Periodic Foundations for Seismic Base Isolation of Small Modular Reactors


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Outline

• Research background
• Introduction to metamaterials – periodic materials
• Theoretical studies of periodic materials
• Design of 1D and 3D periodic material-based seismic isolation systems (periodic foundations)
• Experimental studies of 1D and 3D periodic foundation structural systems
• Finite element simulation of periodic foundation structural systems
• Conclusions
Research background

Damage on Engineering Structures

Building collapse at Cal State Northridge (http://www.scpr.org/northridge-earthquake)

Freeway collapse (FEMA/Robert Eplett)

Collapse of liquid gas tanks due to 1999 Kocaeli Earthquake (Sezen and Whittaker, 2004)

Distorted Trans-Alaska Pipeline after Denali earthquake (Sorensen and Meyer, 2003)

Current practice in civil engineering to isolate both horizontal and vertical seismic waves in critical structures

Major issue: Prone to rocking when subjected to horizontal earthquakes (need additional rocking suppression devices)

Thick rubber layer bearing [1]

Rolling seal type air spring [1]

GERB system [1]

**Introduction to periodic materials**

Periodic materials (phononic crystals) are novel composite developed in the solid-state-physics.

Typical dispersion curve [1]

- Properly designed phononic crystals will have **frequency band gaps**.
- The incoming seismic waves with frequencies inside frequency band gaps will be reflected back.
- Wave propagation with frequency within the frequency band gap.
- Wave propagation with frequency outside of the frequency band gap.

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Current application of periodic materials

The phononic (elastic wave) spectrum\(^1\)

The frequency band gaps can be designed through a proper selection of material and geometric properties of the unit cell constituents.

Experiment on seismic metamaterial
(Brûlé, et al. 2014)

Sound waves guider
(http://kino-ap.eng.hokudai.ac.jp/ktspace.html)

Nanomesh for heat isolation
(Yu, et. al. 2010)

The frequency band gaps can be designed through a proper selection of material and geometric properties of the unit cell constituents.

Current application of periodic materials

Periodic material-based seismic isolation (periodic foundation) developed by UH

1D Periodic foundation\[1\]

2D Periodic foundation\[2\]

3D Periodic foundation\[3\]

Shake Table Tests

Free Field Tests

Theory of periodic materials

Periodic structure to obtain frequency band gaps

Wave equation $\rightarrow$ Dispersion relation $\rightarrow$ Frequency band gaps

Dispersion relation can be derived from the wave equation using:
1. Finite element method (applicable to 1D, 2D, and 3D periodic materials)
2. Transfer matrix method (applicable to 1D periodic materials)
Theory of periodic materials

Finite element method for calculation of dispersion curves

Governing equation of motion for a continuum body with isotropic elastic material

\[ \rho(r) \frac{\partial^2 u}{\partial t^2} = \nabla \left\{ \left[ \lambda(r) + 2\mu(r) \right] (\nabla \cdot u) \right\} - \nabla \times \left[ \mu(r) \nabla \times u \right] \]

Eq.1

Where:
- \( r \) is coordinate vector;
- \( \rho(r) \) is the density
- \( u(r) \) is displacement vector;
- \( \lambda(r) \) and \( \mu(r) \) are the Lamé constants

Periodic boundary condition equation:

\[ u(r + a, t) = e^{iK \cdot a} u(r, t) \]

Eq.2

Where:
- \( K \) is the wave vector
- \( a \) is unit cell length

Apply periodic boundary condition, (Eq.2), to the governing equation, (Eq.1), the wave equation can be simplified into Eigen value problem as follow:

\[ \left( \Omega(K) - \omega^2 M \right) u = 0 \]

Eq.3

Where:
- \( \Omega \) is the stiffness matrix
- \( M \) is the mass matrix

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

Eq.3 can be applied to find dispersion curves of 1D, 2D, and 3D unit cells
Development of design guidelines for periodic materials

Purpose:
- To obtain the first frequency band gap easily without the need to solve the governing equation.
- One can find the appropriate material and geometric properties that satisfy the target frequency band gap.

