Periodic Material-Based Seismic Base Isolators for Small Modular Reactors

NEET-1 Annual Meeting
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Research Team

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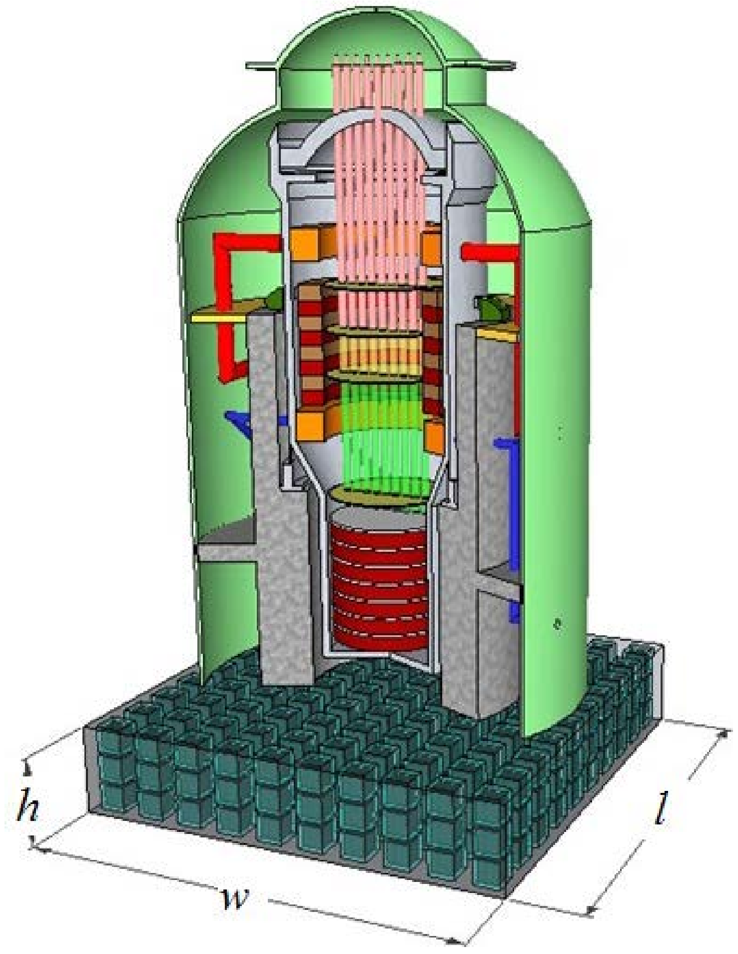
Project overview

Purpose:

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 3D periodic foundation</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>
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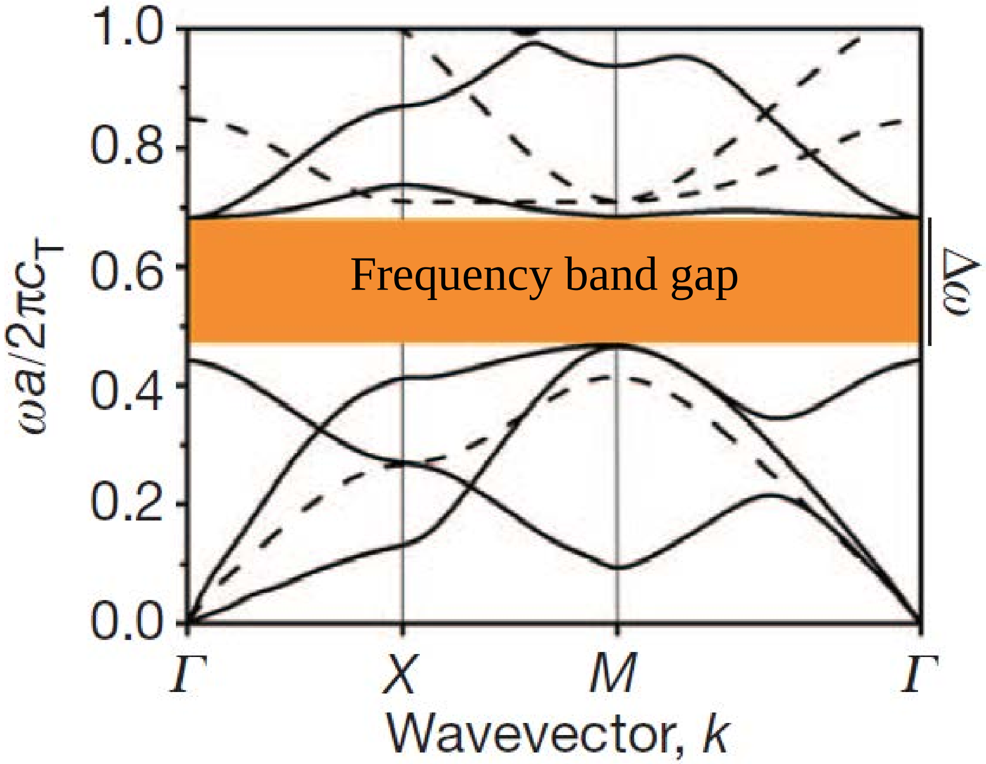
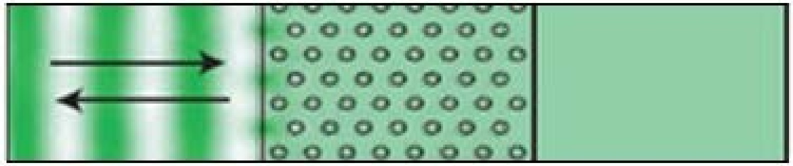
Wave propagation in phononic crystal

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

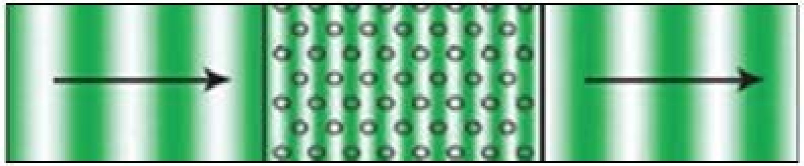
Typical dispersion curve [1]



Wave Propagation [2]



Wave propagation with frequency within the frequency band gap



Wave propagation with frequency outside of the frequency band gap

[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

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: $\mathbf{r}$ is coordinate vector
$\mathbf{u}(\mathbf{r})$ is displacement vector
$\rho(\mathbf{r})$ is the density
$\lambda(\mathbf{r})$ and $\mu(\mathbf{r})$ are the Lamé constant

Periodic 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: $\mathbf{K}$ is the wave vector
$\mathbf{a}$ is unit cell size

Calculating dispersion curve

Applying the periodic boundary condition (Eq.2) to the governing equation, (Eq.1), the wave equation can be transferred into eigen value problem as follow:

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

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

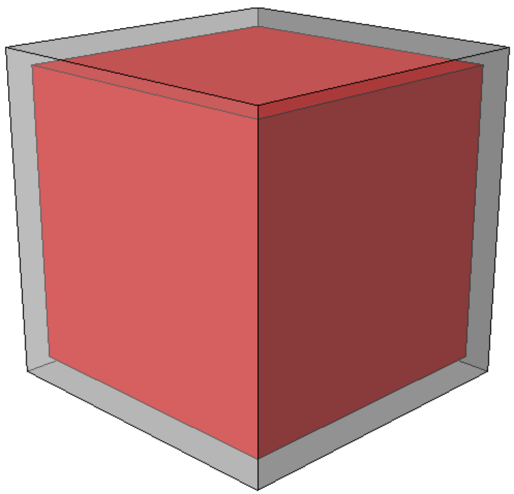
For each wave vector (**K**) a series of corresponding frequencies (ω) can be obtained.

Calculating dispersion curve

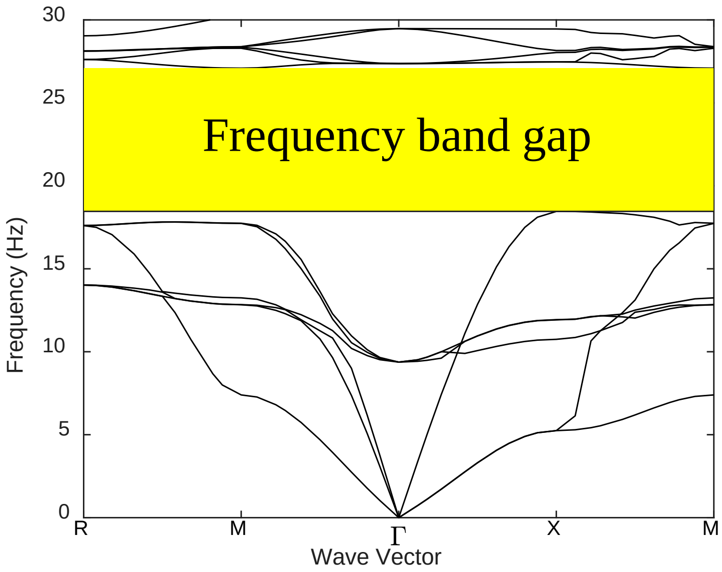
Eigen value problem:

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

Infinite number of unit cells condition



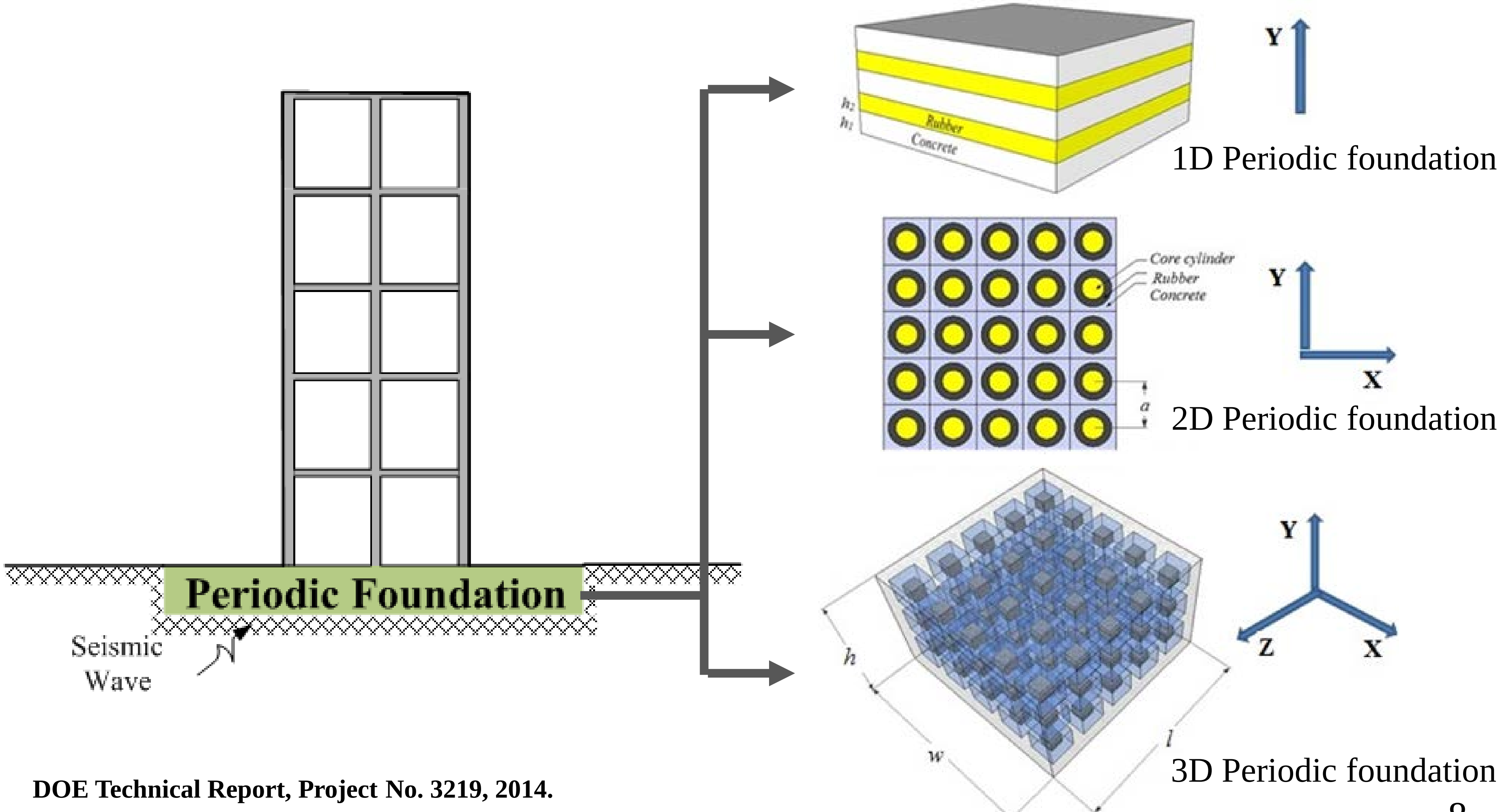
Typical two-component 3D periodic foundation



Typical dispersion curve

Application of phononic crystal

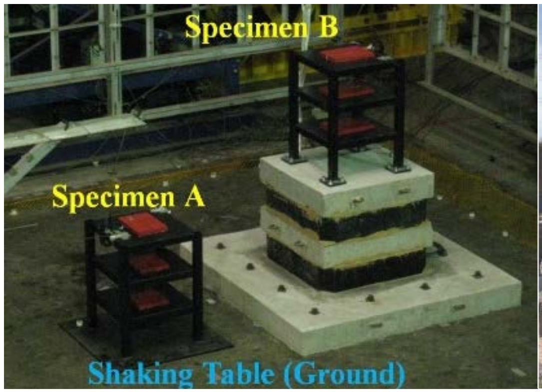
In civil engineering field

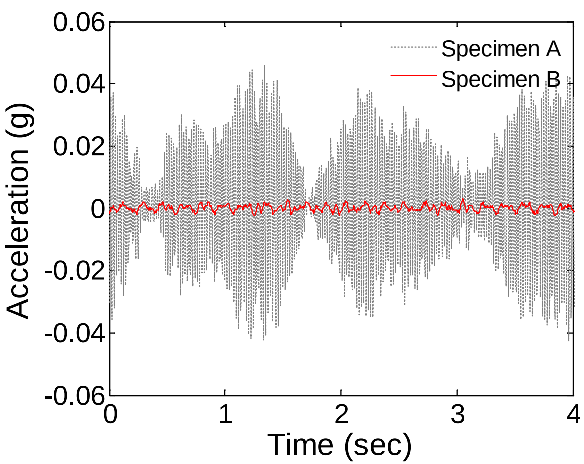


DOE Technical Report, Project No. 3219, 2014.

