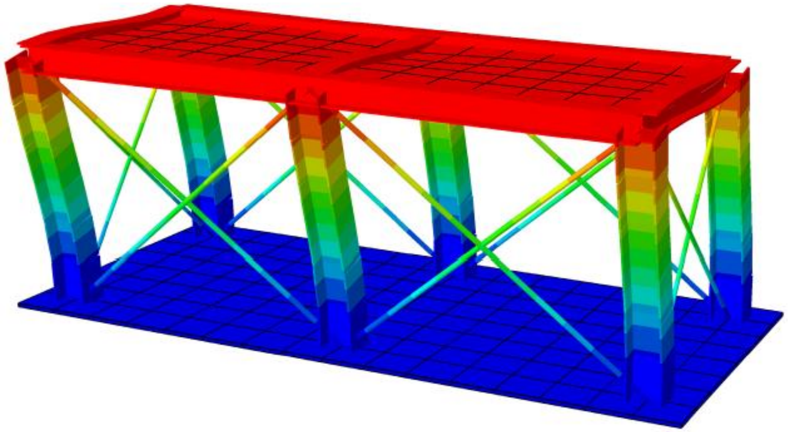
SMR building

Full-scale SMR building



Mode 1 (f_{np} = 6.77 Hz)

Scaled model of SMR building



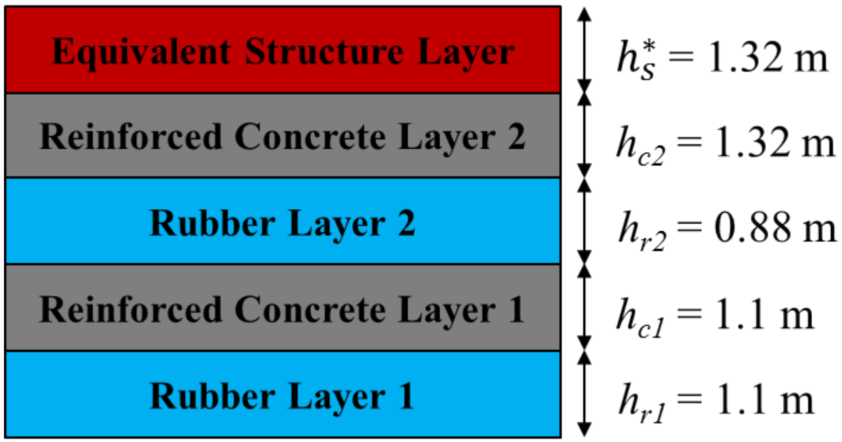
Mode 1 (f_{nm} = 31.1 Hz)

$$f_{nm} = f_{np}\sqrt{22}$$

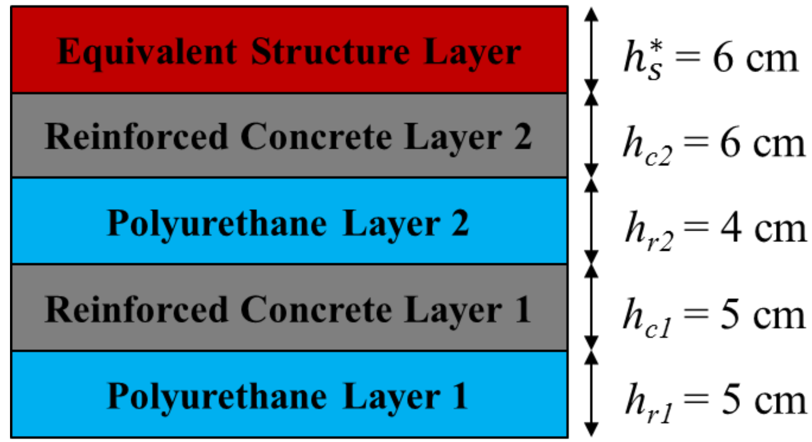
$$= 6.77 \times 4.69 = 31.75\text{Hz} \approx 31.1\text{Hz}$$

Scaled 1D periodic foundation

Full-scale 1D periodic foundation unit cell



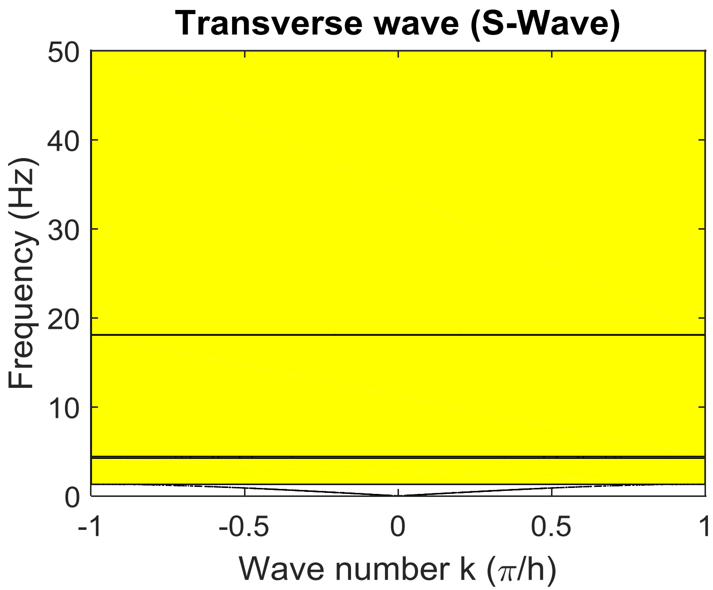
Scaled model of 1D periodic foundation unit cell



	Material for Prototype			Material for Model		
Material	Young's Modulus (MPa)	Density (kg/m^3)	Poisson's Ratio	Young's Modulus (MPa)	Density (kg/m^3)	Poisson's Ratio
Reinforced Concrete	31400	2300	0.2	31400	2300	0.2
Rubber	3.49	1100	0.463	0.1586	1100	0.463
Equivalent superstructure layer	31400	24247.2	0.2	31400	24247.2	0.2

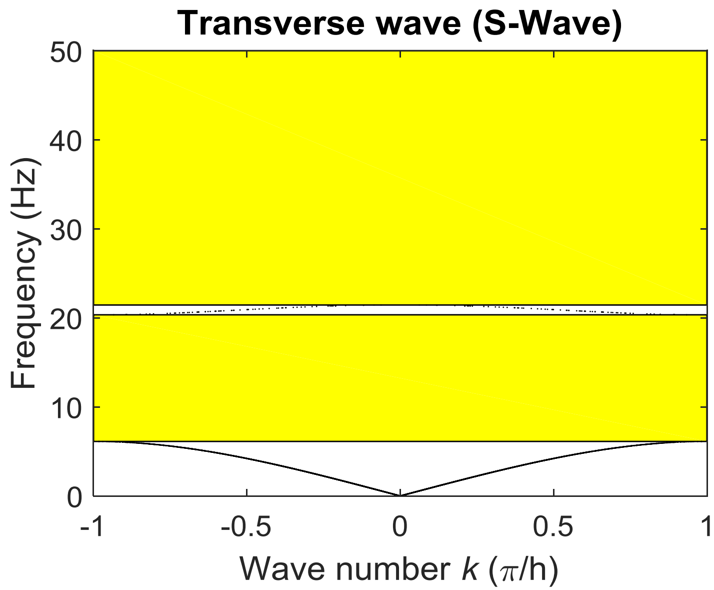
Scaled 1D periodic foundation

Theoretical frequency band gap of full-scale unit cell



1st Frequency band gap = 1.3–4.34 Hz

Theoretical frequency band gap of scaled model unit cell



1st Frequency band gap = 6.12–20.34 Hz

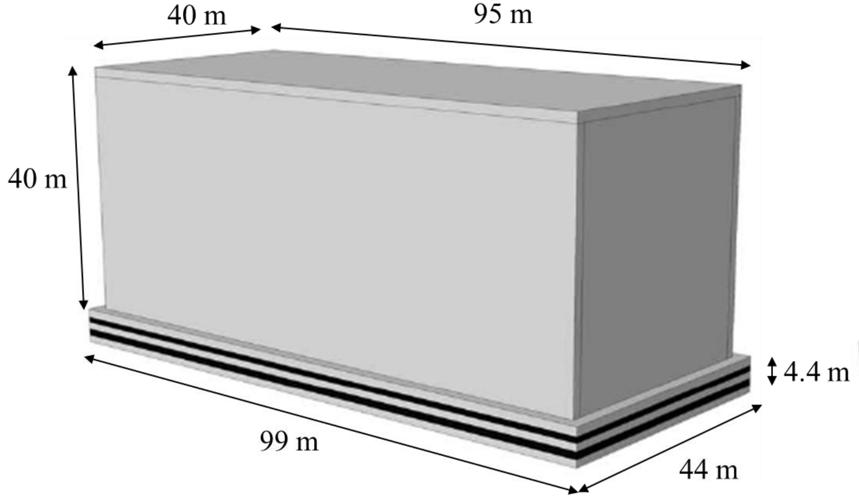
Frequency scale:

Starting of band gap scale: $\frac{f_m}{f_p} = \frac{6.12}{1.3} = 4.7$ close to $\frac{1}{\sqrt{l_r}} = \sqrt{22} = 4.69$

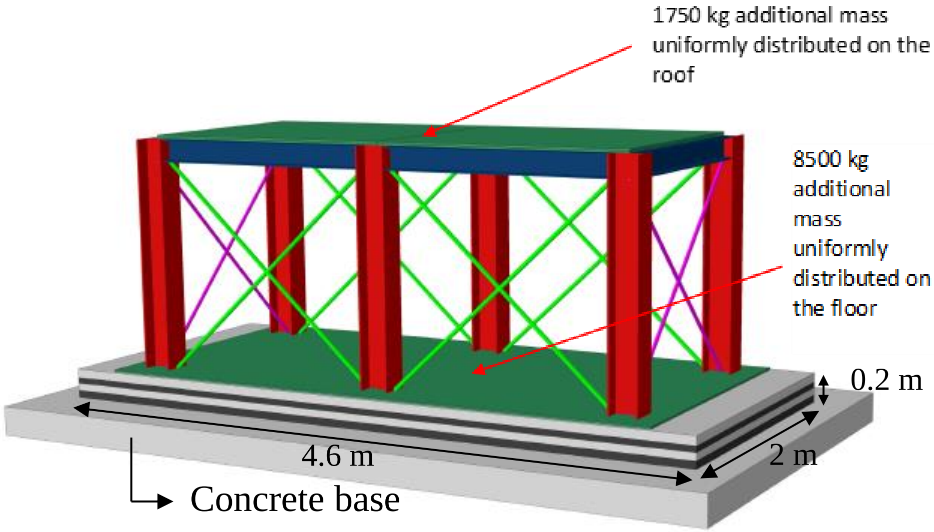
End of band gap scale: $\frac{f_m}{f_p} = \frac{20.34}{4.34} = 4.69$ same as $\frac{1}{\sqrt{l_r}} = \sqrt{22} = 4.69$