Method:
- Perform global sensitivity analysis to find the most dominant individual parameters (from material and geometric properties) and combination of parameters that affect the first frequency band gap.
- Determine how the individual parameters and the combination of the parameters affect the first frequency band gap.
- Find a regression function that can predict the effect of the dominant parameters on the first frequency band gap.
Global sensitivity analysis using Sobol’ method

Sobol’ method is a form of global sensitivity analysis that decomposes the variance of the output of a model or system (applicable to linear and nonlinear systems) into fractions, which can be attributed to inputs or sets of inputs.

1. Decomposition of a mathematical function into a series of increasing order Sobol’ functions

\[ F(x) = F_0 + \sum_{i=1}^{n} F_i(x_i) + \sum_{i=1}^{n} \sum_{j=i+1}^{n} F_{ij}(x_i, x_j) + \ldots + F_{1,\ldots,n}(x_1,\ldots,x_n) \]  \hspace{1cm} \text{Eq.16}

where \( x = (x_1,\ldots,x_n) \) is a set of input parameters

The individual member of the Sobol’ functions in Eq.16 can be calculated as follows:

\[ F_0 = \int_{\Omega^n} F(x)dx \]  \hspace{1cm} \text{Eq.17}

\[ F_i(x_i) = \int_{\Omega^{n-1}} F(x_i,x_{\sim i})dx_{\sim i} - F_0 \]  \hspace{1cm} \text{Eq.18}

\[ F_{ij}(x_i,x_j) = \int_{\Omega^{n-2}} F(x_i,x_j,x_{\sim ij})dx_{\sim ij} - F_i(x_i) - F_j(x_j) - F_0 \]  \hspace{1cm} \text{Eq.19}
Highlight of global sensitivity analysis

2. Calculation of Sobol’ variances

\[
D = \sum_{i=1}^{n} D_i + \sum_{i=1}^{n} \sum_{j=i+1}^{n} D_{ij} + \ldots + D_{i,\ldots,n} \quad \text{Eq.20}
\]

where

\[
D = \int_{\Omega^n} F^2(x) dx - F_0^2 \quad \text{Eq.21}
\]

\[
D_i = \int_{\Omega^1} F_i^2(x_i) dx_i \quad \text{Eq.22}
\]

\[
D_{ij} = \int_{\Omega^2} F_{ij}^2(x_i, x_j) dx_i dx_j \quad \text{Eq.23}
\]

3. Calculation of Sobol’ sensitivity indices

\[
1 = \sum_{i=1}^{n} S_i + \sum_{i=1}^{n} \sum_{j=i+1}^{n} S_{ij} + \ldots + S_{i,\ldots,n} \quad \text{Eq.24}
\]

where

\[
S_i = \frac{D_i}{D} \quad \text{Eq.25}
\]

\[
S_{ij} = \frac{D_{ij}}{D} \quad \text{Eq.26}
\]
Global sensitivity analysis of periodic materials

Parameters used in sensitivity analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus ratio ($E_2/E_1$)</td>
<td>10-10,000</td>
</tr>
<tr>
<td>Density ratio ($\rho_2/\rho_1$)</td>
<td>1-1000</td>
</tr>
<tr>
<td>Thickness ratio ($h_2/h_1$)</td>
<td>0.11-9</td>
</tr>
<tr>
<td>Poisson’s ratio of material in the first layer ($\nu_1$)</td>
<td>0-0.463</td>
</tr>
<tr>
<td>Poisson’s ratio of material in the second layer ($\nu_2$)</td>
<td>0-0.463</td>
</tr>
</tbody>
</table>

Note that the wave equation was nondimensionalized so that the sensitivity analysis results are valid for the whole phononic spectrum.
Global sensitivity analysis of periodic materials

Starting of 1\textsuperscript{st} frequency band gap of S-Wave

\textbf{Sobol’ indices}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{sobol_indices_graph.png}
\end{figure}