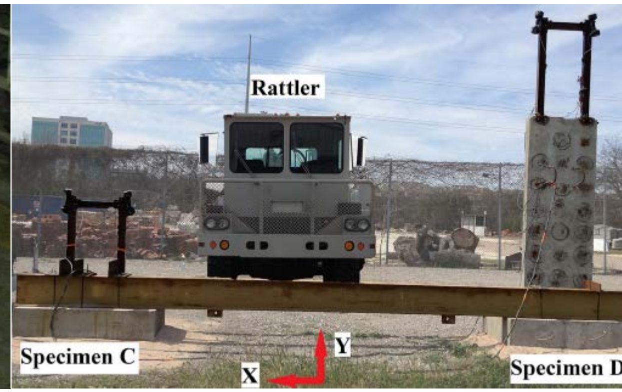
Experimental study on periodic foundation

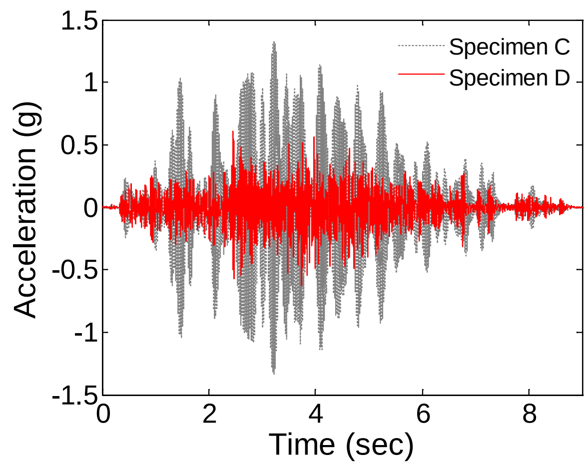
1D Periodic foundation



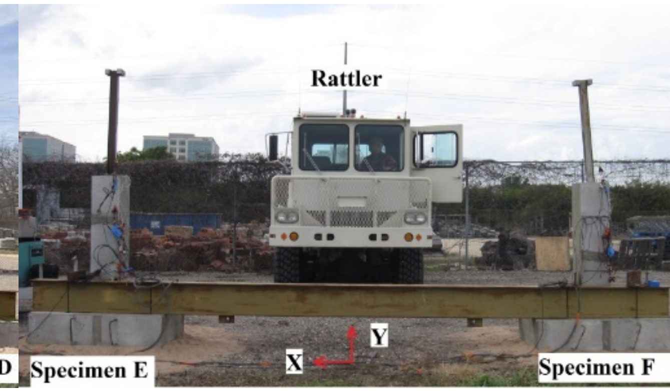


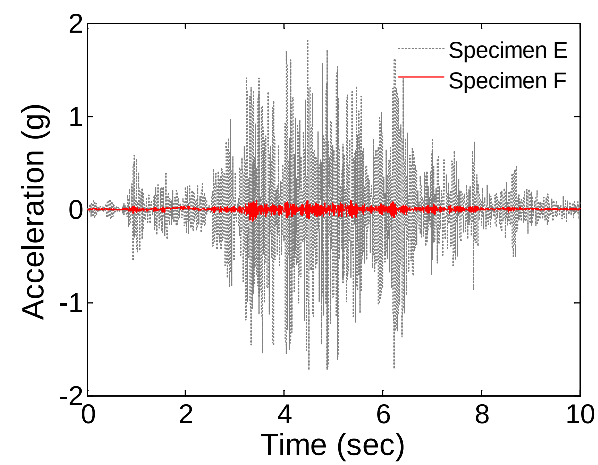
2D Periodic foundation





3D Periodic foundation

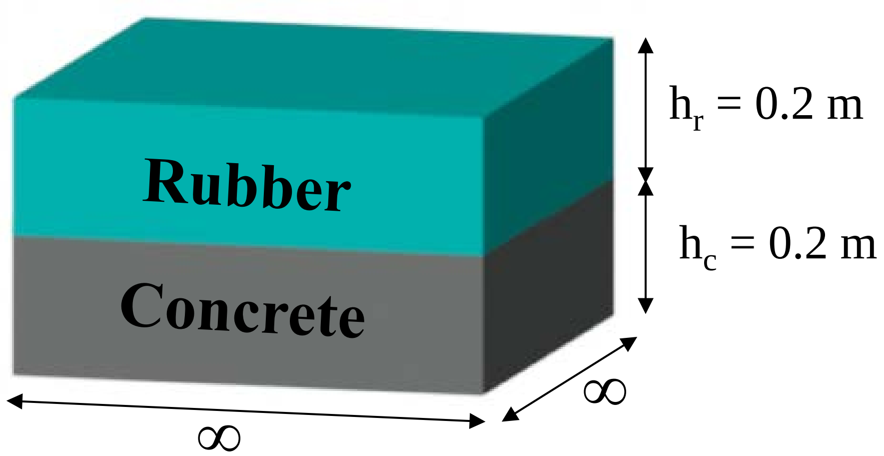




DOE Technical Report, Project No. 3219, 2014.

1D Periodic Foundations

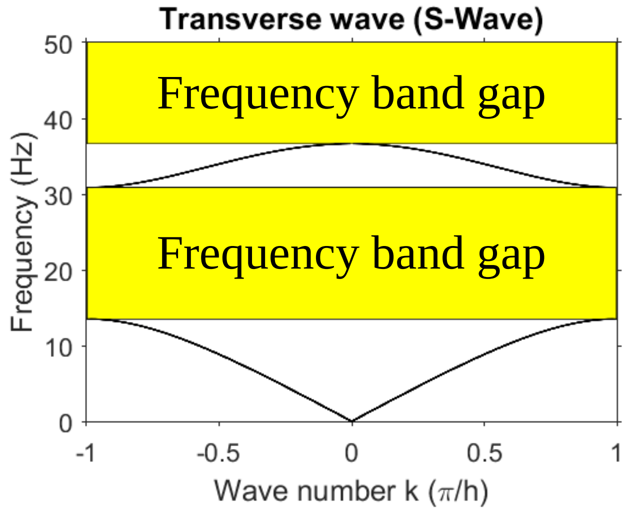
One unit cell of 1D periodic foundation

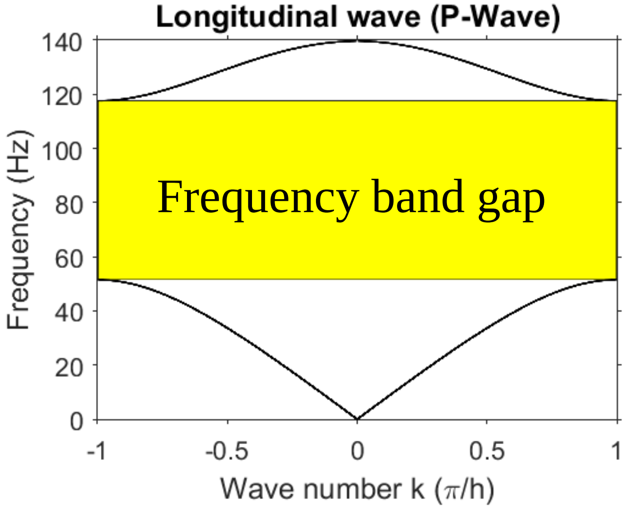


Fix material properties

Material	Young's Modulus (Pa)	Density (kg/m^3)	Poisson's Ratio
Concrete	3.14×10^{10}	2300	0.2
Rubber	5.8×10^{5}	1300	0.463

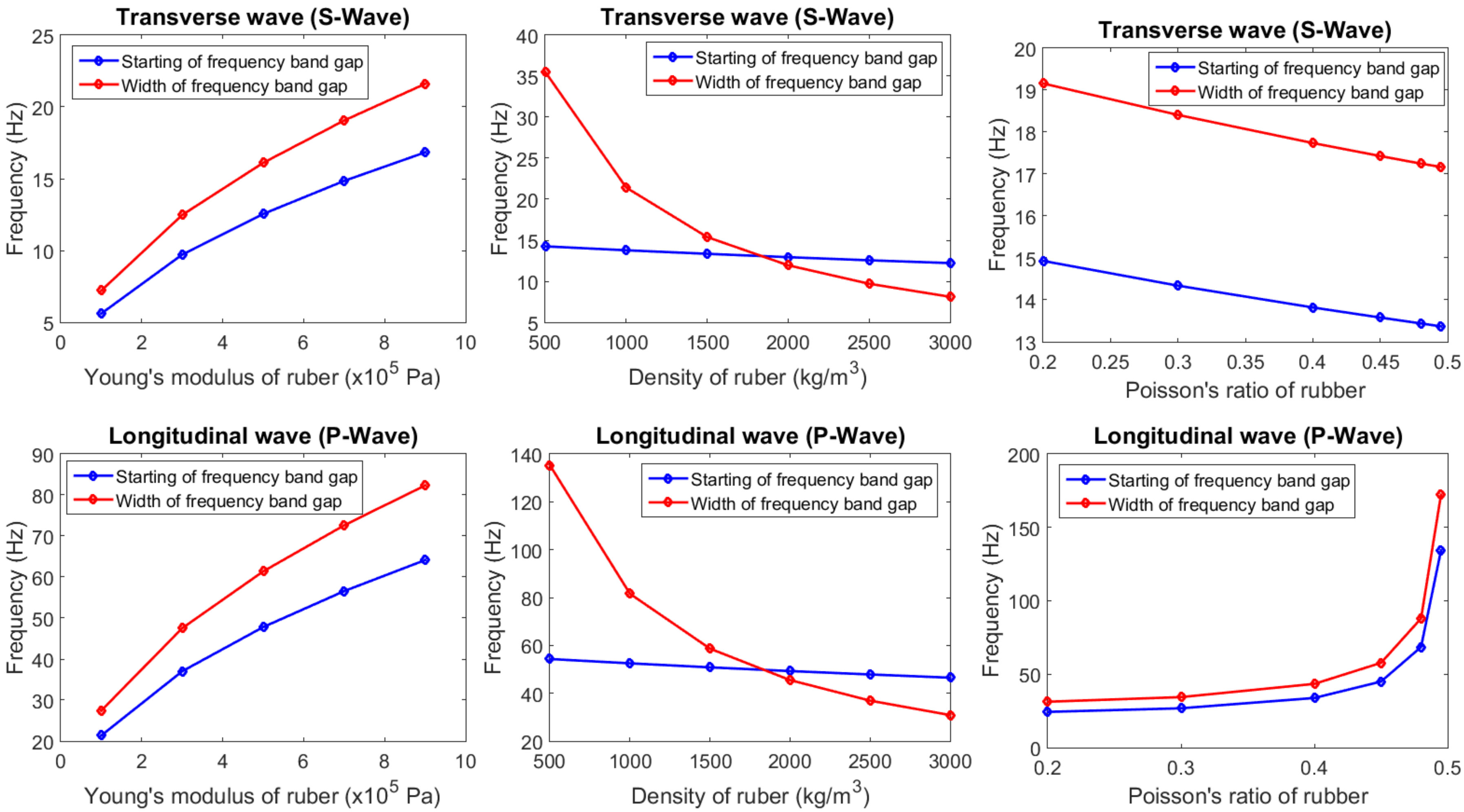
Dispersion curve for infinite number of unit cells