Scaled 1D periodic foundation

Prototype design

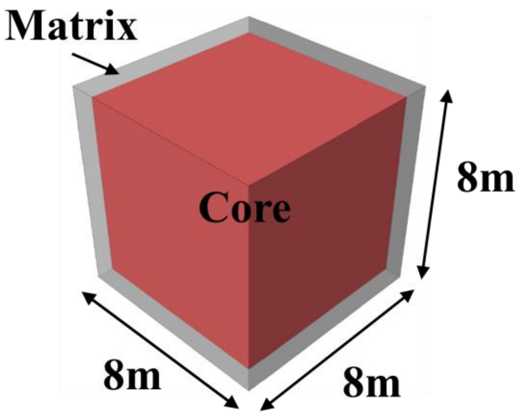


Model design



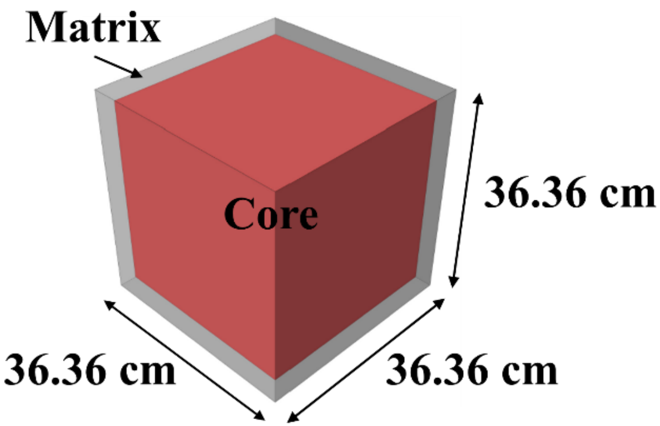
Scaled 3D periodic foundation

Full-scale 3D periodic foundation unit cell



Unit cell size = 8 m; Core size = 7.2 m;

Scaled model of 3D periodic foundation unit cell

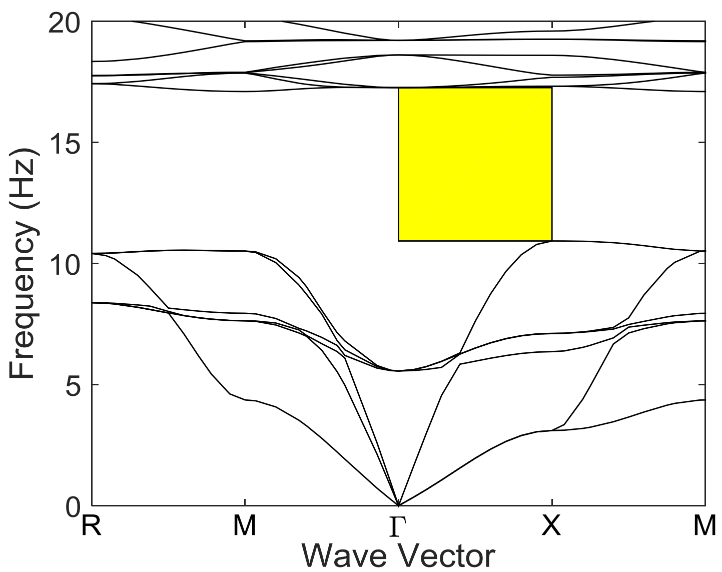


Unit cell size = 36.36 cm; Core size = 32.5 cm;

	Material for Prototype			Material for Model		
Material	Young's Modulus (MPa)	Density (kg/m^3)	Poisson's Ratio	Young's Modulus (Pa)	Density (kg/m^3)	Poisson's Ratio
Concrete	31400	2300	0.2	31400	2300	0.2
Rubber	3.49	1100	0.463	0.1586	1100	0.463

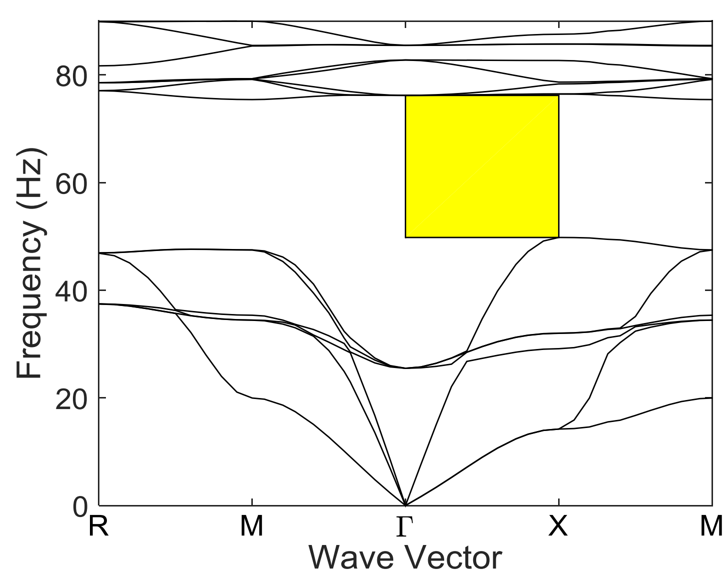
Scaled 3D periodic foundation

Theoretical frequency band gap of full-scale unit cell



Frequency band gap = 11.18–17.16 Hz

Theoretical frequency band gap of scaled model unit cell



Frequency band gap = 50.9–75.03 Hz

Frequency scale:

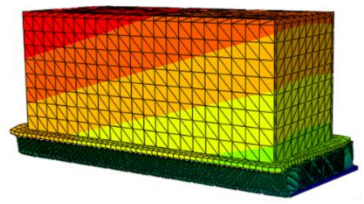
Starting of band gap scale: $\frac{f_m}{f_p} = \frac{50.9}{11.18} = 4.55$ Close to $\sqrt{22} = 4.69$

End of band gap scale: $\frac{f_m}{f_p} = \frac{75.03}{17.16} = 4.37$ Close to $\sqrt{22} = 4.69$

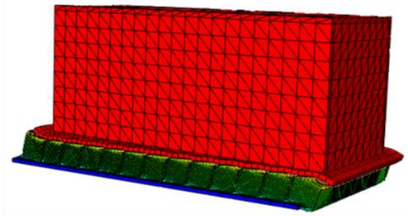
Modal Comparison

Mode shapes and natural frequencies of structure system

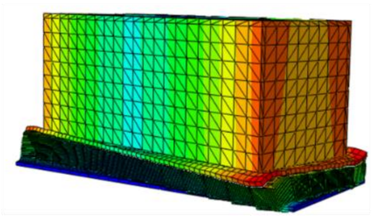
Full-scale structure system



Mode 1 (f_n = 0.86 Hz)

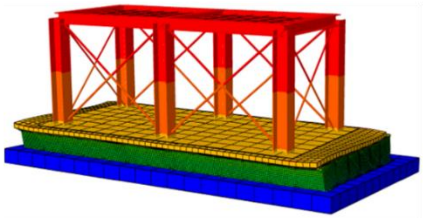


Mode 2 (f_n = 0.91 Hz)

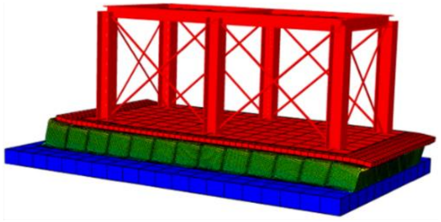


Mode 3 (f_n = 0.95 Hz)

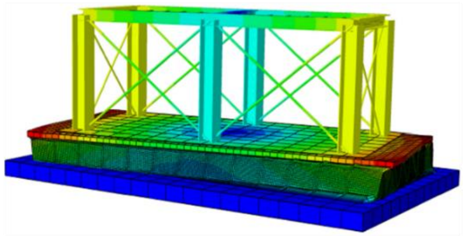
Scaled model of structure system



Mode 1 (f_n = 4.06 Hz)



Mode 2 (f_n = 4.17 Hz)



Mode 3 (f_n = 4.76 Hz)

Frequency scale:

Mode 1 scale $$\frac{4.06}{0.86} = 4.72$$

Mode 2 scale $$\frac{4.17}{0.91} = 4.58$$

Mode 3 scale $$\frac{4.76}{0.95} = 5.01$$

Task 4: Experimental Study of Periodic Foundations

Fabrication of test specimen

Construction of superstructure

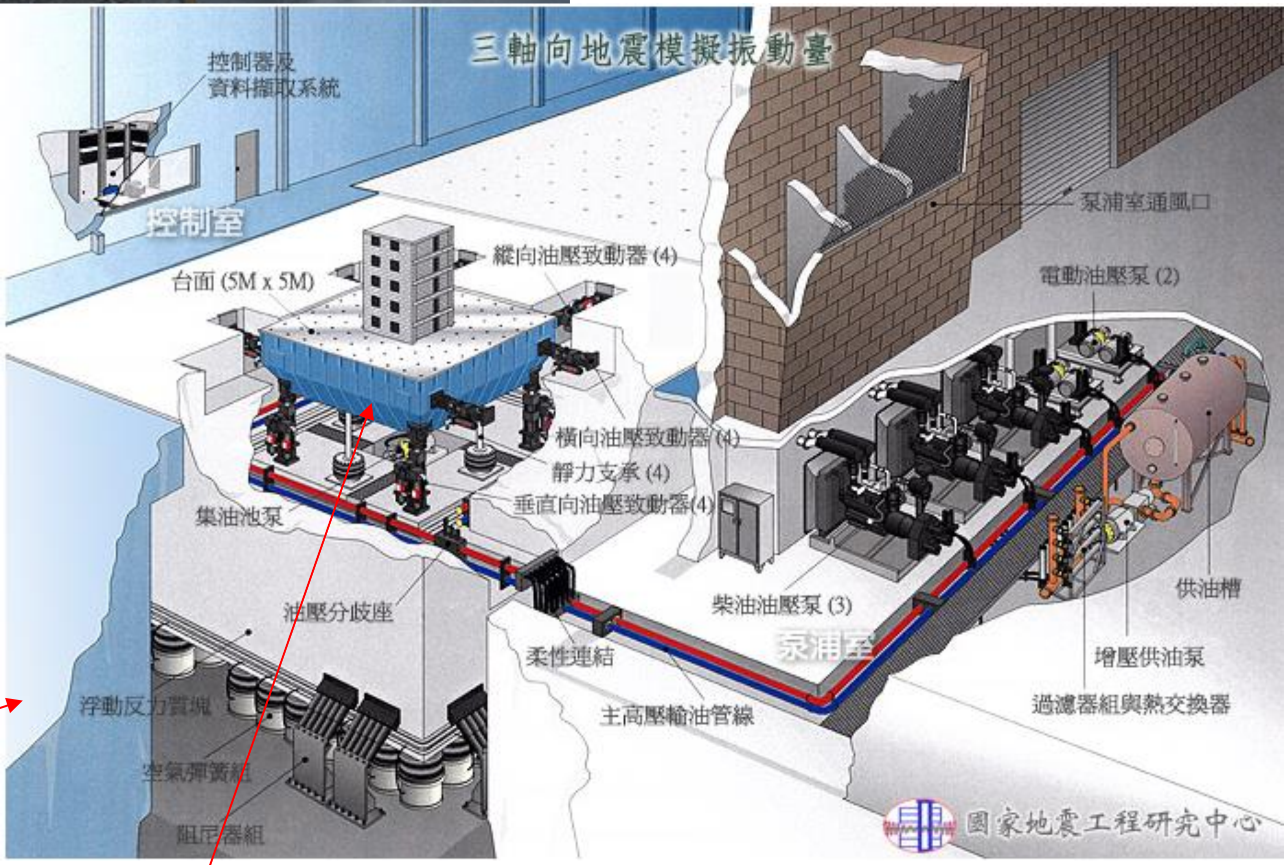
Casting of concrete layers

Resin solution and polyurethane glue

Construction of 1D periodic foundation

Test Facility

NARLabs 國家實驗研究院
國家地震工程研究中心
National Center for Research on Earthquake Engineering



12 actuators to simulate motions in 6 degrees of freedom

Experimental test of 1D periodic foundation

Case 1

Case 2

Case 3

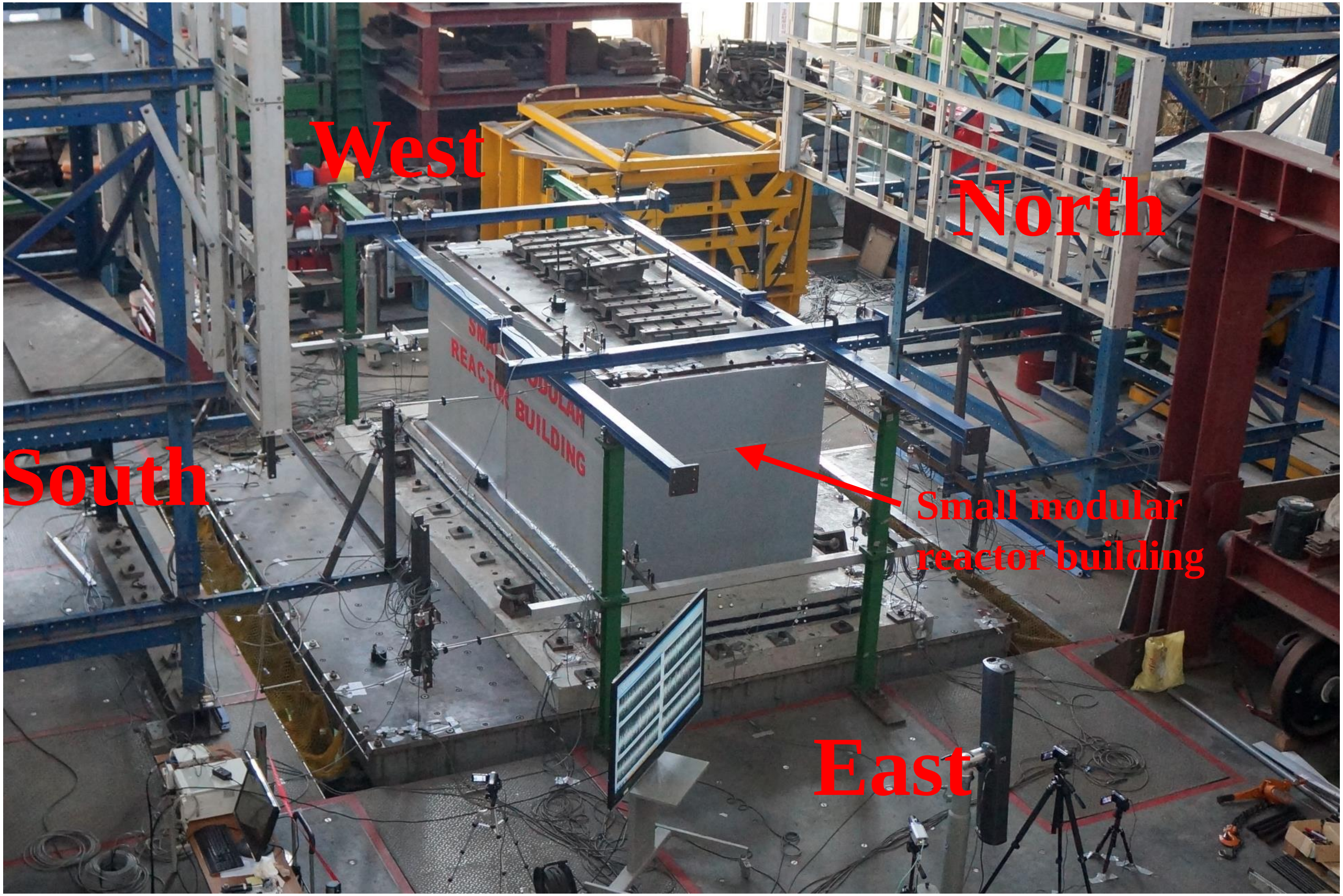
Case 4

Experimental test of 1D periodic foundation

Test items:

- For Cases 1 and 3 (foundations tests)
  - ➢ Scanning frequency tests in 3 directions (horizontal, vertical, and torsional)
- For Cases 2 and 4 (structure systems tests)
  - ➢ White noise tests in 3 directions (horizontal, vertical, and torsional)
  - ➢ Scanning frequency tests in 3 directions (horizontal, vertical, and torsional)
  - ➢ Seismic tests in 3 directions (horizontal, vertical, and torsional)
  - ➢ Harmonic tests in 3 directions (horizontal, vertical, and torsional)

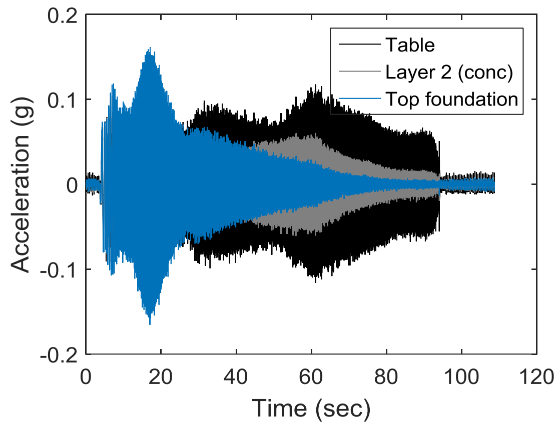
Test setup

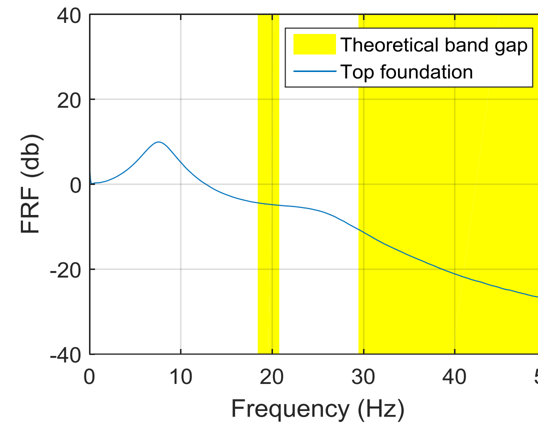

West
North
South
SMALL MODULAR
REACTOR BUILDING
Small modular
reactor building
East

Scanning frequency tests for foundations (Cases 1 and 3)

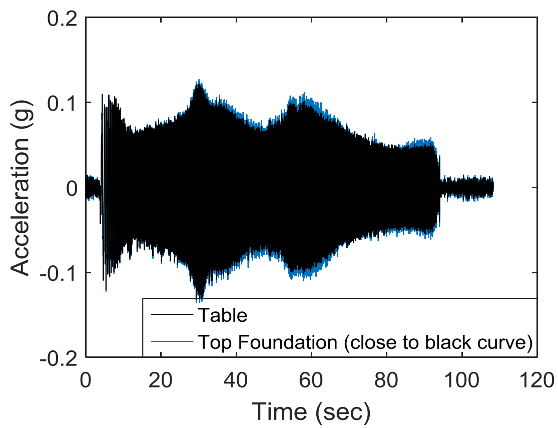
Horizontal direction

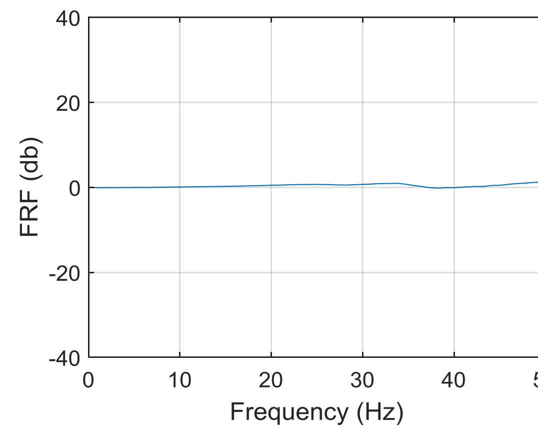
Case 1





Case 3



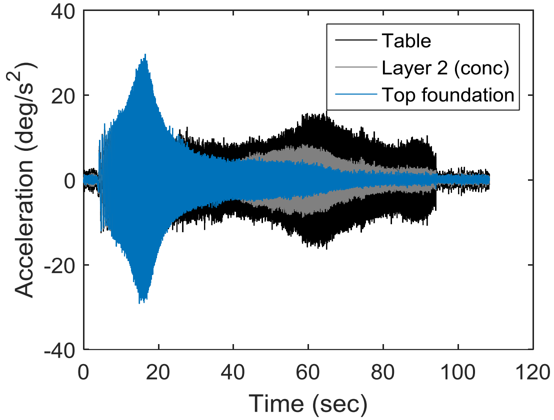


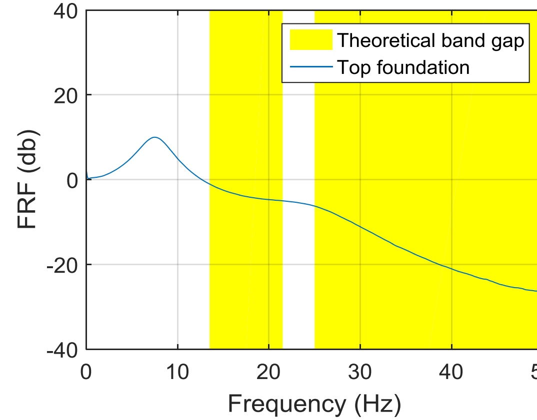
- Attenuation zone in horizontal direction for Case 1 is found at 12.74 – 50 Hz, which is close to theoretical frequency band gaps.
- In Case 3, the response at the top of concrete foundation is the same as input, which implies the foundation is rigidly attached to the shake table.