\textbf{Sobol’ functions of dominant parameters}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{sobol_functions_graph.png}
\end{figure}
Global sensitivity analysis of periodic materials

Width of 1st frequency band gap of S-Wave

Sobol’ indices

Sobol’ functions of dominant parameters
Design equations for 1\textsuperscript{st} frequency band gap subjected to S-Wave

Starting of 1\textsuperscript{st} frequency band gap (S-Wave) = 0.1265 + \( F\left(\rho_2 / \rho_1\right) + F\left(\rho_2 / \rho_1 , h_2 / h_1\right) + F\left(h_2 / h_1\right) \)

where

\[
F\left(\rho_2 / \rho_1\right) = -1239.088 e^{-0.4557 \log(\rho_2 / \rho_1)} - 1238.816 e^{-0.4555 \log(\rho_2 / \rho_1)}
\]

\[
F\left(\rho_2 / \rho_1 , h_2 / h_1\right) = -0.02746 + 0.02426 \log(\rho_2 / \rho_1) + 0.1143 \log(h_2 / h_1) - 0.001248 \log^2(\rho_2 / \rho_1) - 0.2258 \log(\rho_2 / \rho_1) \log(h_2 / h_1) + 0.9419 \log^2(h_2 / h_1) - 0.001116 \log^3(\rho_2 / \rho_1) + 0.1204 \log^2(\rho_2 / \rho_1) \log(h_2 / h_1) - 0.09103 \log(\rho_2 / \rho_1) \log^2(h_2 / h_1) + 0.0001409 \log^4(\rho_2 / \rho_1) - 0.02031 \log(\rho_2 / \rho_1) \log(h_2 / h_1) + 0.0142 \log^2(\rho_2 / \rho_1) \log^2(h_2 / h_1)
\]

\[
F\left(h_2 / h_1\right) = 0.01339 \log^3(h_2 / h_1) + 0.06029 \log^2(h_2 / h_1) + 0.0114 \log(h_2 / h_1) - 0.01822
\]
Design equations for 1st frequency band gap subjected to S-Wave

Width of 1st frequency band gap (S-Wave) = 0.5484 + \( F\left(\frac{h_2}{h_1}\right) + F\left(\frac{E_2}{E_1}, \frac{h_2}{h_1}\right) + F\left(\frac{\rho_2}{\rho_1}, \frac{h_2}{h_1}\right) + F\left(\frac{E_2}{E_1}\right) + F\left(\frac{\rho_2}{\rho_1}\right) \)

where

\[
F\left(\frac{h_2}{h_1}\right) = \frac{2.7534 \log\left(\frac{h_2}{h_1}\right) - 0.4961}{1 - 0.2172 \log\left(\frac{h_2}{h_1}\right) - 0.7975 \log\left(\frac{h_2}{h_1}\right) + 0.04177 \log^2\left(\frac{h_2}{h_1}\right) + 0.3198 \log^2\left(\frac{h_2}{h_1}\right)}
\]

\[
F\left(\frac{E_2}{E_1}, \frac{h_2}{h_1}\right) = \frac{0.2233 \log\left(E_2/E_1\right) - 0.08928 \log\left(h_2/h_1\right) + 0.3128 \log\left(E_2/E_1\right) \log\left(h_2/h_1\right)}{1 - 0.2172 \log\left(E_2/E_1\right) - 0.7975 \log\left(h_2/h_1\right) + 0.04177 \log^2\left(E_2/E_1\right) + 0.3198 \log^2\left(h_2/h_1\right)}
\]

\[
F\left(\frac{\rho_2}{\rho_1}, \frac{h_2}{h_1}\right) = \frac{-0.1193 + 0.0735 \log\left(\frac{\rho_2}{\rho_1}\right) + 0.4151 \log\left(h_2/h_1\right) - 0.2566 \log\left(\frac{\rho_2}{\rho_1}\right) \log\left(h_2/h_1\right)}{1 - 0.2974 \log\left(\frac{\rho_2}{\rho_1}\right) - 0.8122 \log\left(h_2/h_1\right) + 0.0607 \log^2\left(\frac{\rho_2}{\rho_1}\right) + 0.1766 \log^2\left(h_2/h_1\right) + 0.08275 \log\left(\frac{\rho_2}{\rho_1}\right) \log\left(h_2/h_1\right)}
\]