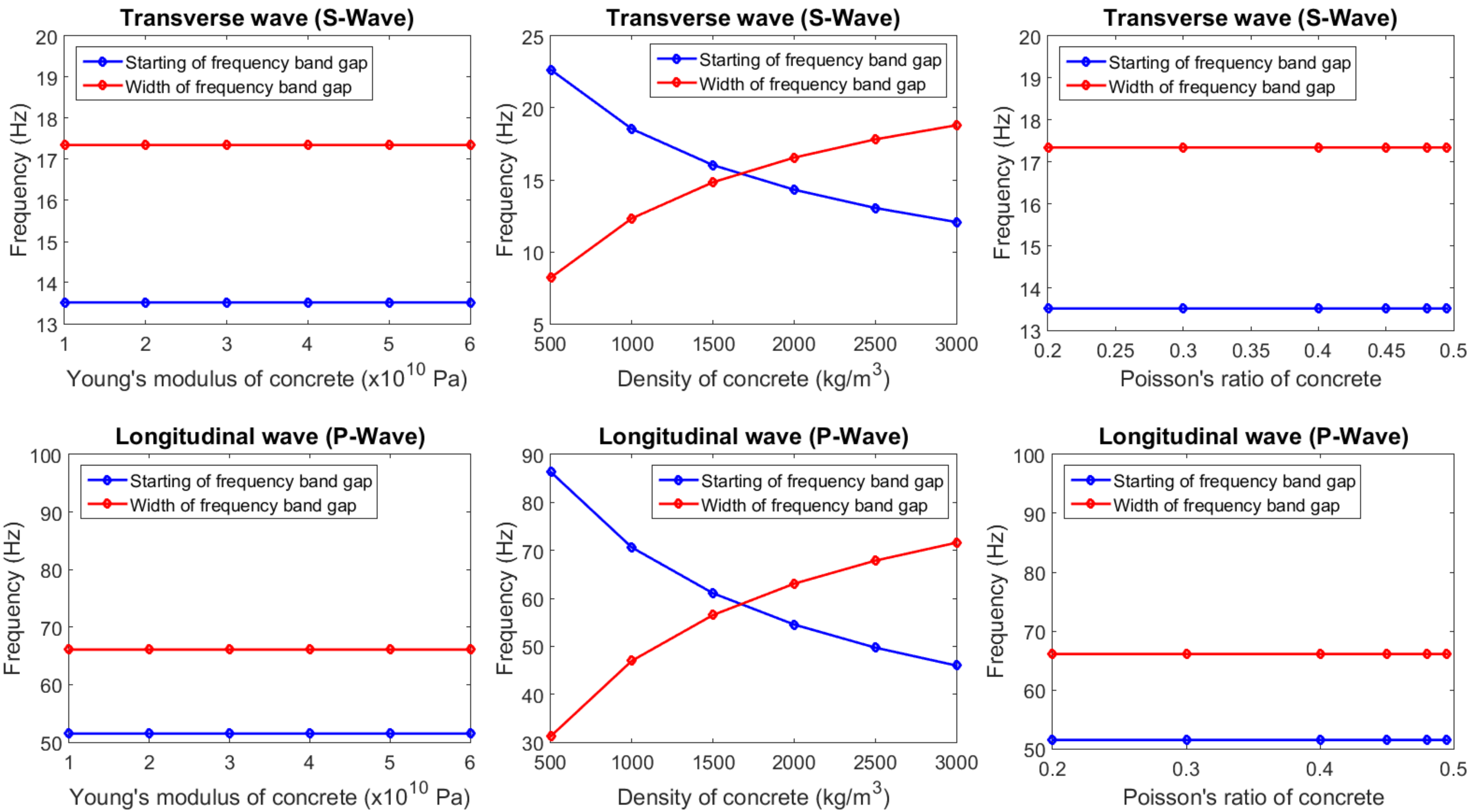
Parametric study of 1D periodic foundations

Effect of rubber material properties on the first frequency band gap



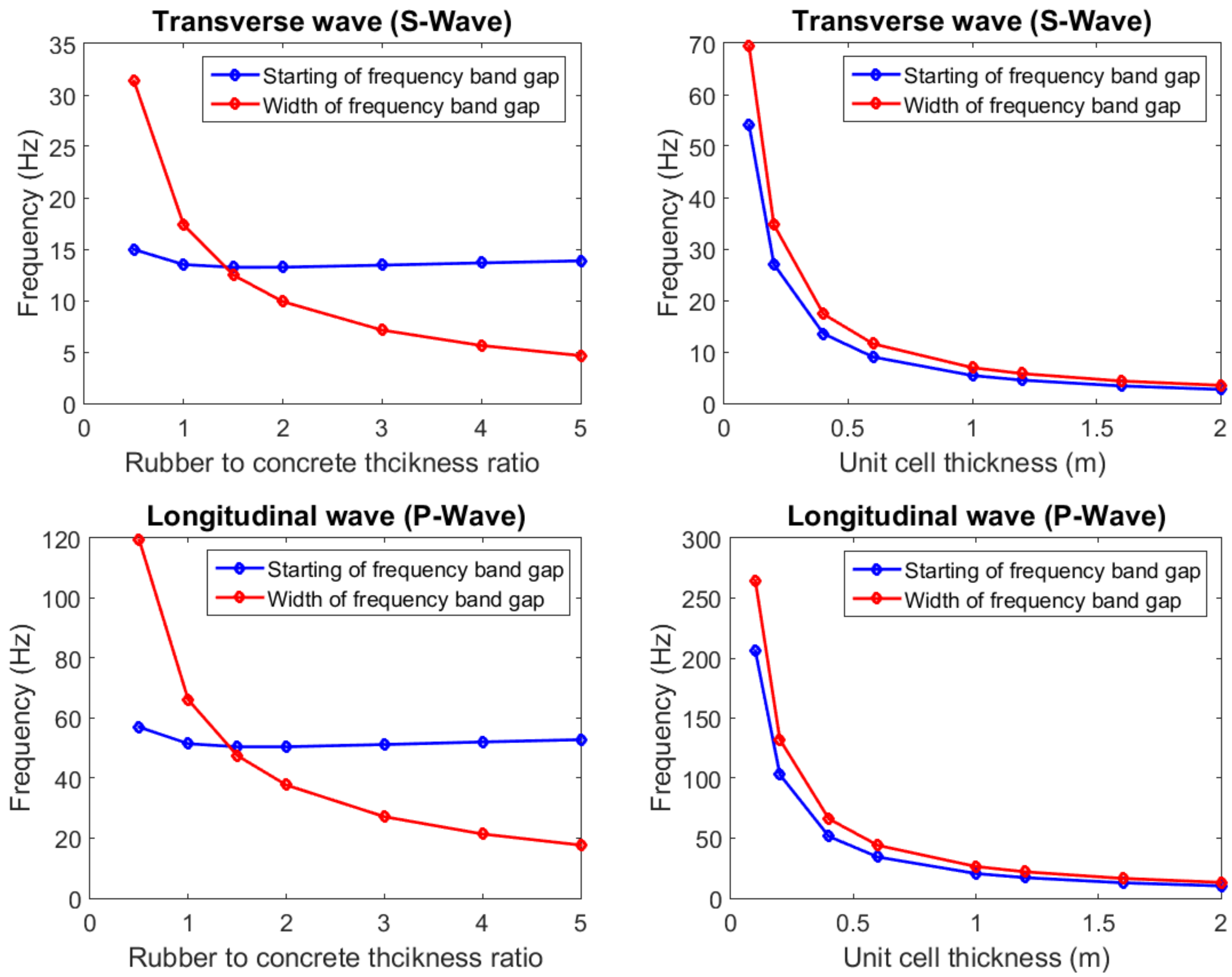
Parametric study of 1D periodic foundations

Effect of concrete material properties on the first frequency band gap



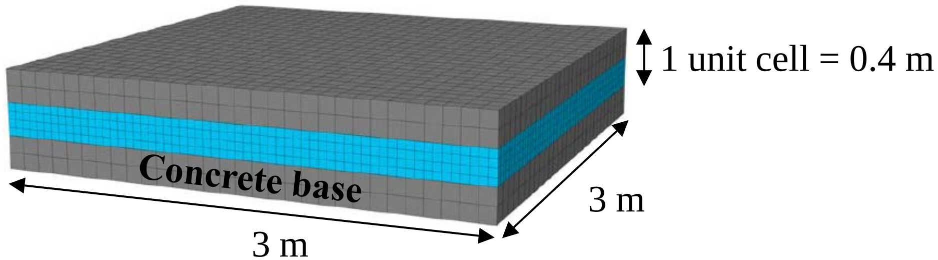
Parametric study of 1D periodic foundations

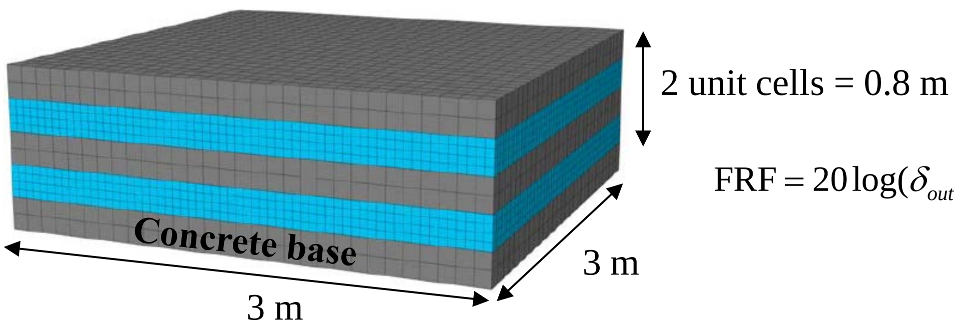
Effect of geometric properties on the first frequency band gap



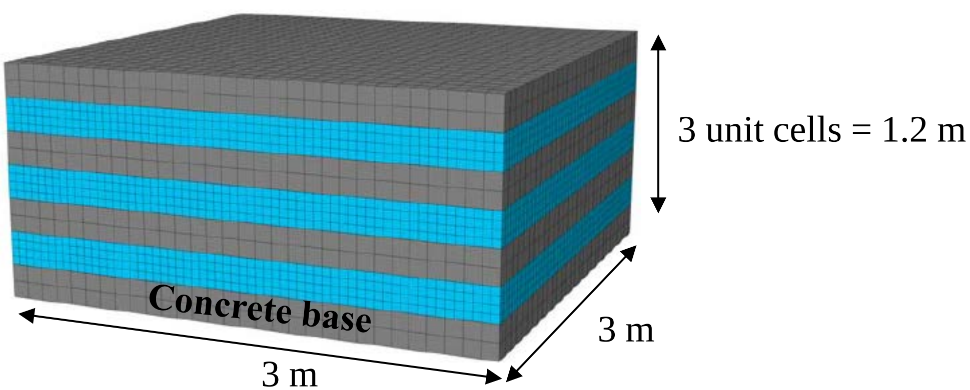
Parametric study of 1D periodic foundations

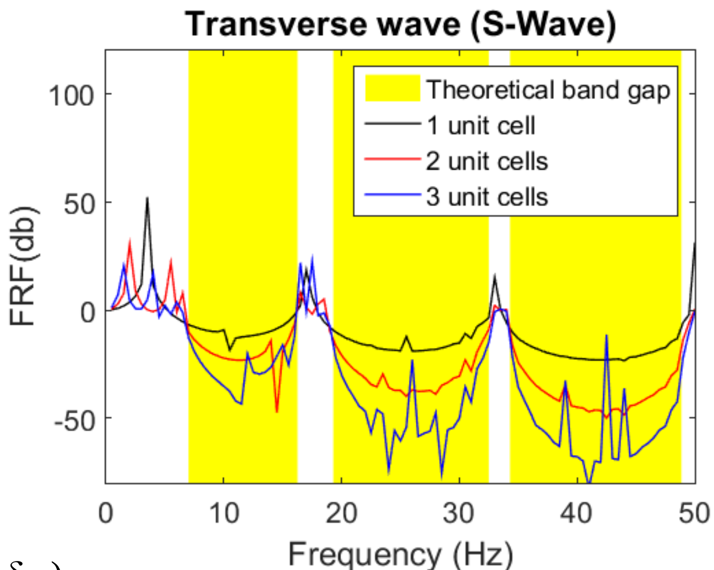
Effect of number of unit cells

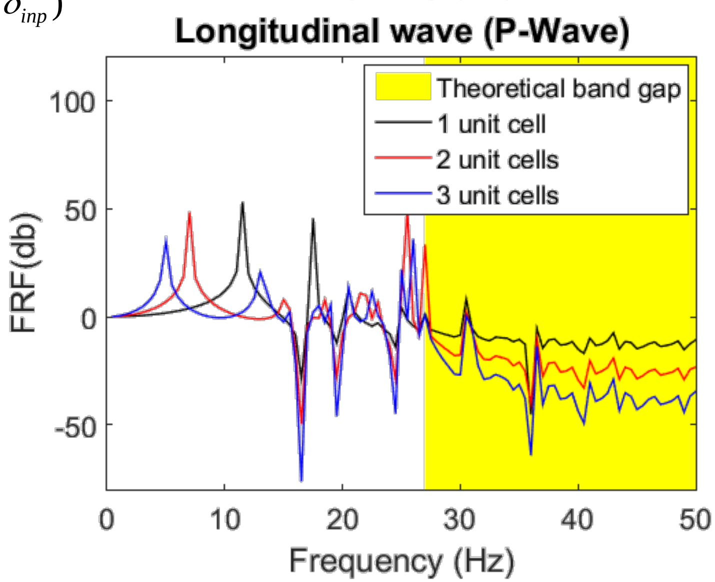




$$\mathrm{FRF} = 20\log(\delta_{out} / \delta_{inp})$$



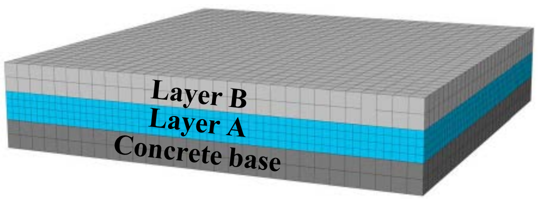




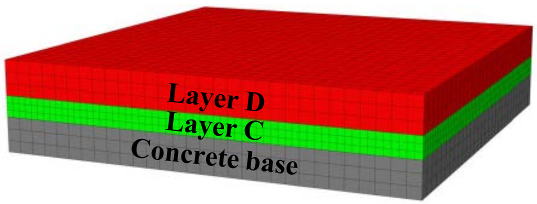
Parametric study of 1D periodic foundations