Scanning frequency tests for foundations (Cases 1 and 3)

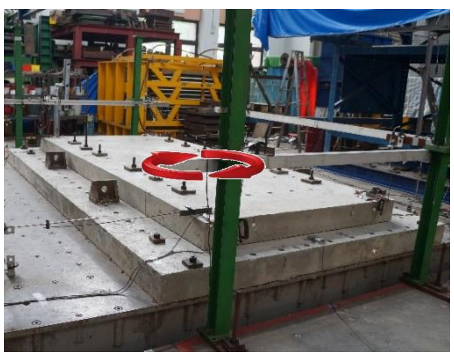
Torsional mode

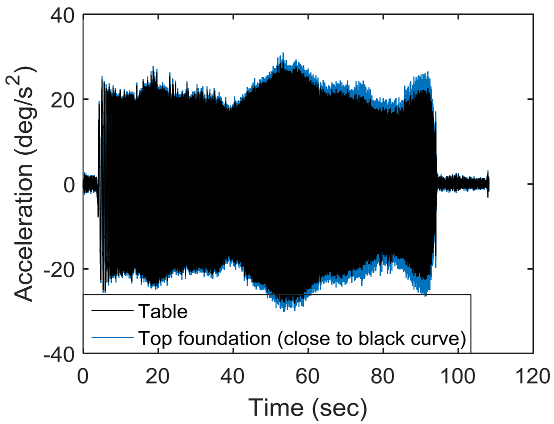
Case 1

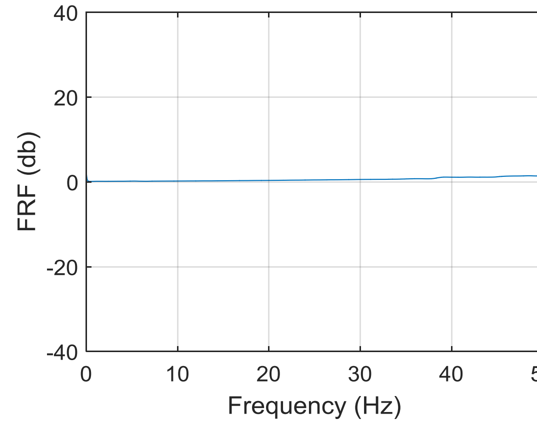




Case 3



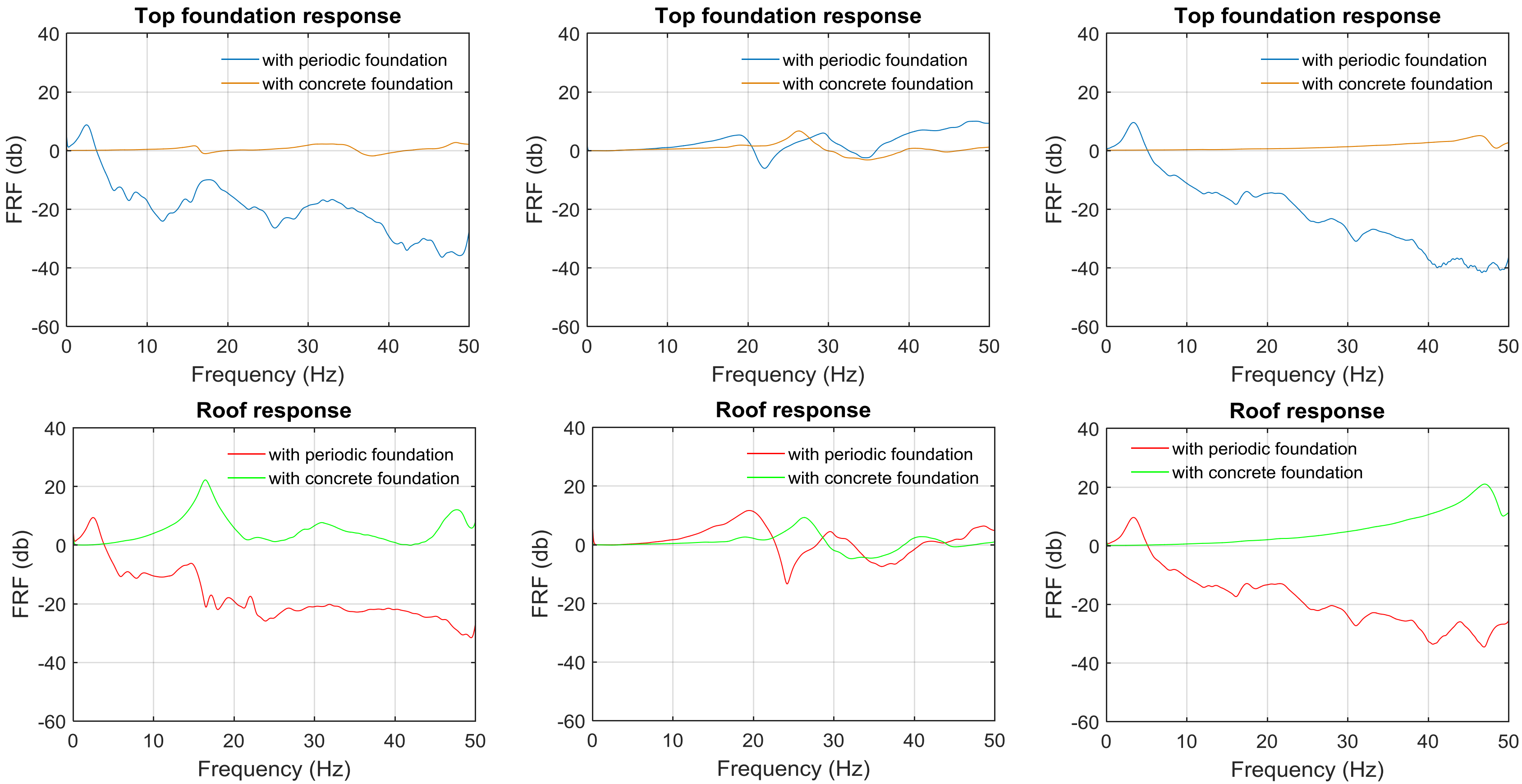




- Attenuation zone in torsional mode for Case 1 is found at 12.7 – 50 Hz, which is close to theoretical frequency band gaps.
- In Case 3, the response at the top of concrete foundation is the same as input, which implies the foundation is rigidly attached to the shake table.

Scanning frequency tests for structure systems (Cases 2 and 4)

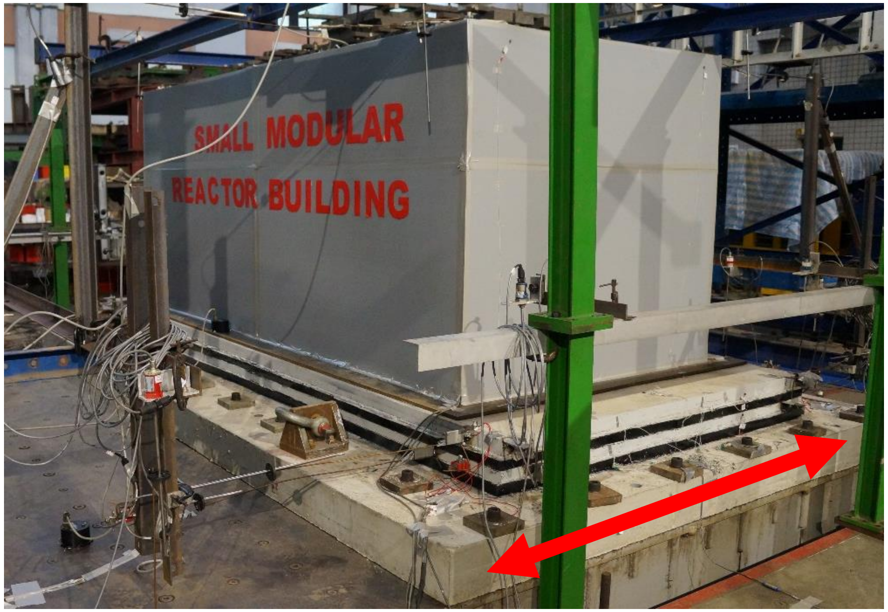
Horizontal direction | Vertical direction | Torsional mode



- In Case 2, large response reductions are observed in all three directions. Where FRF of -10 and -20 respectively correspond to 68.38% and 90% response reduction.
- In Case 4, the responses at the roof are mostly amplified in all three directions.