\[
F\left(\frac{E_2}{E_1}\right) = \frac{0.1783 \log^2\left(E_2/E_1\right) + 1.7591 \log\left(E_2/E_1\right) - 5.1888}{1 - 0.2172 \log\left(E_2/E_1\right) - 0.7975 \log\left(h_2/h_1\right) + 0.04177 \log^2\left(E_2/E_1\right) + 0.3198 \log^2\left(h_2/h_1\right)}
\]

\[
F\left(\frac{\rho_2}{\rho_1}\right) = \frac{-2.6891 \log^2\left(\frac{\rho_2}{\rho_1}\right) + 5.817 \log\left(\frac{\rho_2}{\rho_1}\right) - 0.8474}{-2.4232 \log^2\left(\frac{\rho_2}{\rho_1}\right) - 2.4232 \log^2\left(\frac{\rho_2}{\rho_1}\right) + 3.7597 \log\left(\frac{\rho_2}{\rho_1}\right) + 19.9635}
\]
Full scale design of 1D and 3D periodic foundations

Small modular reactor (SMR) building as the superstructure

Cutaway elevation view

Overhead plan view

Courtesy of:

NuScale Power™
Finite element model of representative of NuScale’s SMR Building

Material Properties:
- Reinforced concrete ($E_s = 31400$ MPa, $\rho = 2300$ kg/m$^3$, $\nu = 0.2$)

Mass of non-structural components:
- Water in reactor pool = 5.09 million gallon = $19.28 \times 10^6$ kg
- Small modular reactors (12 units) = $12 \times (8 \times 10^5) = 9.6 \times 10^6$ kg
- Crane and utilities = $8 \times 10^5$ kg
Design of 1D periodic foundation
(Combined unit cell with equivalent structure layer)

Equivalent Structure Layer
Concrete Layer 2
Rubber Layer 2
Concrete Layer 1
Rubber Layer 1

\[ h_s^* = 1.32 \text{ m} \]
\[ h_{c2} = 1.32 \text{ m} \]
\[ h_{r2} = 0.88 \text{ m} \]
\[ h_{c1} = 1.1 \text{ m} \]
\[ h_{r1} = 1.1 \text{ m} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus (Pa)</th>
<th>Density (kg/m³)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>(3.14 \times 10^{10})</td>
<td>2300</td>
<td>0.2</td>
</tr>
<tr>
<td>Rubber</td>
<td>(3.49 \times 10^6)</td>
<td>1300</td>
<td>0.463</td>
</tr>
<tr>
<td>Equivalent Super</td>
<td>(3.14 \times 10^{10})</td>
<td>24247.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Transverse wave (S-Wave)

Longitudinal wave
Design of 1D periodic foundation

Damping ratio:
\[ \xi_{\text{concrete}} = 4 \% \]
\[ \xi_{\text{rubber}} = 10 \% \]

Frequency response:
\[ \text{FRF} = 20 \log(\frac{\delta_{\text{out}}}{\delta_{\text{inp}}}) \]
where:
\[ \delta_{\text{out}} = \text{amplitude of output disp} \]
\[ \delta_{\text{inp}} = \text{amplitude of input disp} \]
Design of 3D periodic foundation

One unit cell of 3D periodic foundation

Matrix

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

8m

Core

8m

8m

Dispersion curve for infinite number of unit cells

Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus (MPa)</th>
<th>Density (kg/m³)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced Concrete</td>
<td>31400</td>
<td>2300</td>
<td>0.2</td>
</tr>
<tr>
<td>Rubber</td>
<td>3.49</td>
<td>1100</td>
<td>0.463</td>
</tr>
</tbody>
</table>