Effect of combined unit cells

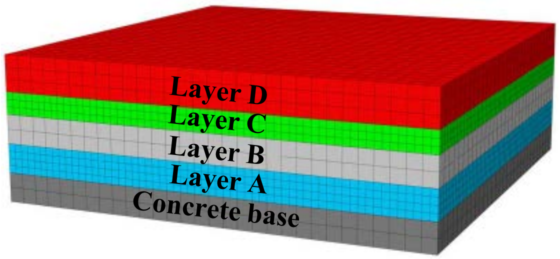
Unit cell-1

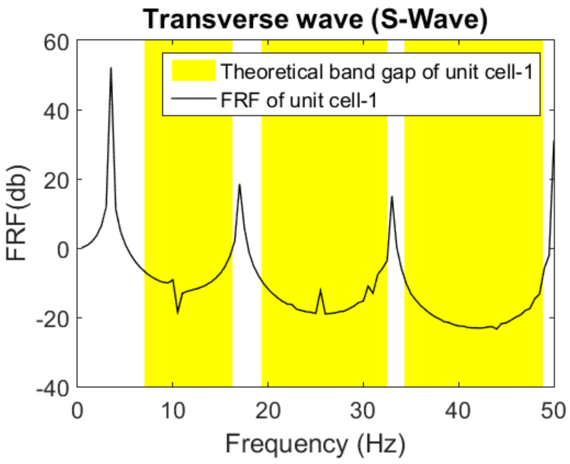


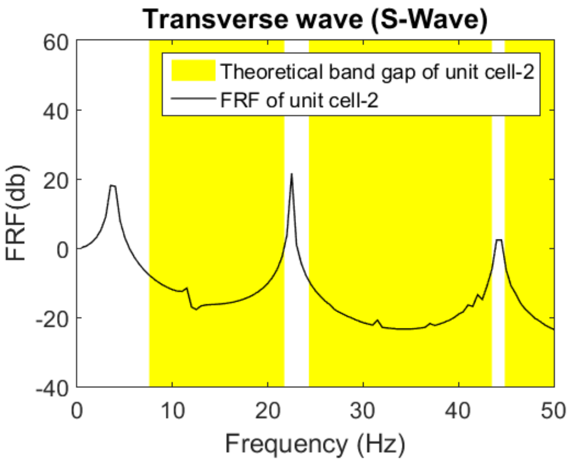
Unit cell-2

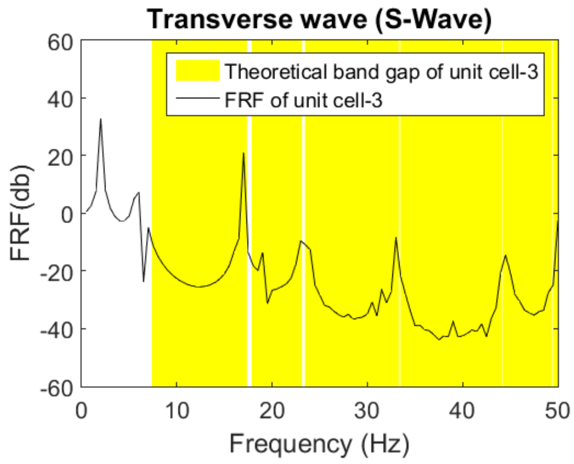


Unit cell-3





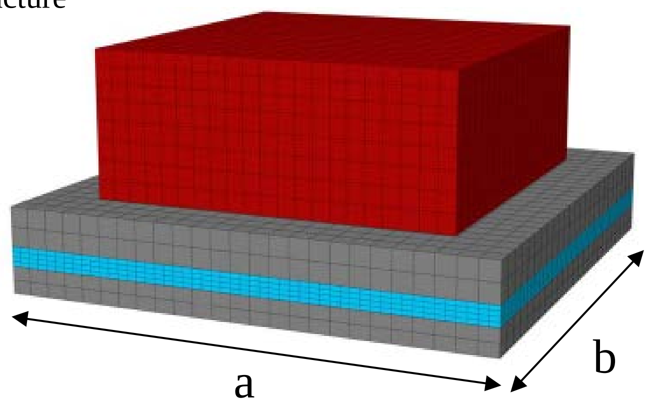




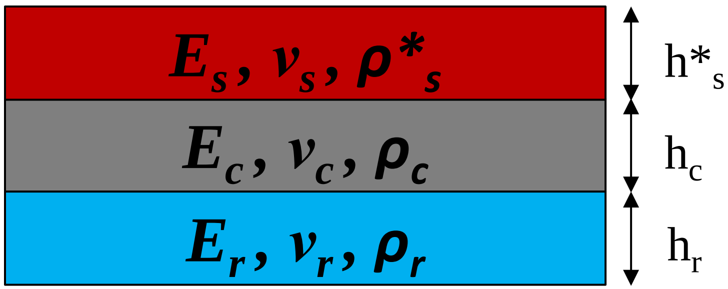
Parametric study of 1D periodic foundations

Effect of superstructure

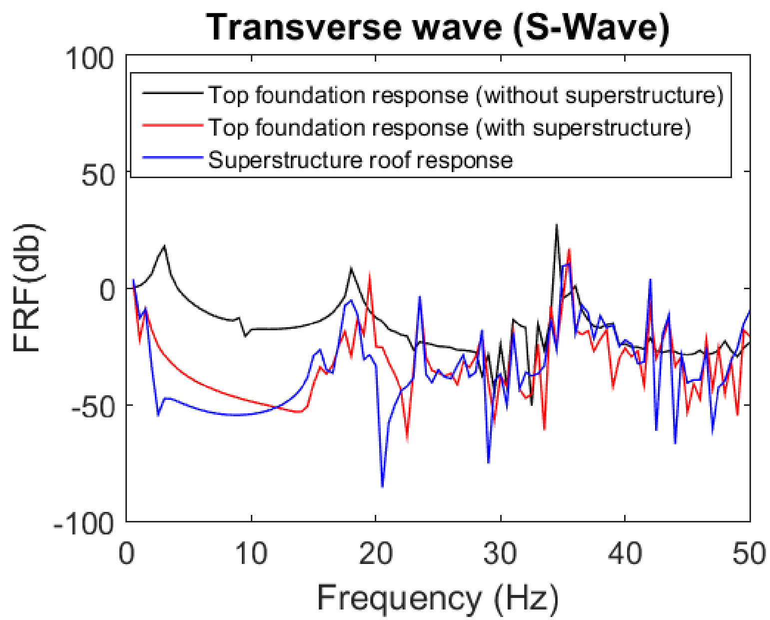
$f_{superstructure}$ =10 Hz

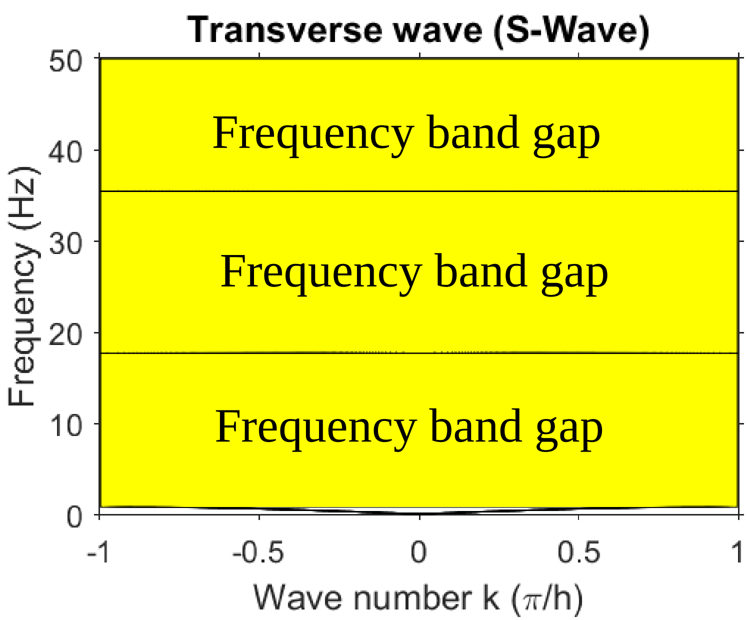


Equivalent model



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

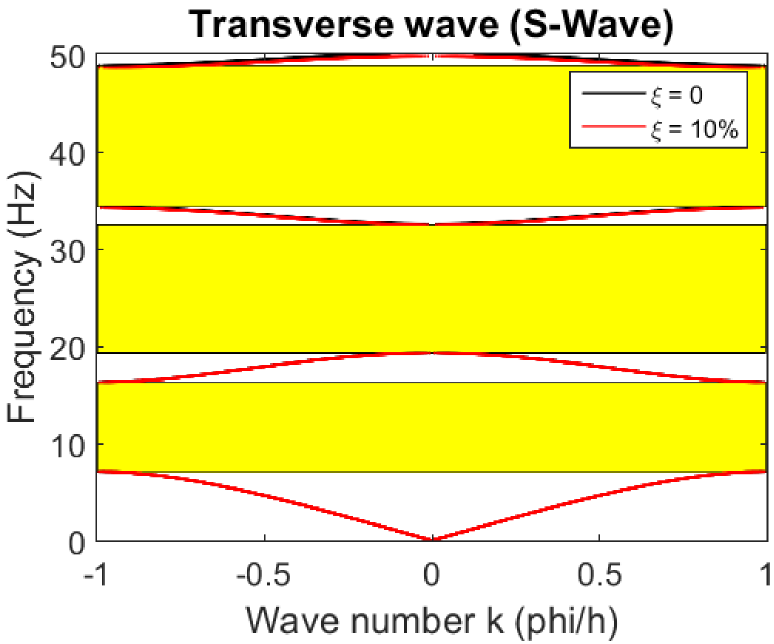


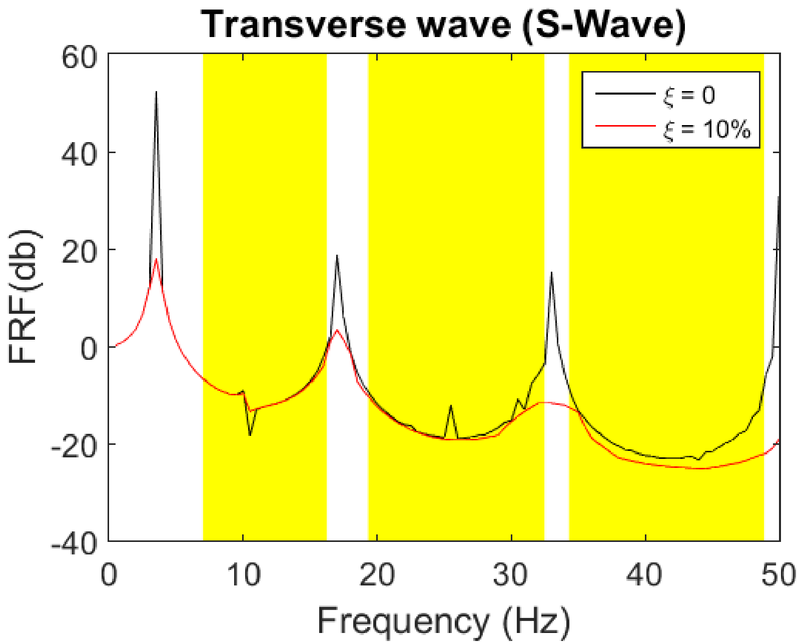


Parametric study of 1D periodic foundations

Effect of damping

$$\omega_d(\mathbf{K}) = \omega(\mathbf{K})\sqrt{1-\zeta(\mathbf{K})^2} \quad \text{[1]}$$



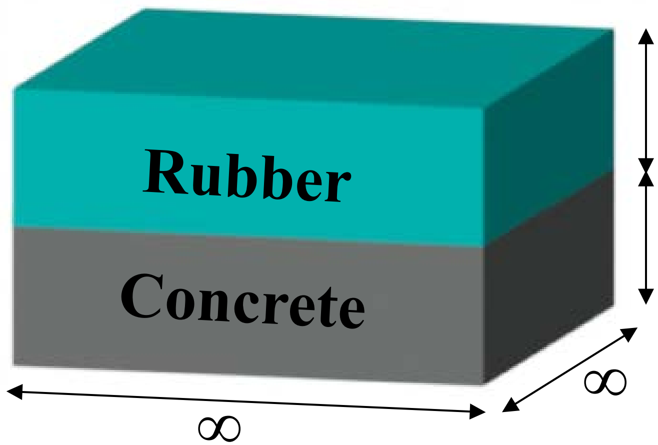


[1] Hussein, M. I. (2009). Theory of damped Bloch waves in elastic media. *Physical Review B, 80*(21), 212301.