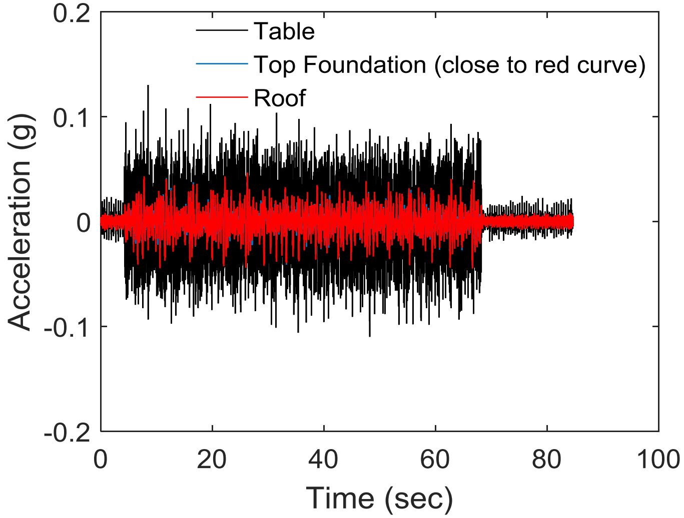
White noise tests for structure systems (Cases 2 and 4)

Case 2 white noise test in horizontal direction

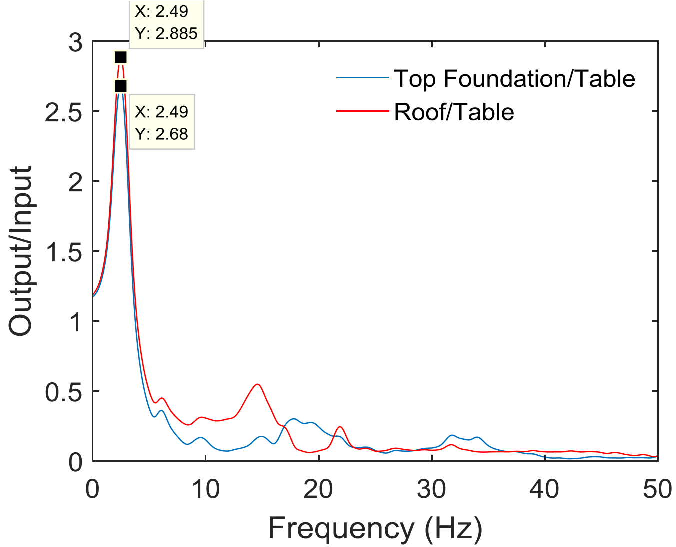


Natural frequency of structure system is 2.5 Hz (close to analytical result)

Acceleration response



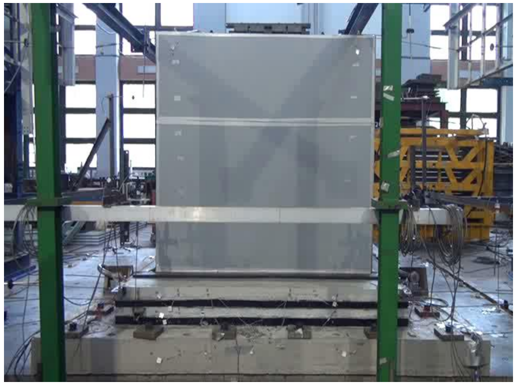
Normalized Frequency spectra

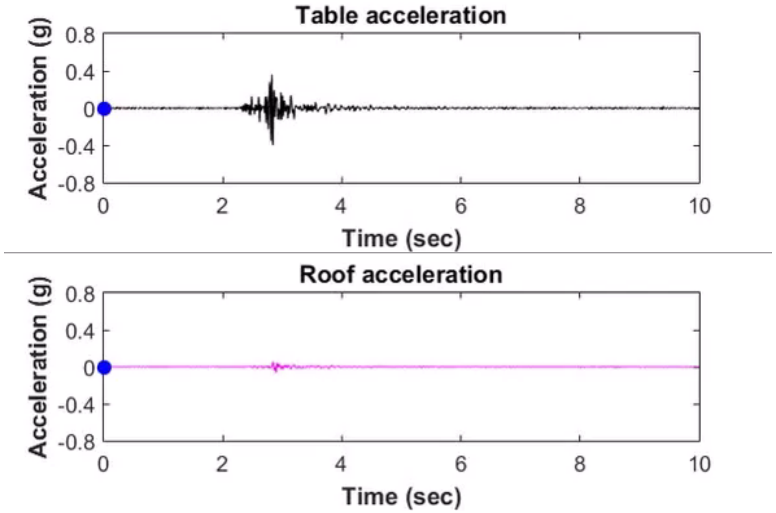


Seismic tests for structure systems in horizontal direction (Cases 2 and 4)

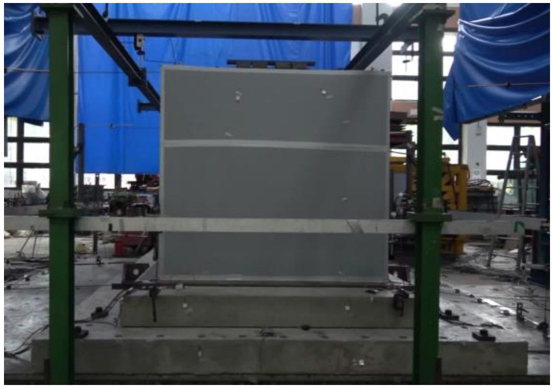
Earthquake event: **Gilroy** (05/14/2002)
Station: Gilroy array #3
Orientation: 58^{O}

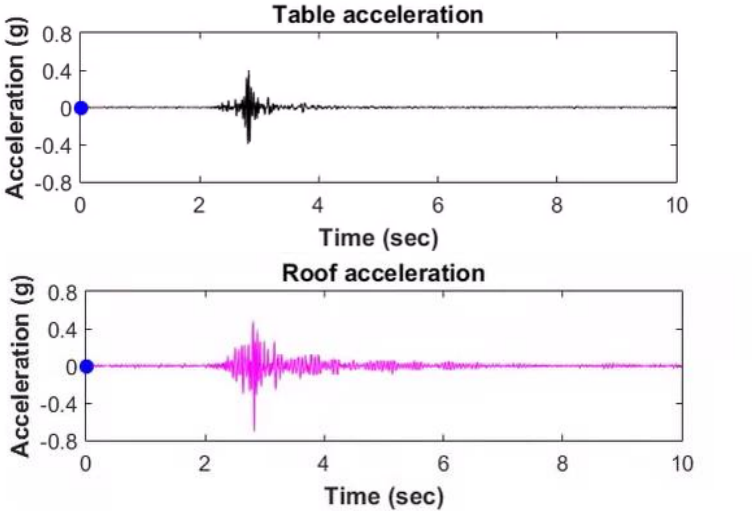
Case 2 (with periodic foundation)





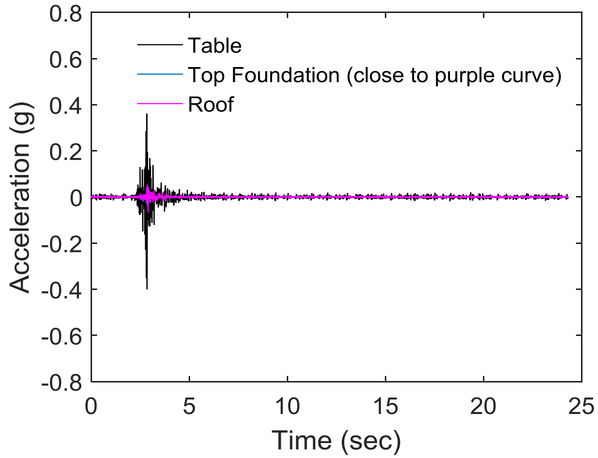
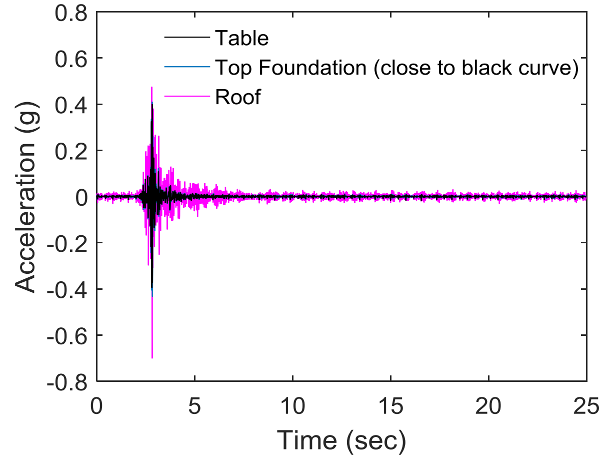
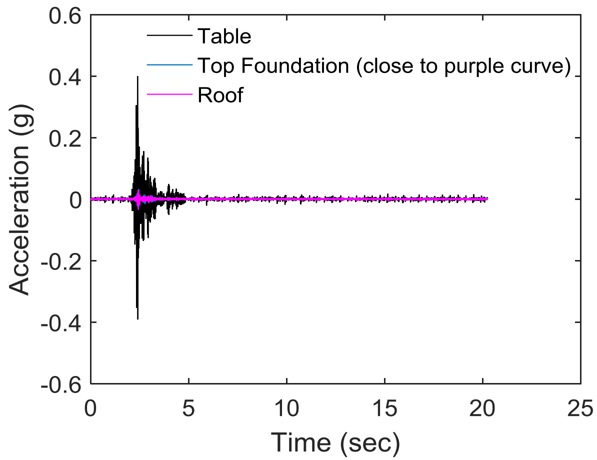
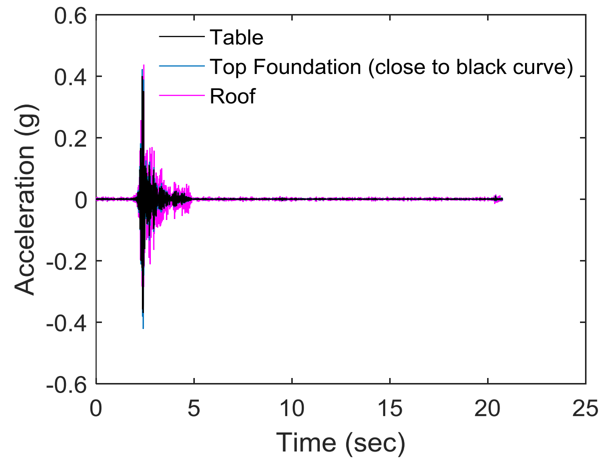
Case 4 (with concrete foundation)





Seismic tests for structure systems in horizontal direction (Cases 2 and 4)

Main frequency content of earthquake is inside frequency band gaps of periodic foundation

Earthquake	**With periodic foundation**	**With concrete foundation**
Gilroy		
Oroville		

Gilroy, with periodic foundation:

Gilroy, with concrete foundation:

Oroville, with periodic foundation:

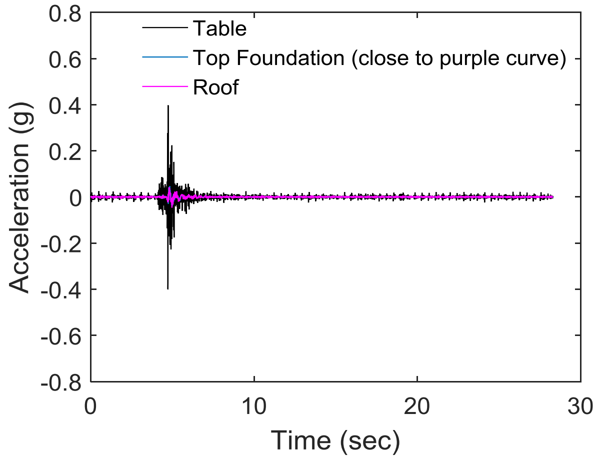
Oroville, with concrete foundation:

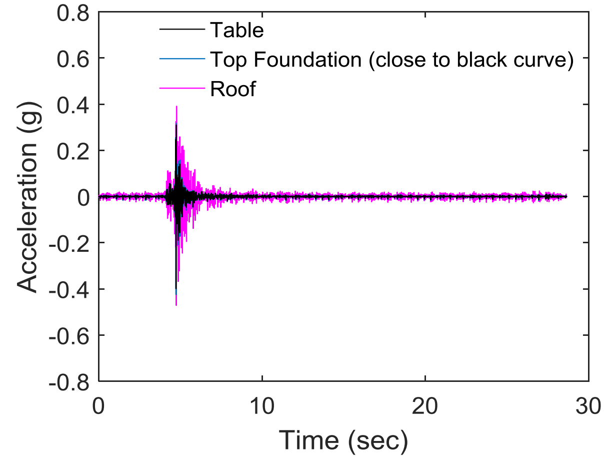
Seismic tests for structure systems in horizontal direction (Cases 2 and 4)

Main frequency content of earthquake is inside frequency band gaps of periodic foundation

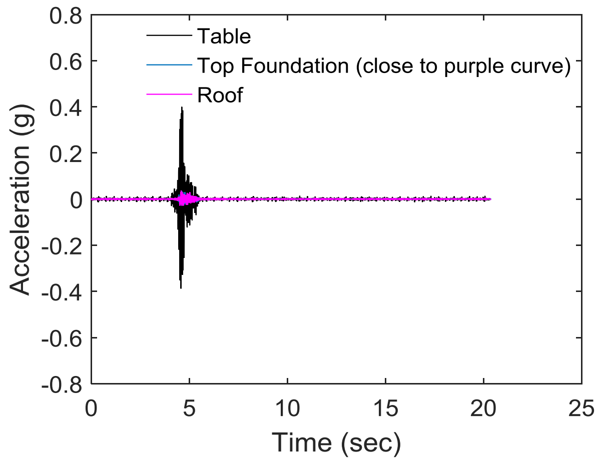
Earthquake	**With periodic foundation**	**With concrete foundation**

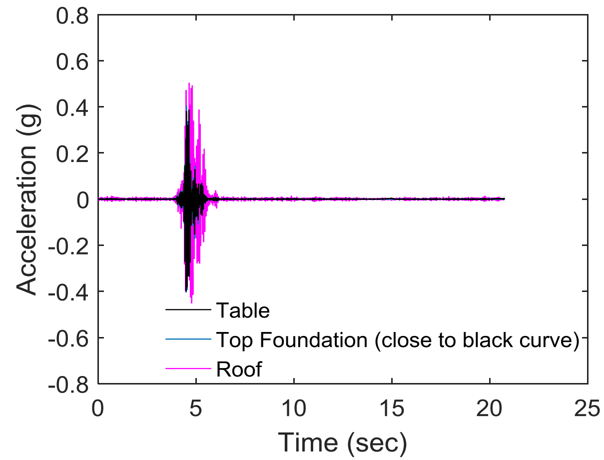
Anza





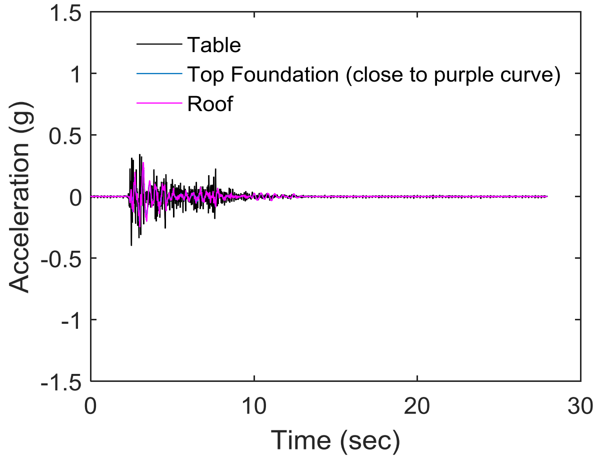
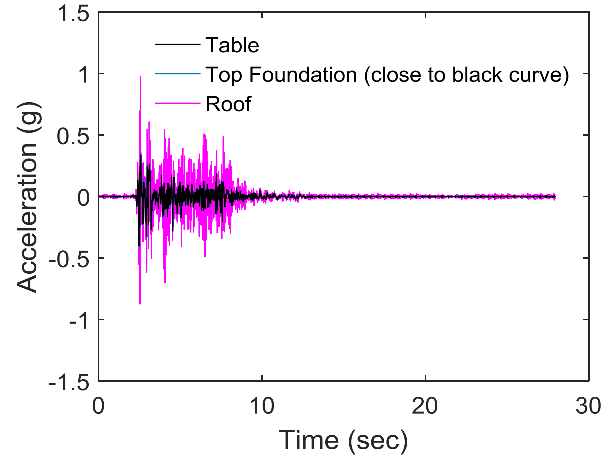
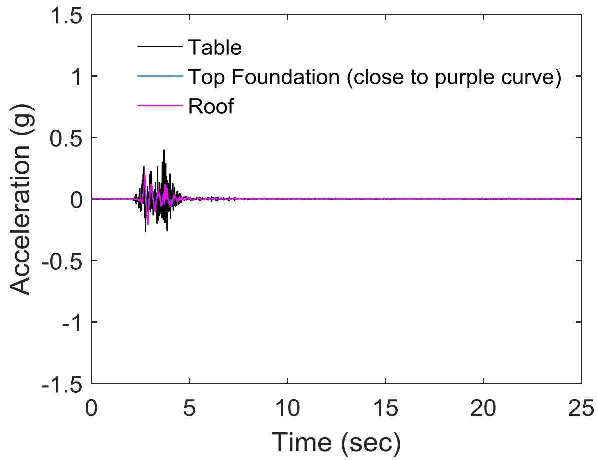
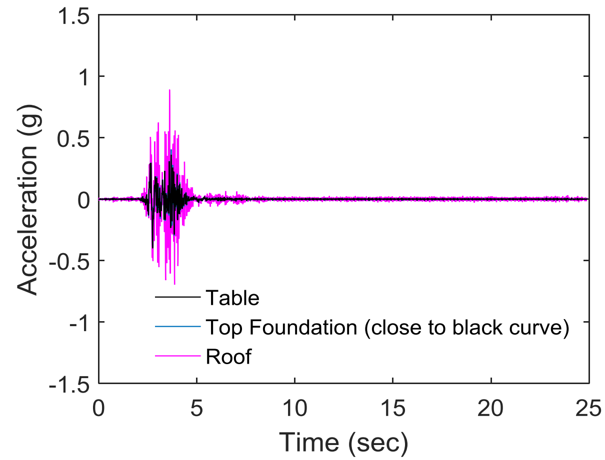
Bishop





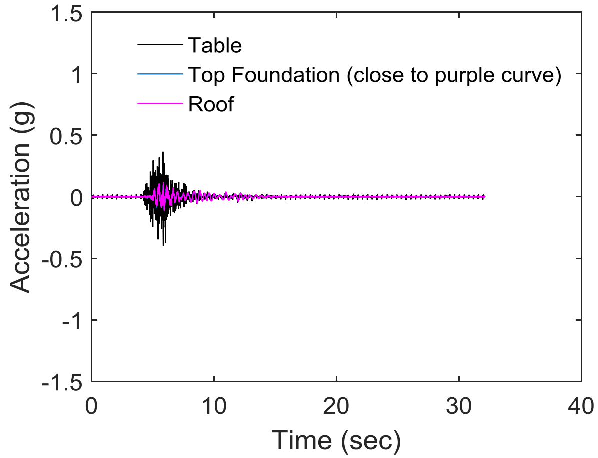
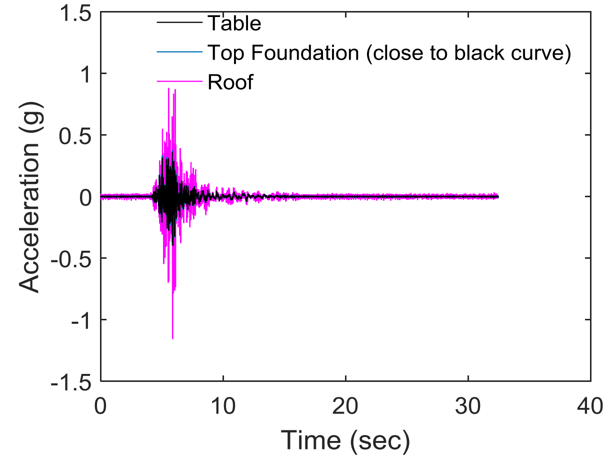
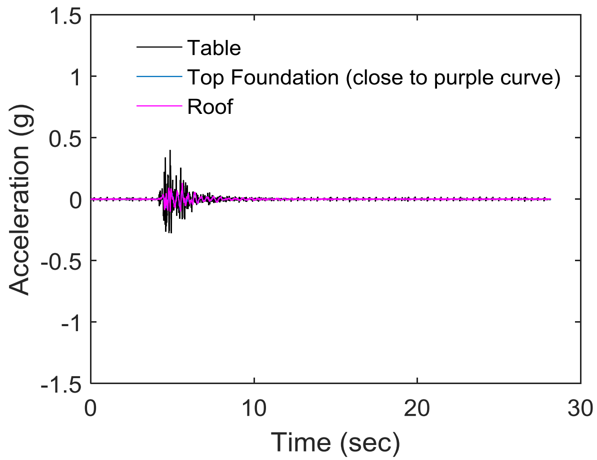
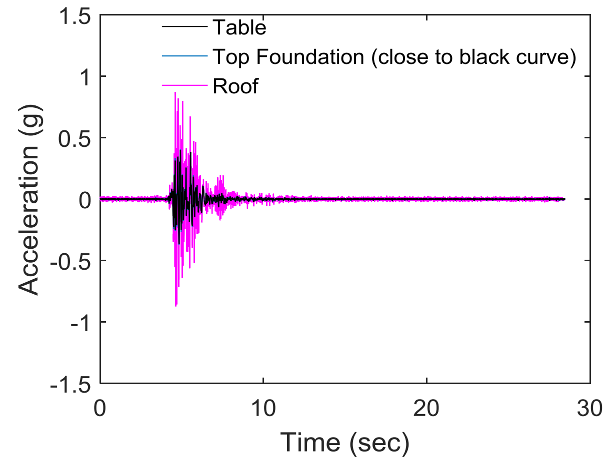
Seismic tests for structure systems in horizontal direction (Cases 2 and 4)