Starting of 1st frequency band gap = 11.18 Hz
Width of 1st frequency band gap = 5.98 Hz
Damping ratio:
\[ \xi_{\text{concrete}} = 4 \% \]
\[ \xi_{\text{rubber}} = 10 \% \]

Frequency response:
\[
\text{FRF} = 20 \log(\frac{\delta_{\text{out}}}{\delta_{\text{inp}}})
\]
where:
\[ \delta_{\text{out}} = \text{amplitude of output disp} \]
\[ \delta_{\text{inp}} = \text{amplitude of input disp} \]
Similitude requirements for dynamic models

Essential scaled parameters:

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

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

Superstructure design

reactor building

reactor building

pool water

crane

Small modular reactor

(a) NuScale SMR Building

(b) Finite element model of prototype building

Natural frequency 6.77 Hz

Natural frequency 31.1 Hz

(c) Modal analysis result of prototype building

(d) Modal analysis result of scaled (1:22) model
Design of 1D periodic foundation structural system model

Designed structural system

1,750 kg additional mass uniformly distributed on the roof

8500 kg additional mass uniformly distributed on the floor

0.2 m

4.6 m

2 m

Concrete base

Designed periodic foundation unit cell with equivalent structure layer

Equivalent Structure Layer

1. Reinforced Concrete Layer 2
2. Polyurethane Layer 2
3. Reinforced Concrete Layer 1
4. Polyurethane Layer 1

h_s = 6 cm
h_c2 = 6 cm
h_r2 = 4 cm
h_c1 = 5 cm
h_r1 = 5 cm

Theoretical frequency band gap

2nd Frequency band gap
21.44–50 Hz

1st Frequency band gap
6.12–20.34 Hz

Frequency response function

Theoretical band gap
Top foundation/Superstructure floor
Roof

Frequency (Hz)

Transverse wave (S-Wave)

Longitudinal wave (P-Wave)

FRF (db)

Frequency (Hz)
Design of 3D periodic foundation structural system model

**Designed structural system**

- **Top PF point A**
- **Top PF point B**
- **Top PF point C**

1750 kg additional mass uniformly distributed on the roof

8500 kg additional mass uniformly distributed on the floor

**Unit cell**

- **RC**
- **Polyurethane**
- **36.4 cm**

**Transverse wave (S-Wave)**

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>FRF (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-150</td>
</tr>
<tr>
<td>10</td>
<td>-100</td>
</tr>
<tr>
<td>20</td>
<td>-50</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>

**Longitudinal wave (P-Wave)**

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>FRF (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-150</td>
</tr>
<tr>
<td>10</td>
<td>-100</td>
</tr>
<tr>
<td>20</td>
<td>-50</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>
Fabrication of test specimen

Construction of superstructure

Casting of concrete layers

Resin solution and polyurethane glue

Construction of 1D periodic foundation
Fabrication of test specimen

Casting of concrete cores

Resin solution and polyurethane glue

Construction of 3D periodic foundation
Experimental study of 1D and 3D periodic foundations

**Test Cases**

- Case 1 (RC foundation only)
- Case 3 (1D periodic foundation only)
- Case 5 (3D periodic foundation only)
- Case 2 (RC foundation-structure system)
- Case 4 (1D periodic foundation-structure system)
- Case 6 (3D periodic foundation-structure system)
Excitation types

- For Cases 2, 4, and 6 (structure systems tests)
  - White noise tests in 3 directions (horizontal, vertical, and torsional)
  - Frequency sweeping 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

East
Measurement systems

Accelerometers (measure acceleration)  Tempsonics (measure displacement)

NDI optotrak optical measurements (measure displacement)
White noise tests for structural systems
To obtain natural frequencies of structural systems

**Case 2**
(with RC foundation)

freq = 16.41 Hz

**Case 4**
(with 1D periodic foundation)

freq = 2.49 Hz

**Case 6**
(with 3D periodic foundation)

freq = 2.78 Hz

**In horizontal direction**

**In vertical direction**

**In torsional mode**

freq = 26.86 Hz

freq = 19.63 Hz

freq = 20 Hz

freq = 46.88 Hz

freq = 3.42 Hz

freq = 4 Hz
- Attenuation zones for 1D and 3D periodic-foundation structural systems were obtained in the horizontal direction, vertical direction, and torsional mode.
- For the structural system with RC foundation, the responses at the roof are mostly amplified in all three directions.
Shake table test results