Design guidelines of 1D periodic foundations

One unit cell of 1D periodic foundations

Fix geometric properties

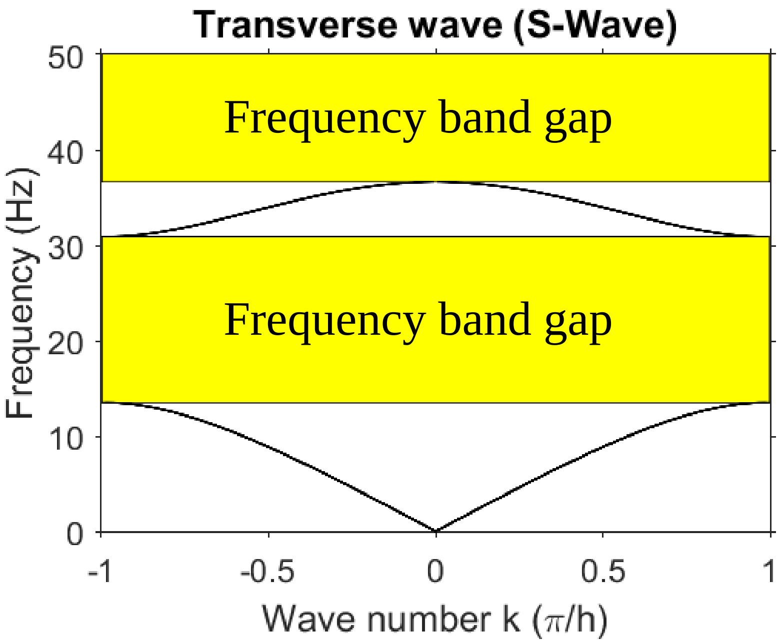


Unit cell size = 1
Rubber to concrete thickness ratio = 1

Fix material properties

Material	Young's Modulus (Pa)	Density (kg/m^3)	Poisson's Ratio
Concrete	3.14×10^{10}	2300	0.2
Rubber	5.8×10^{5}	1300	0.463

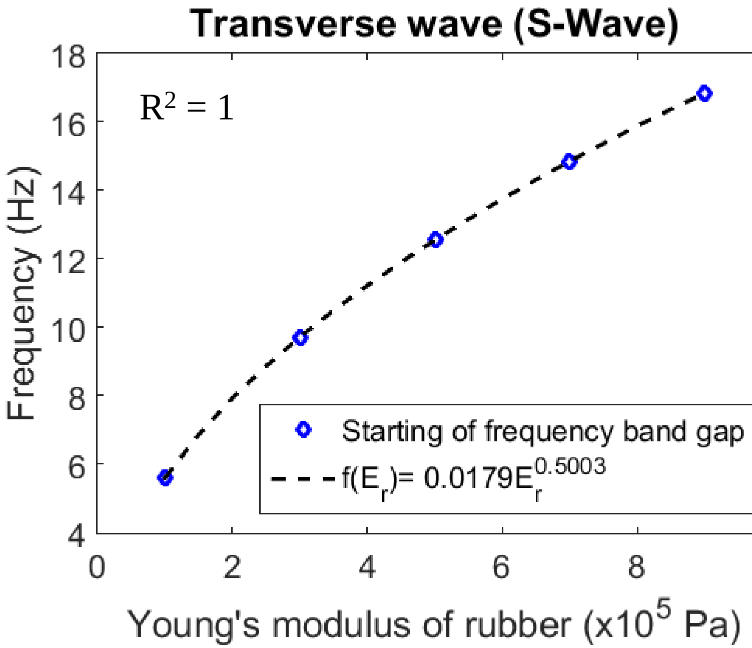
Dispersion curve for infinite number of unit cells

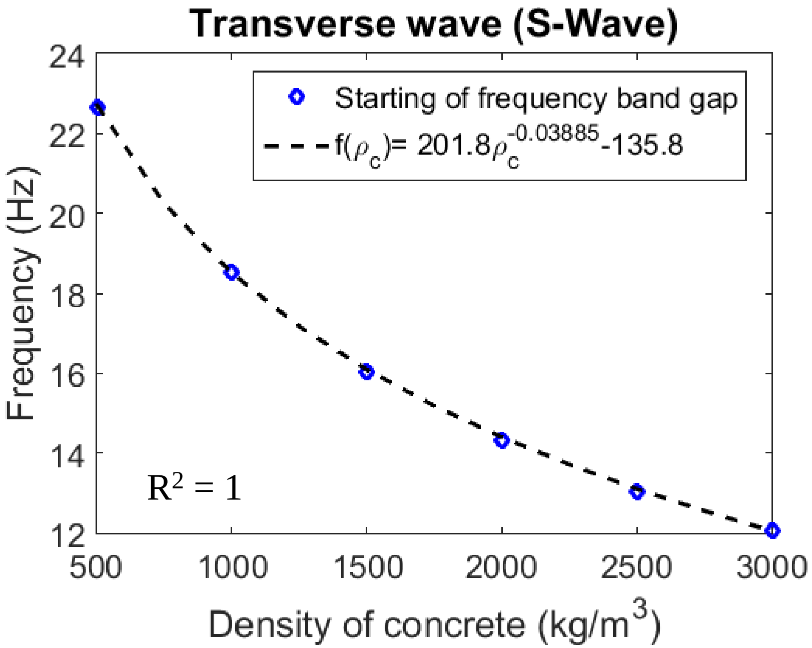


Starting of 1st frequency band gap = 13.51 Hz
Width of 1st frequency band gap = 17.36 Hz

Design guidelines of 1D periodic foundations

Perform regression on each contributing factor





Normalized by the starting of frequency band gap from fixed property

Function of Young's modulus of rubber $F_1(\mathrm{E}_r) = \dfrac{0.01769\,\mathrm{E}_r^{\;0.5003}}{13.51} = 1.3094\times10^{-3}\,\mathrm{E}_r^{\;0.5003}$

Function of density of concrete $F_4(\rho_c) = \dfrac{201.8\rho_c^{\;-0.03885} - 135.8}{13.51} = 14.937\rho_c^{\;-0.03885} - 10.0518$

Design guidelines of 1D periodic foundations

S-Wave design parameter

Parameter	**Function**
Young's modulus of rubber (E_r)	$F_1(E_r) = 1.3094\times10^{-3} E_r^{0.5003}$
Density of rubber (ρ_r)	$F_2(\rho_r) = \left(2.814\rho_r + 1.627\times10^5\right)/\left(13.51\rho_r + 13.6451\times10^4\right)$
Poisson's ratio of rubber (ν_r)	$F_3(\nu_r) = -0.4139\nu_r^{0.6263} + 1.2561$
Density of concrete (ρ_c)	$F_4(\rho_c) = 14.937\rho_c^{-0.03885} - 10.0518$
Unit cell size (S)	$F_5(S) = 0.4/S$
Rubber to concrete thickness ratio (r)	$F_6(r) = 0.6403e^{-2.878r} + 0.9489e^{0.01594r}$

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

Design guidelines of 1D periodic foundations

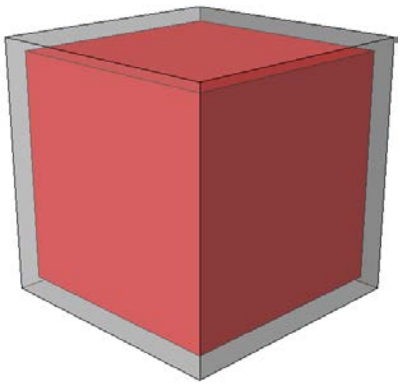
S-Wave design parameters

Parameter	**Function**
Young's modulus of rubber (E_r)	$G_1(E_r) = 1.3185\times10^{-3}\, E_r^{\;0.4996}$
Density of rubber (ρ_r)	$G_2(\rho_r) = 98.0991\rho_r^{\;-0.5964} - 0.3632$
Poisson's ratio of rubber (ν_r)	$G_3(\nu_r) = -0.4112\nu_r^{\;0.6325} + 1.2523$
Density of concrete (ρ_c)	$G_4(\rho_c) = -11.6244\rho_c^{\;-0.03885} + 9.6025$
Unit cell size (S)	$G_5(S) = 0.4 / S$
Rubber to concrete thickness ratio (r)	$G_6(r) = r^{-0.8319}$

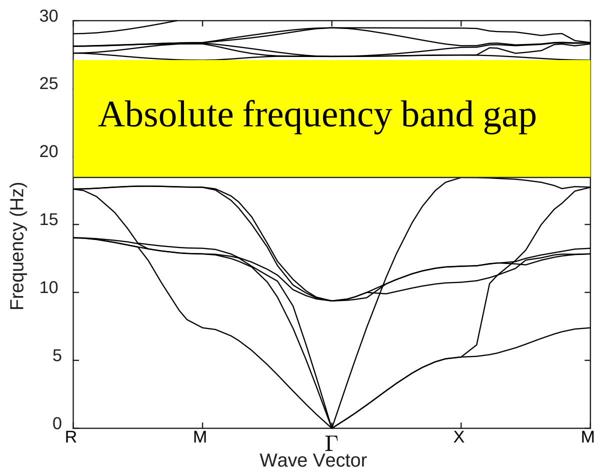
Width of frequency band gap = $17.36G_1(E_r)G_2(\rho_r)G_3(\nu_r)G_4(\rho_c)G_5(S)G_6(r)$

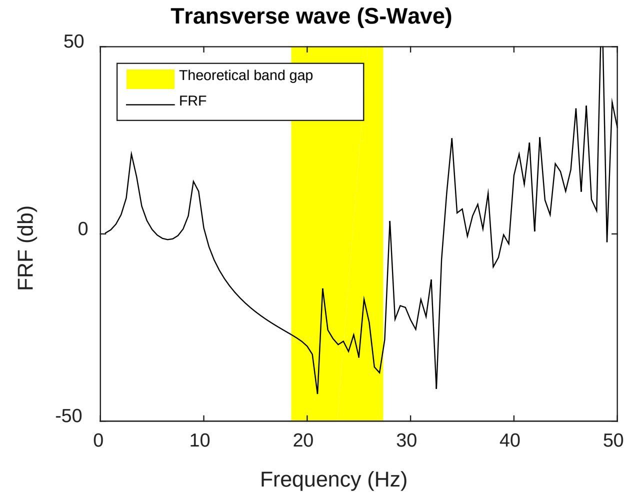
3D Periodic Foundations

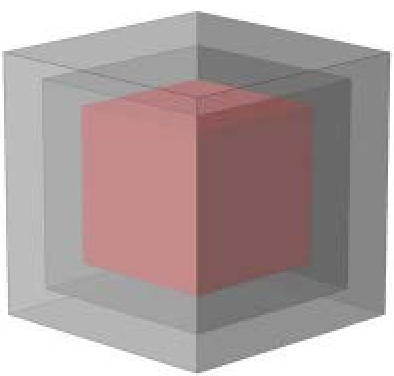
Types of unit cell in 3D periodic foundation



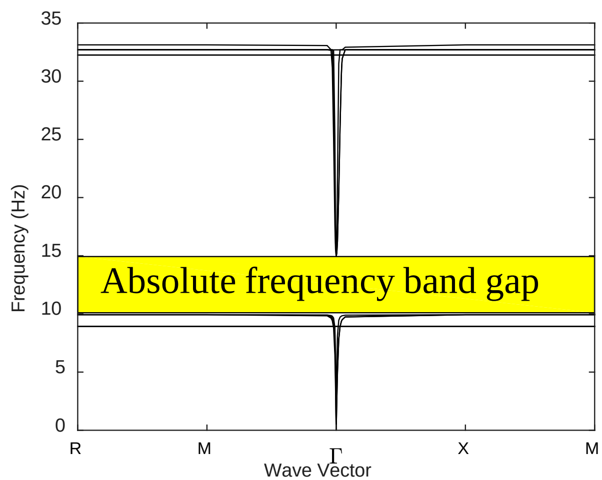
Two components

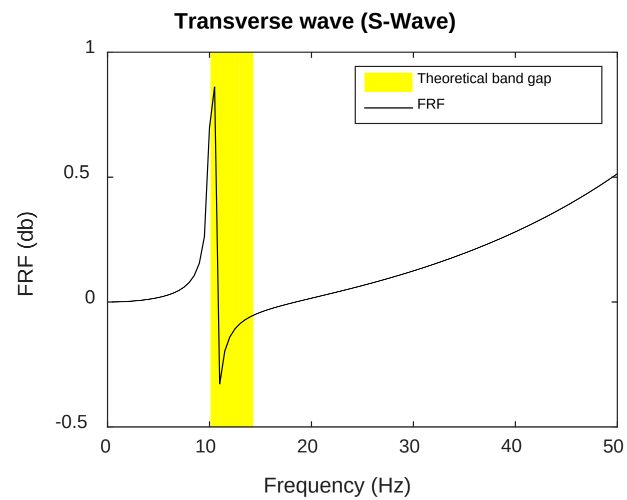






Three components

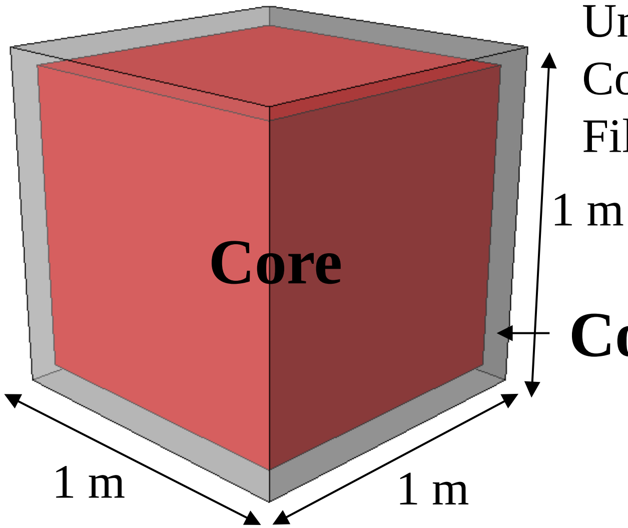




3D Periodic Foundations

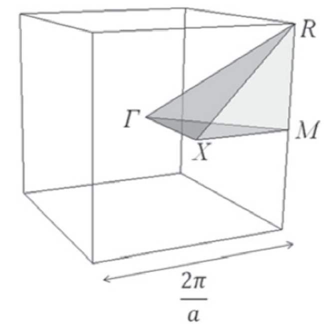
One unit cell of two-component 3D periodic foundation