Main frequency content of earthquake is widely distributed

Earthquake	With periodic foundation	With concrete foundation
El Centro		
San Fernando		

Seismic tests for structure systems in horizontal direction (Cases 2 and 4)

Main frequency content of earthquake is widely distributed

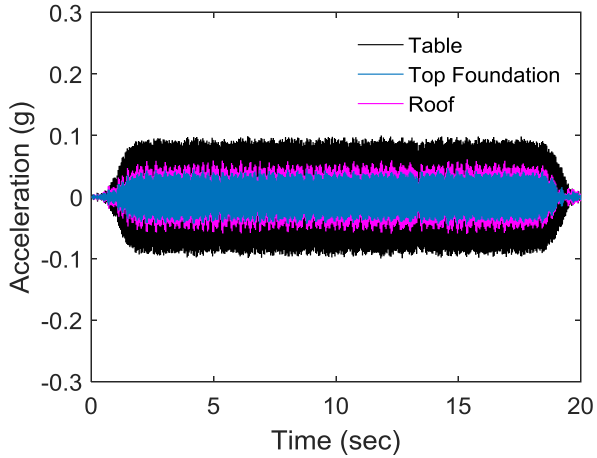
Earthquake	With periodic foundation	With concrete foundation
Northridge		
Loma Prieta		

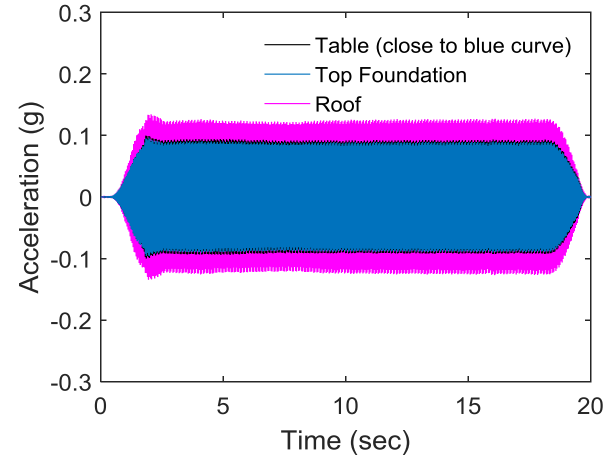
Harmonic tests for structure systems in vertical direction (Cases 2 and 4)

Frequency is inside frequency band gaps of periodic foundation

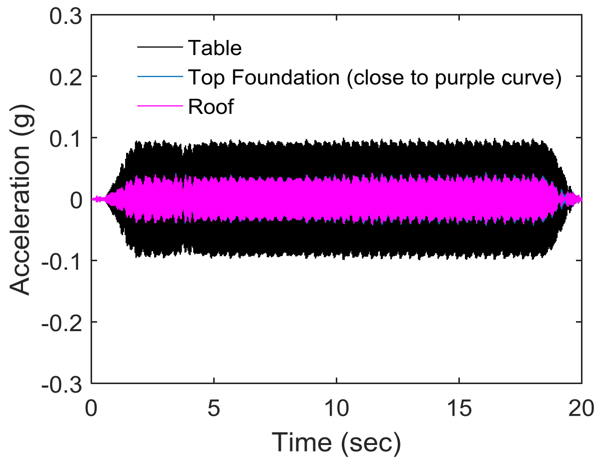
Wave | **With periodic foundation** | **With concrete foundation**

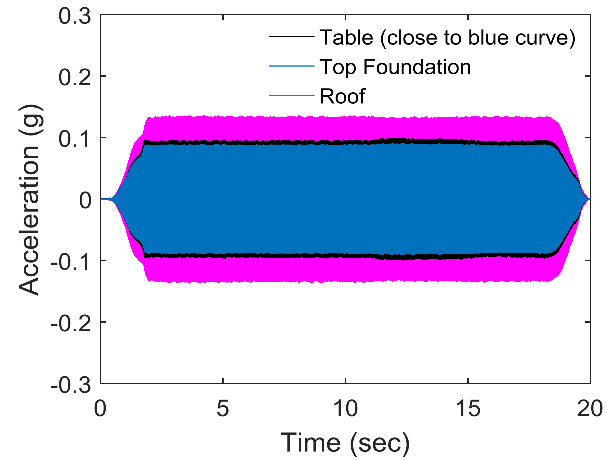
Sine 24 Hz





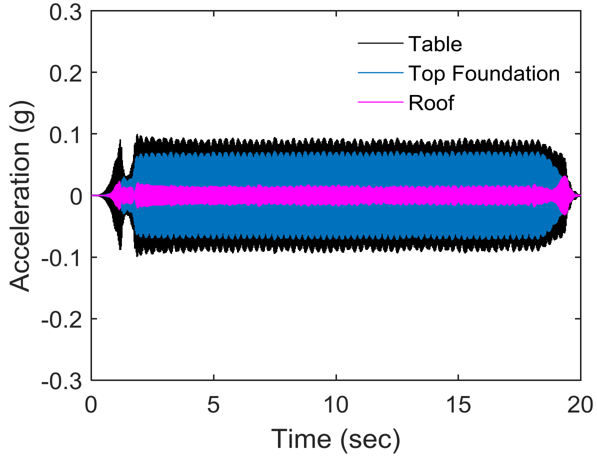
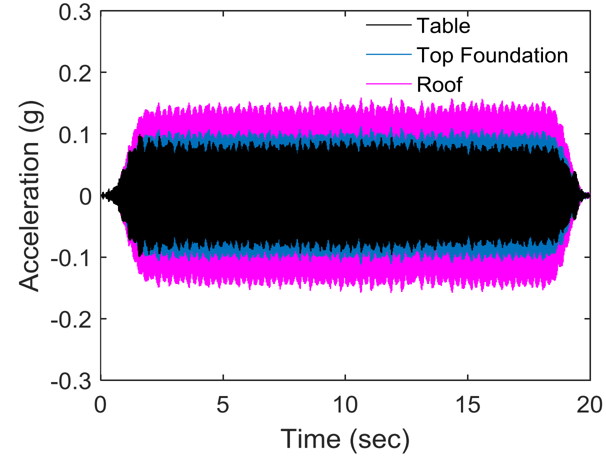
Sine 25 Hz





Harmonic tests for structure systems in vertical direction (Cases 2 and 4)

Frequency is inside frequency band gaps of periodic foundation

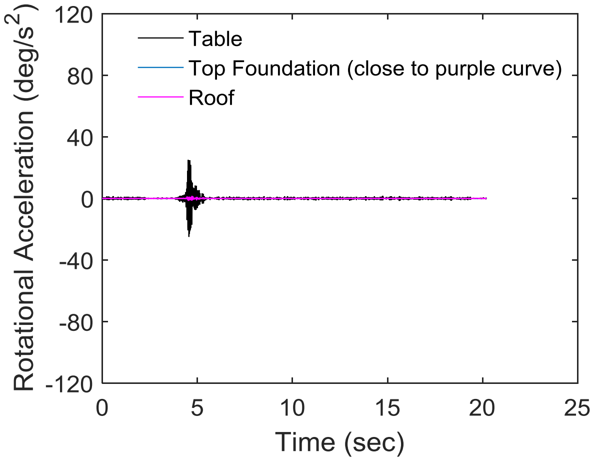
Wave	**With periodic foundation**	**With concrete foundation**
Sine 34 Hz		

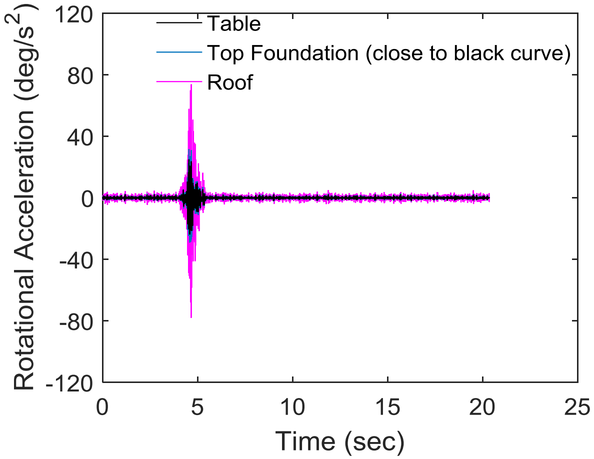
Seismic tests for structure systems in torsional mode (Cases 2 and 4)

With periodic foundation | **With concrete foundation**

Earthquake Bishop

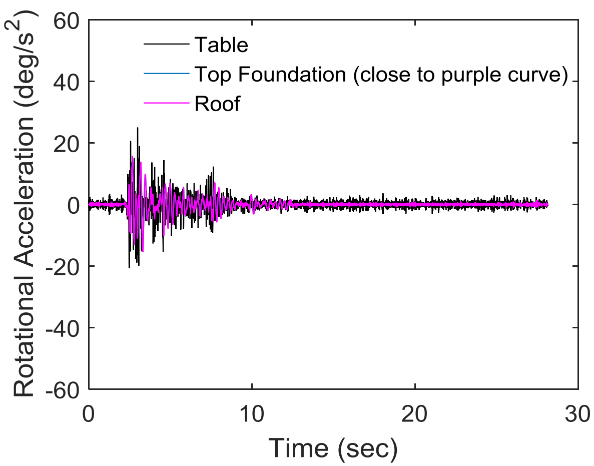
(Main frequency content of earthquake is inside frequency band gaps of periodic foundation)