Seismic test results in the horizontal direction

Acceleration responses at roof of superstructures in time domain

(a) Bishop Earthquake

(b) Gilroy Earthquake

(c) Oroville Earthquake

frequency domain

Amplitude (g)
Shake table test results

Seismic test results in the horizontal direction

Roof to shake table relative displacement

(a) Bishop Earthquake

(b) Oroville Earthquake
Seismic test results in the **horizontal direction**

**Roof rotation**

(a) Bishop Earthquake

(b) Gilroy Earthquake

(c) Oroville Earthquake

Note:
A researcher [1] shows that a building structure isolated using air spring systems with oil dampers for rocking suppression has a building rotation of $2.12 \times 10^{-4}$ rad. Therefore, the rocking in periodic foundation structural systems are negligible.

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Seismic test results in the vertical direction

Acceleration responses at roof of superstructures in time domain

- (a) Anza Earthquake
- (b) Bishop Earthquake
- (c) Gilroy Earthquake

frequency domain
Shake table test results

Harmonic test results in the vertical direction
Acceleration responses at roof of superstructures in time domain

Seismic test results in the Torsional mode
Acceleration responses at roof of superstructures in time domain
Finite element (FE) simulation of polyurethane sample

Polyurethane sample

FE model of polyurethane sample
Material model: Hyperelastic Marlow model

Compression test
Finite element (FE) simulation of periodic foundation structural systems

Natural frequencies of **1D** periodic foundation structural system

- **Horizontal direction**
  - FE freq = 2.61 Hz, Test freq = 2.49 Hz

- **Vertical direction**
  - FE freq = 19.59 Hz, Test freq = 19.63 Hz

- **Torsional mode**
  - FE freq = 3.03 Hz, Test freq = 3.42 Hz

Natural frequencies of **3D** periodic foundation structural system

- **Horizontal direction**
  - FE freq = 3.14 Hz, Test freq = 2.78 Hz

- **Vertical direction**
  - FE freq = 18.4 Hz, Test freq = 20 Hz

- **Torsional mode**
  - FE freq = 4 Hz, Test freq = 4 Hz
Finite element (FE) simulation of periodic foundation structural systems

Frequency band gap of 1D periodic foundation structural system

**Horizontal direction**

![Graph for Horizontal direction](image)

**Vertical direction**

![Graph for Vertical direction](image)

**Torsional mode**

![Graph for Torsional mode](image)

Frequency band gap of 3D periodic foundation structural system

**Horizontal direction**

![Graph for Horizontal direction](image)

**Vertical direction**

![Graph for Vertical direction](image)

**Torsional mode**

![Graph for Torsional mode](image)
Finite element (FE) simulation of periodic foundation structural systems

1D periodic foundation structural system

- **Top of Periodic Foundation**
  - 
  - (a) Gilroy Earthquake in the **horizontal** direction
  - (b) Sine Wave 24 Hz in the **vertical** direction
  - (c) El Centro Earthquake in the **torsional** mode

3D periodic foundation structural system

- **Roof of Superstructure**
  - (a) Anza Earthquake in the **horizontal** direction
  - (b) Bishop Earthquake in the **vertical** direction
  - (c) Bishop Earthquake in the **torsional** mode
Conclusions

1. The existence of frequency band gaps in periodic foundations is experimentally verified.

2. The incoming seismic waves having frequencies falling inside the frequency band gaps will be filtered out by the periodic foundations.

3. The periodic foundations are capable of isolating the incoming waves in both the horizontal and vertical direction as well as the torsional mode.

4. The rocking on the periodic foundation structural systems is negligible.

5. Finite element simulation can predict the behavior of periodic foundation structural systems to a good degree of accuracy.
Thank You