Fix geometric properties

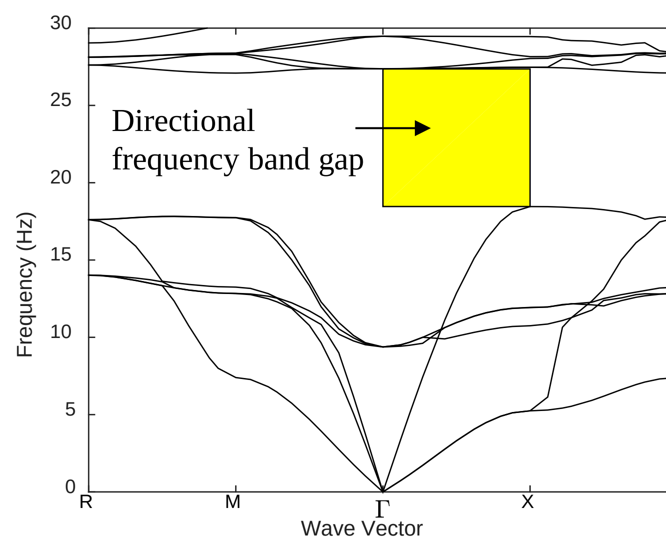


Unit cell size = 1 m
Core size = 0.9 m
Filling ratio = 0.729

First irreducible Brillouin zone



Dispersion curve for infinite number of unit cells

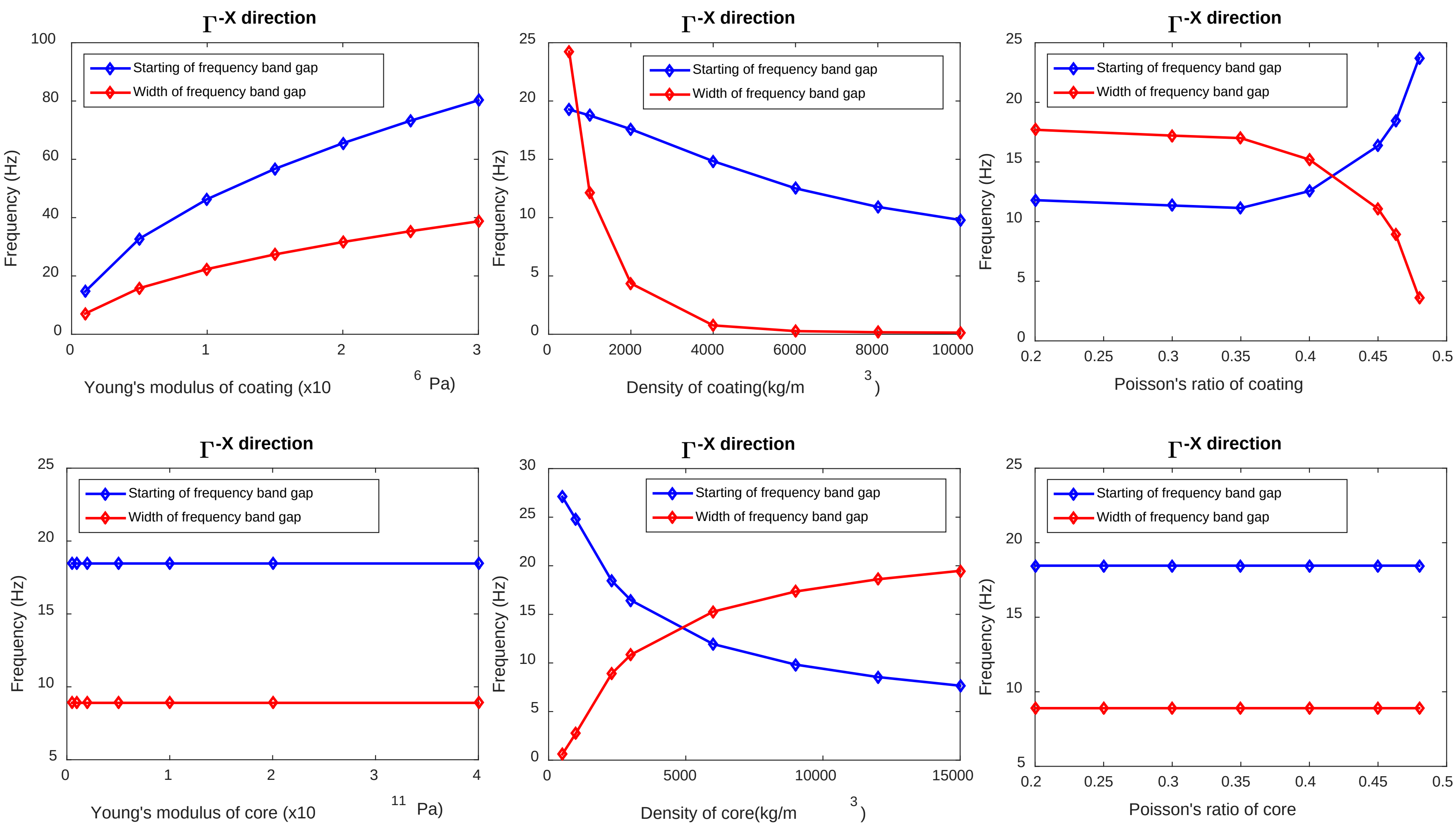


Fix material properties

Component	Young's Modulus (Pa)	Density (kg/m^3)	Poisson's Ratio
Core	4×10^{10}	2300	0.2
Coating	1.586×10^5	1277	0.463

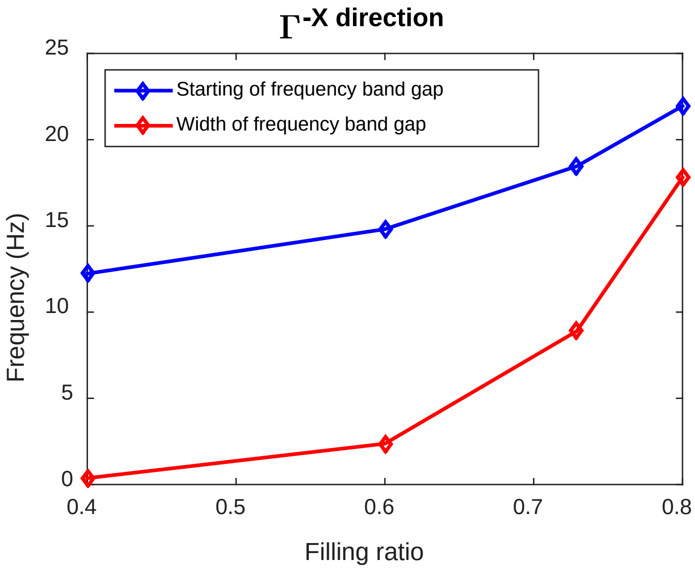
Parametric study of 3D periodic foundations

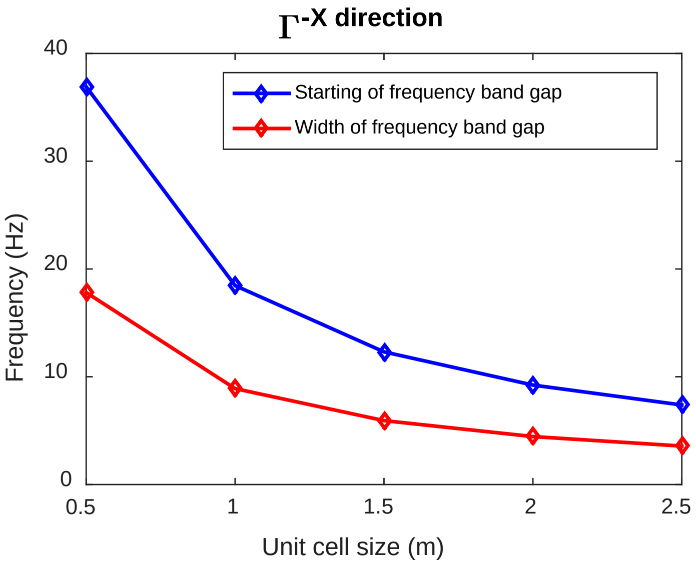
Effect of material properties on the first directional frequency band gap



Parametric study of 3D periodic foundations

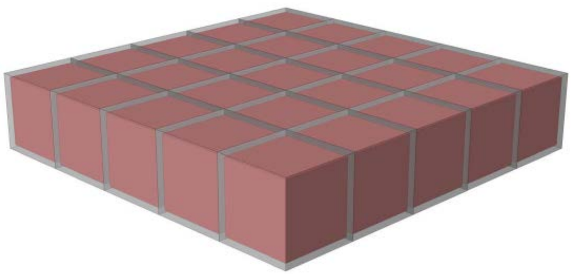
Effect of geometric properties on the first directional frequency band gap



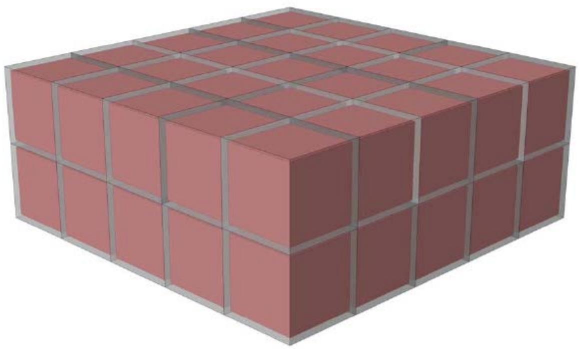


Parametric study of 3D periodic foundation

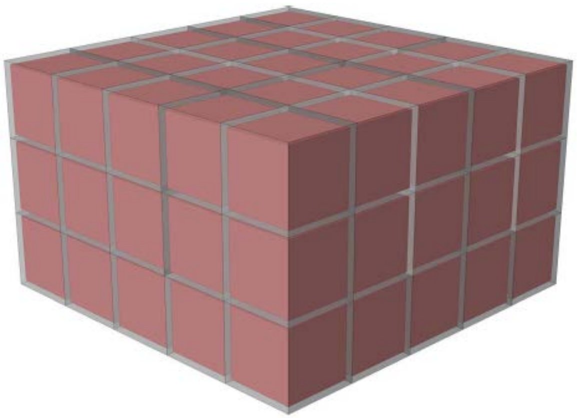
Effect of number of layer in vertical direction