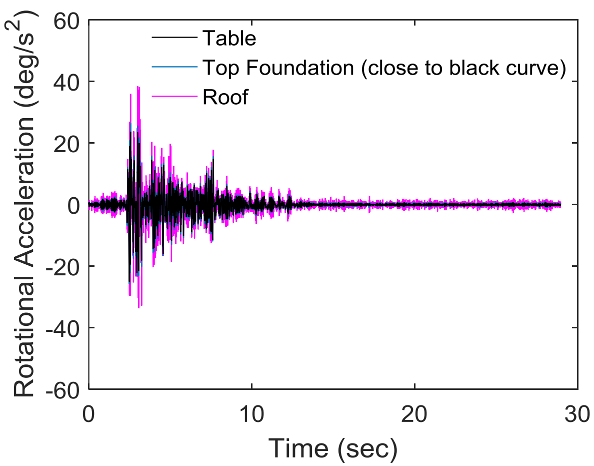




El Centro

(Main frequency content of earthquake is widely distributed)

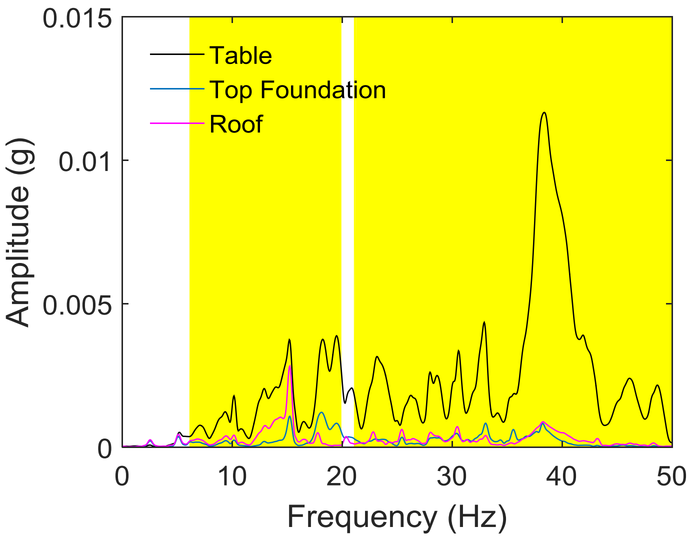




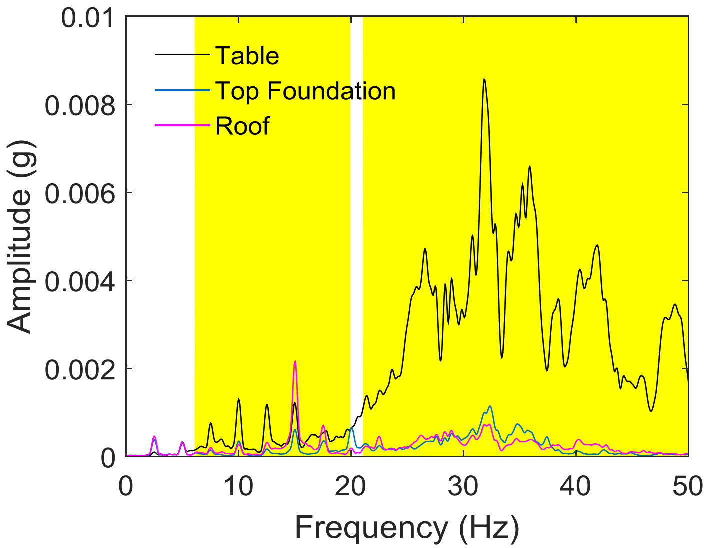
Discussions

Effect of frequency band gap on acceleration response

Bishop



Oroville

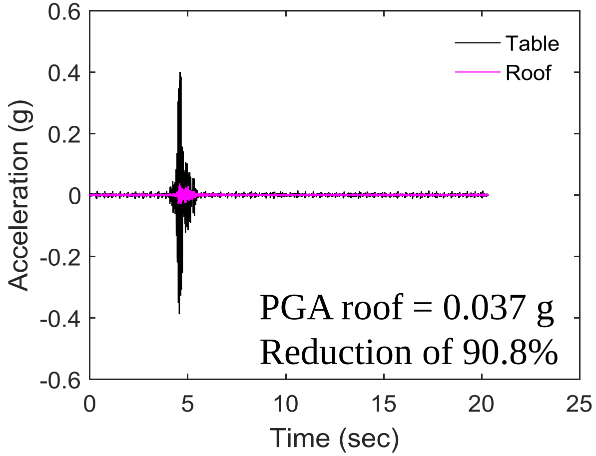


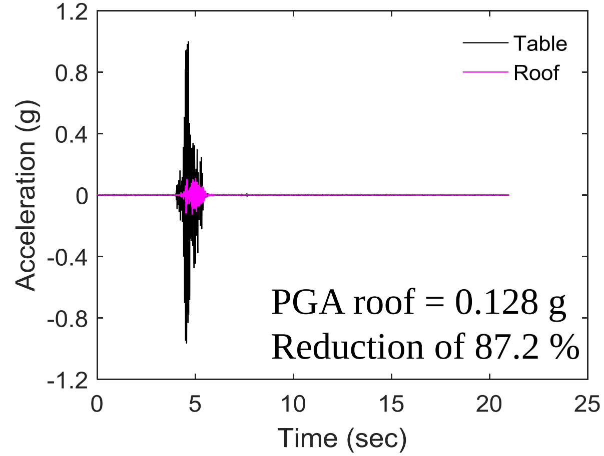
Discussions

Effect of frequency band gap on acceleration response

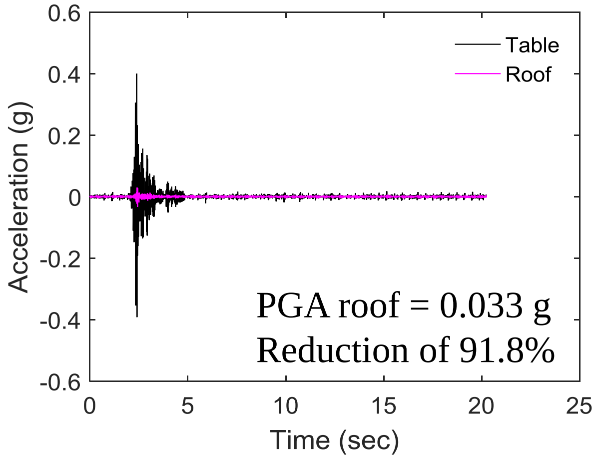
Earthquake | **PGA at table 0.4 g** | **PGA at table 1 g**

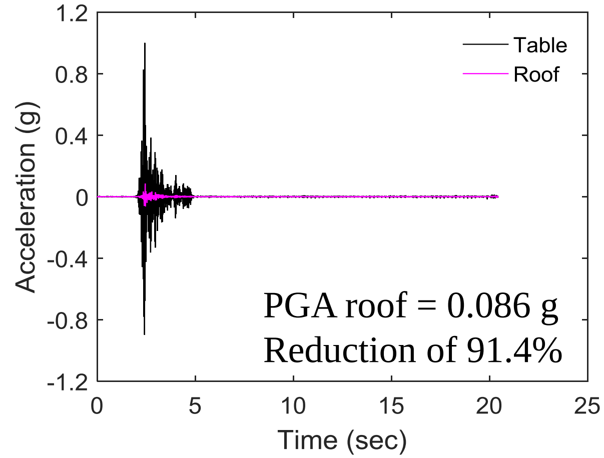
Bishop





Oroville

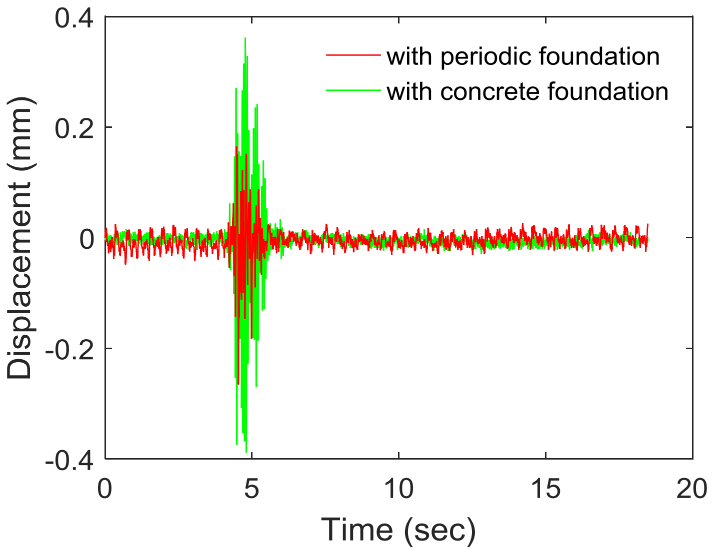




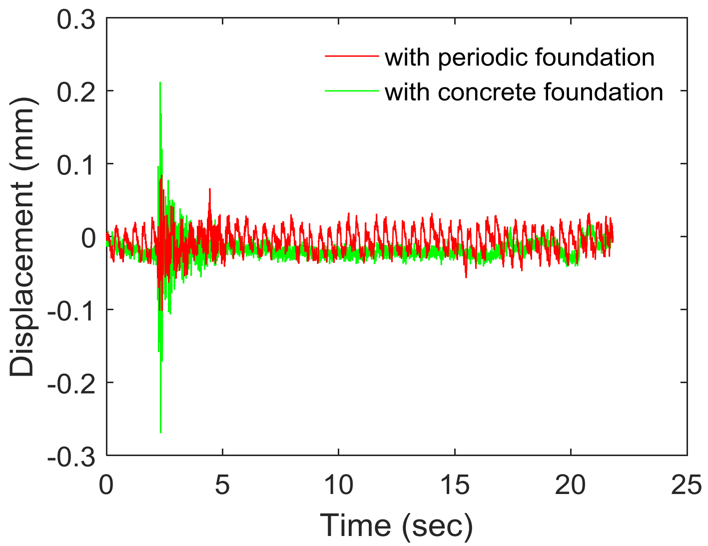
Discussions

Roof to table relative displacement response

Bishop



Oroville



Conclusions

- The basic concept on how to find the frequency band gaps was reviewed.
- A set of design guidelines for periodic foundations was proposed.
- The test specimen of 1D periodic foundation has been constructed, and some tests have been performed.
- The test results show that periodic foundations can effectively reduce the vibration response when the frequency contents of the incoming waves are within the frequency band gap of the periodic foundation supported SMR building.

Thank you for your attention.