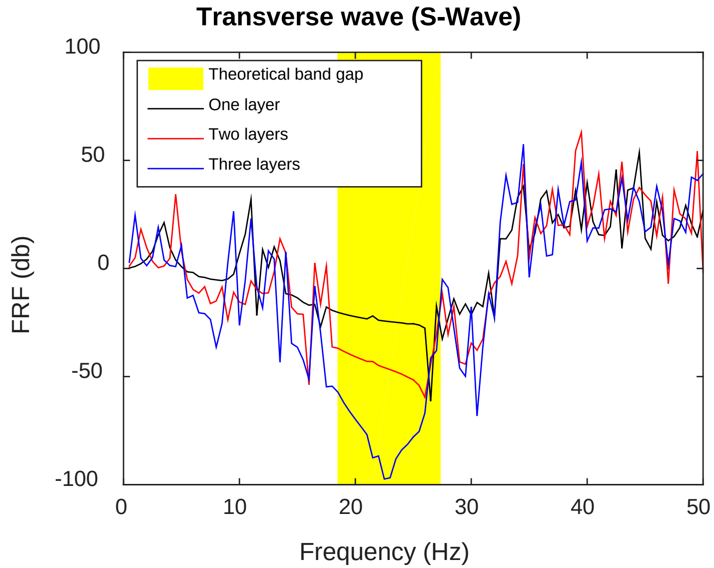
(a) One layer

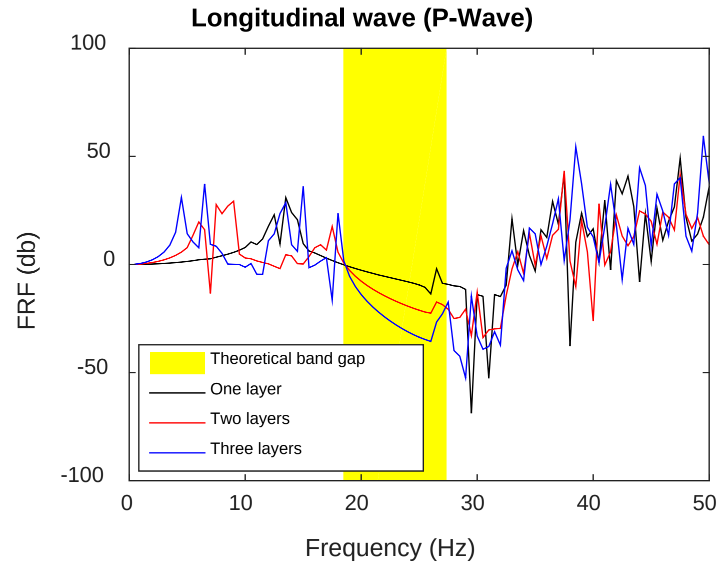


(b) Two layers



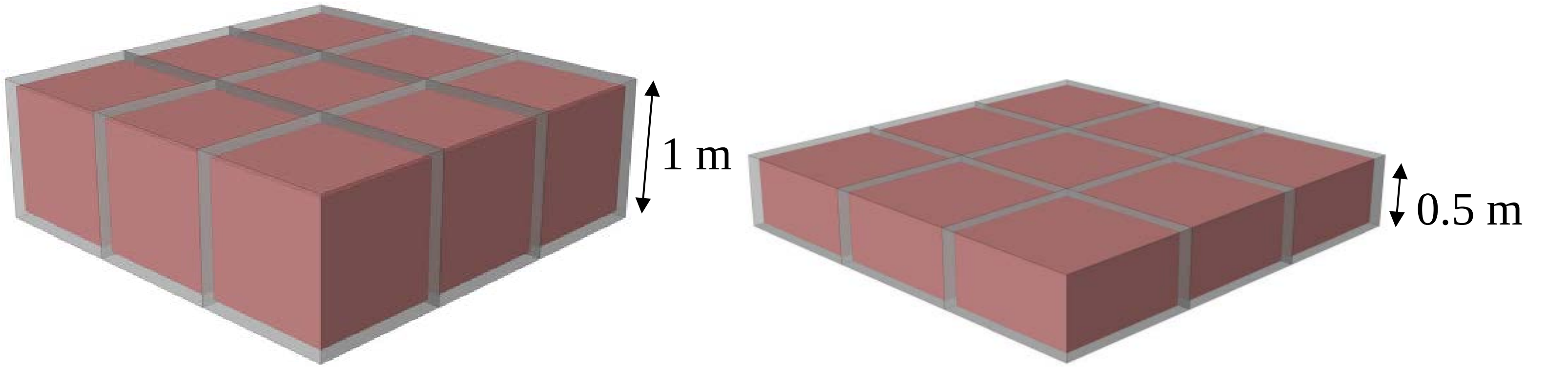
(b) Three layers



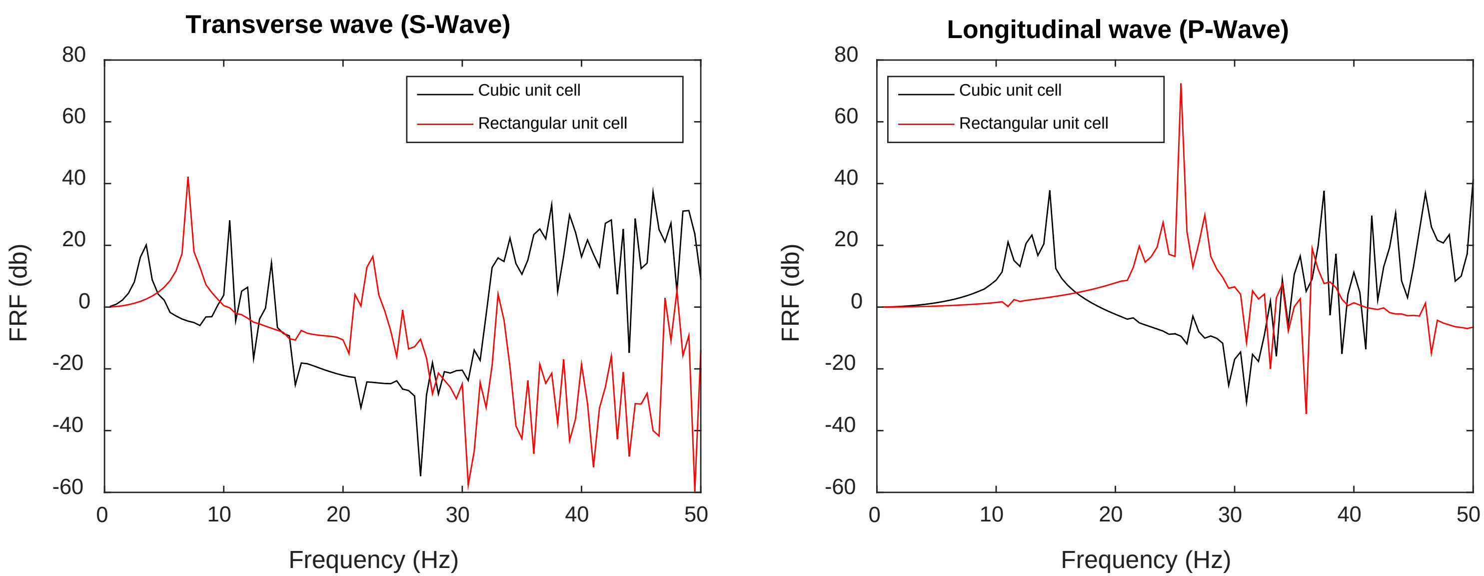


Parametric study of 3D periodic foundations

Effect of suppressed unit cell



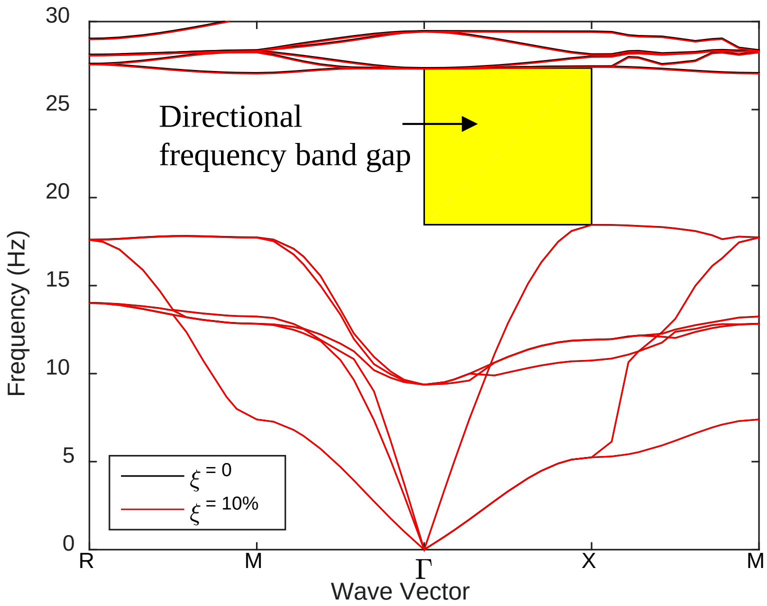
(a) Cubic unit cell (b) Rectangular unit cell

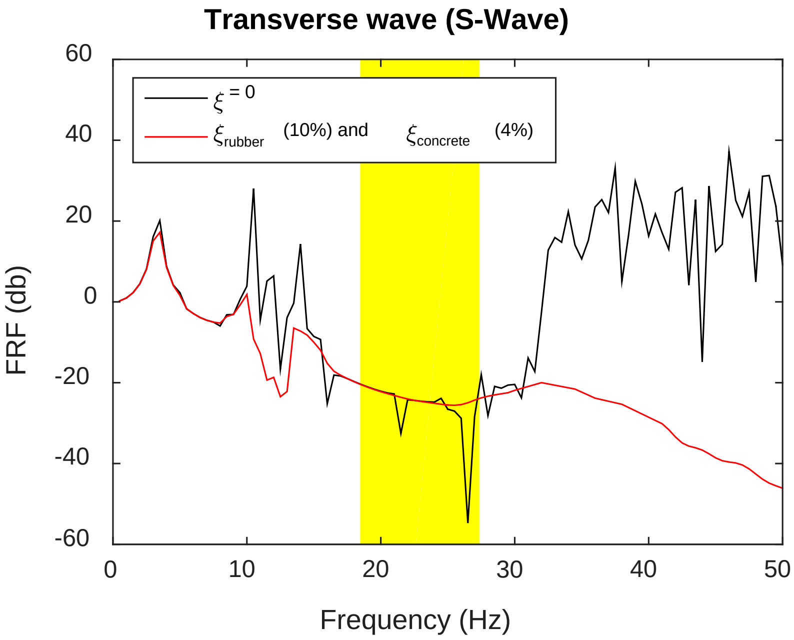


Parametric study of 3D periodic foundations

Effect of damping

$$\omega_d(\mathbf{K}) = \omega(\mathbf{K})\sqrt{1-\zeta(\mathbf{K})^2}$$ **[1]**



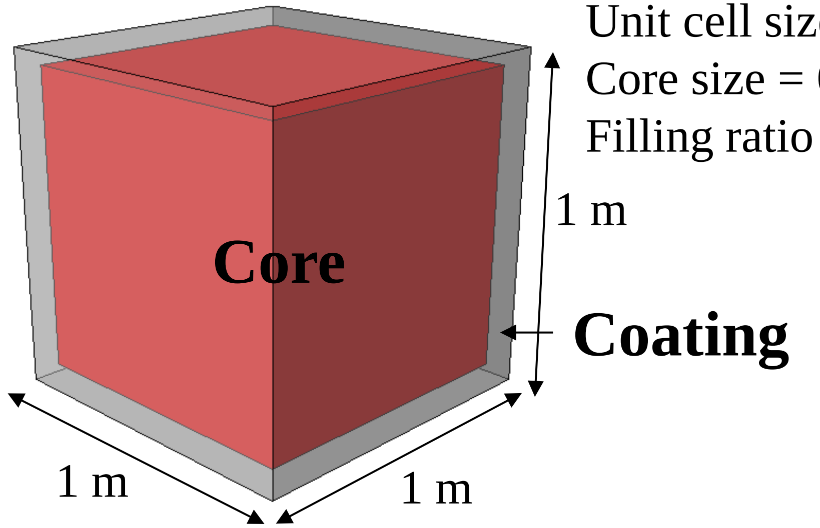


[1] Hussein, M. I. (2009). Theory of damped Bloch waves in elastic media. *Physical Review B, 80*(21), 212301.

Design guidelines of 3D periodic foundations

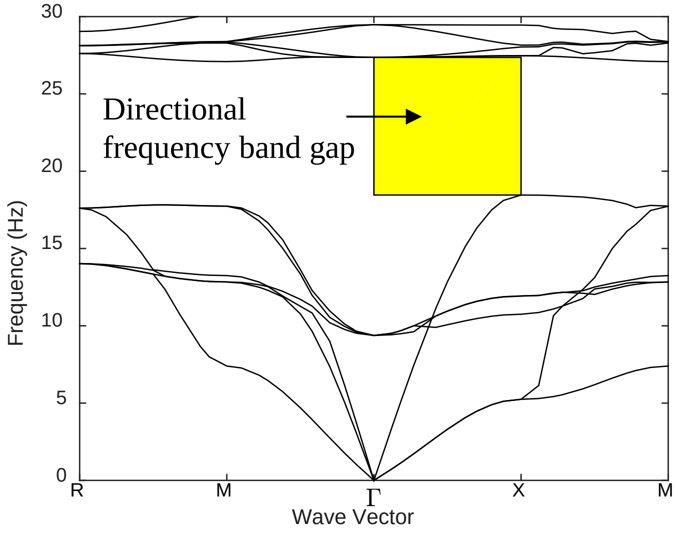
One unit cell of two components 3D periodic foundation

Fix geometric properties



Unit cell size = 1 m
Core size = 0.9 m
Filling ratio = 0.729

Dispersion curve for infinite number of unit cells



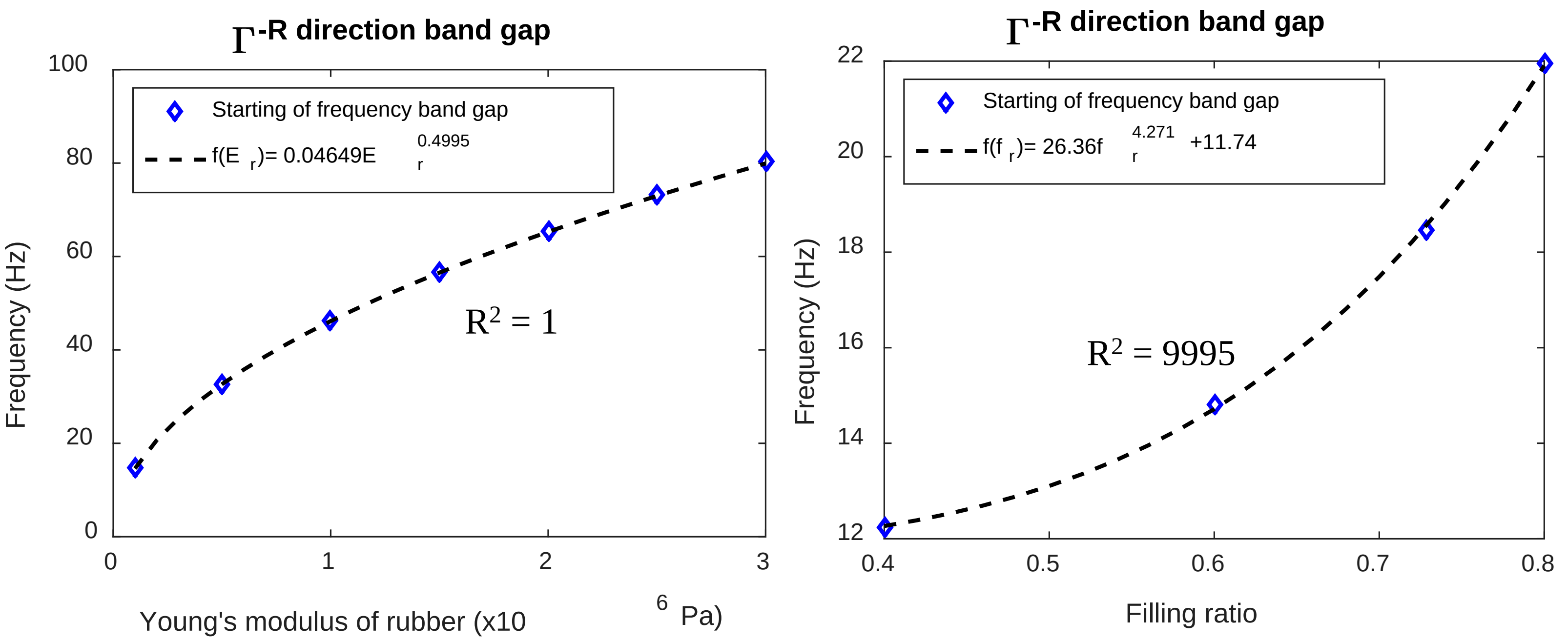
Fix material properties

Component	Young's Modulus (Pa)	Density (kg/m^3)	Poisson's Ratio
Core	4×10^{10}	2300	0.2
Coating	1.586×10^{5}	1277	0.463

Starting of 1st frequency band gap = 18.46 Hz
Width of 1st frequency band gap = 8.9 Hz

Design guidelines of 3D periodic foundations

Perform regression on each contributing factor



Normalized by the starting of frequency band gap from fixed property

Function of Young's modulus of rubber $J_1(\mathrm{E}_r) = \dfrac{0.04649\,\mathrm{E}_r^{\ 0.4995}}{18.46} = 2.5184 \times 10^{-3}\,\mathrm{E}_r^{\ 0.4995}$

Function of filling ratio $J_6(\mathrm{f_r}) = \dfrac{26.36\mathrm{f_r}^{\ 4.271} + 11.74}{18.46} = 1.428\mathrm{f_r}^{\ 4.271} + 0.636$

Design guidelines of 3D periodic foundations

Design parameter

Parameter	**Function**
Young's modulus of rubber (E_r)	$J_1(E_r) = 2.5184\times10^{-3}\,E_r^{\;0.4995}$
Density of rubber (ρ_r)	$J_2(\rho_r) = 0.9 + 0.1793\cos(0.000187\rho_r) - 0.3282\sin(0.000187\rho_r)$
Poisson's ratio of rubber (ν_r)	$J_3(\nu_r) = 0.688e^{-0.3911\nu_r} + 9.6479\times10^{-7}e^{28.14\nu_r}$
Density of concrete (ρ_c)	$J_4(\rho_c) = 0.9832e^{-0.0004377\rho_c} + 0.7053e^{-3.557\times10^{-5}\rho_c}$
Unit cell size (S)	$J_5(S) = 1/S$
Filling ratio (f_r)	$J_6(f_r) = 1.428f_r^{\;4.271} + 0.636$

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

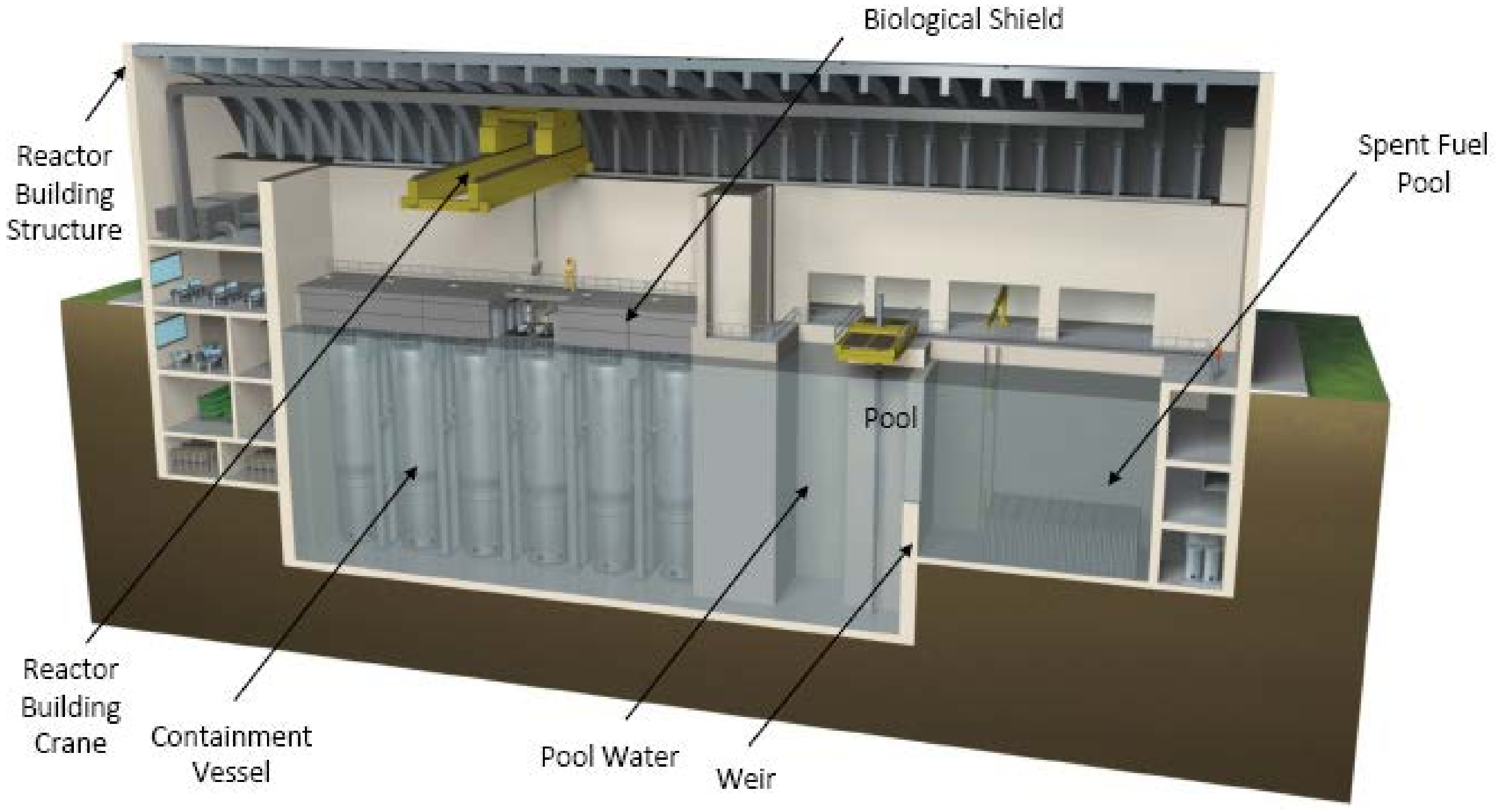
Design guidelines of 3D periodic foundations

Design parameter

Parameter	**Function**
Young's modulus of rubber (E_r)	$K_1(E_r) = 2.51\times10^{-3} E_r^{0.5001}$
Density of rubber (ρ_r)	$K_2(\rho_r) = \left(0.0003842\rho_r^{2} - 5.454\rho_r + 19290\right)\big/\left(8.9\rho_r + 1661.63\right)$
Poisson's ratio of rubber (ν_r)	$K_3(\nu_r) = -8488.764\nu_r^{11.76} + 1.9472$
Density of concrete (ρ_c)	$K_4(\rho_c) = 1.7506e^{1.512\times10^{-5}\rho_c} - 2.1157e^{-0.0004053\rho_c}$
Unit cell size (S)	$K_5(S) = 1/S$
Filling ratio (f_r)	$K_6(f_r) = 10.064 f_r^{7.252}$

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

NuScale Reactor Building



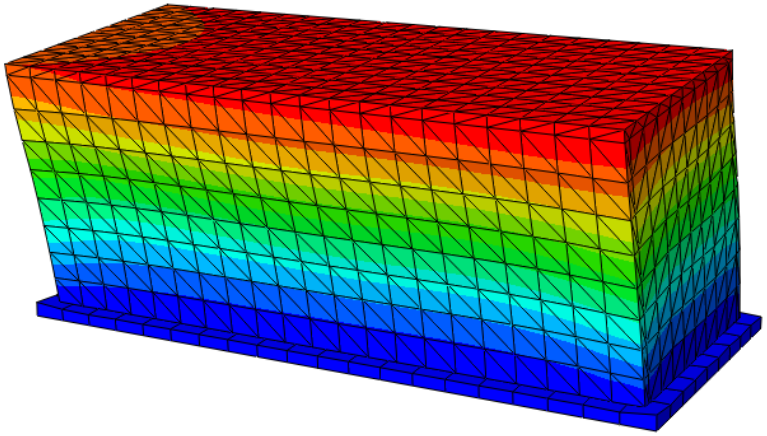
Finite element model of reactor building

Nuclear reactor building is made of reinforced concrete.

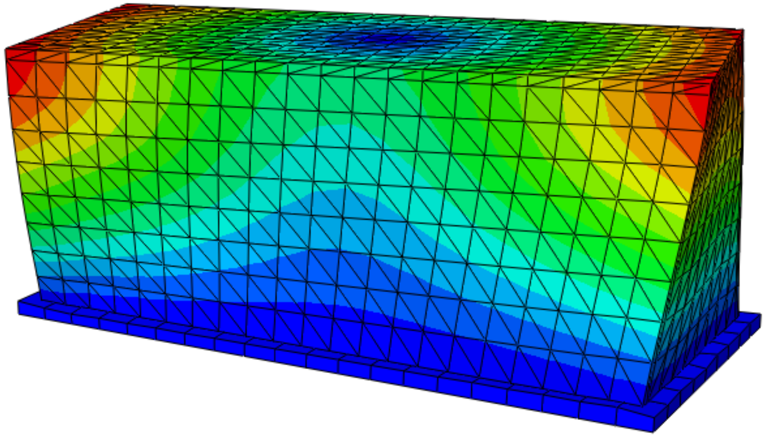
Superimposed dead load:

- Water in the reactor pool = 7 million gallon
- Crane + utilities = 800 ton
- Small modular reactors = 12@800 ton

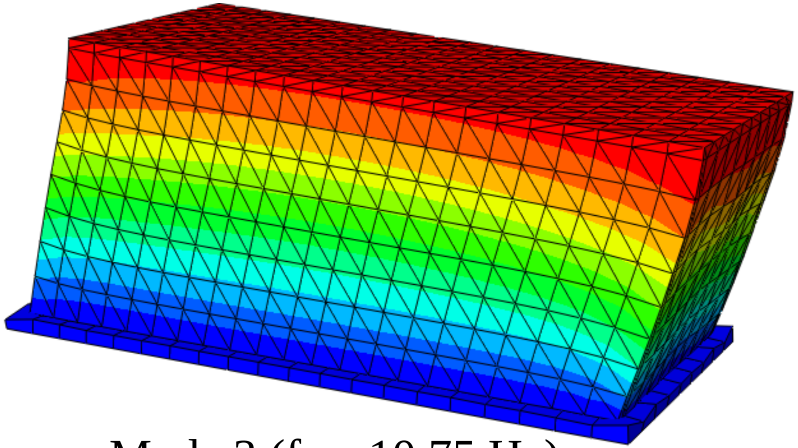
Finite element model of reactor building



Mode 1 (f_n = 6.13 Hz)



Mode 2 (f_n = 10 Hz)



Mode 3 (f_n = 10.75 Hz)

Conclusions

- Basic theory of periodic foundations have been understood.
- Behavior of 1D and 3D periodic foundations have been critically examined.
- Simplified design guidelines for 1D and 3D periodic foundations have been proposed.
- Simplified drawing of reactor building has been obtained from NuScale Power.
- Project will proceed on schedule.

Thank you.