UNIVERSITÀ DEGLI STUDI DI TRENTO

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3rd WORKSHOP ON SEISMIC METAMATERIALS

3D LOCALLY RESONANT PERIODIC FOUNDATIONS WITH LOW FREQUENCY BAND GAPS FOR SEISMIC PROTECTION OF FUEL STORAGE TANKS

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XP-resilience

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OUTLINE

- Motivation and EU Project XP-Resilience
- Metamaterial Concept
- Foundation Design
- Functionality Check
- Redesign of the Foundation
- Vertical component damping SSI
- Conclusions

XP-resilience

Motivation

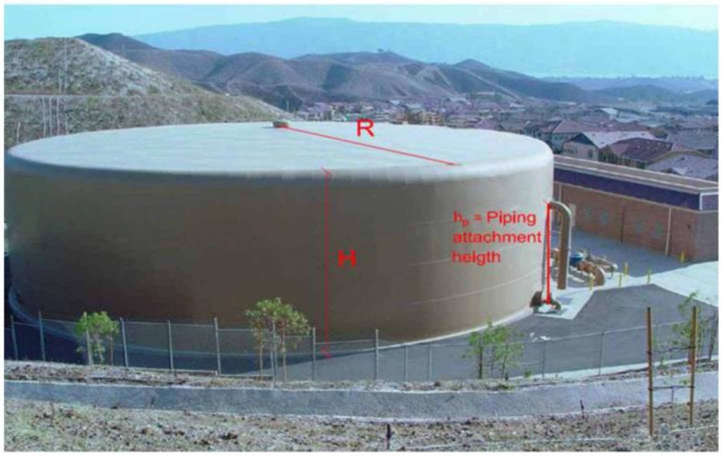
- Protection of high risk structures
- No “Devices” needed
- Vertical component damping
- Simplification of design process
- Damping of multiple frequencies

XP-resilience

- EU Research Project
- Protection of Petrochemical Plants through Metamaterials

Petrochemical Plants

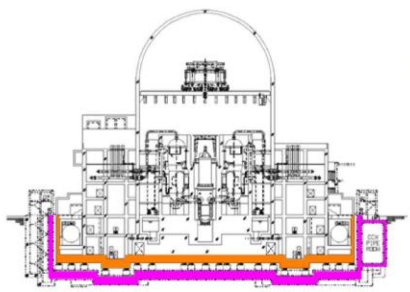
- Variable liquid level -> variable impulsive frequencies
- Danger of Domino-Effect

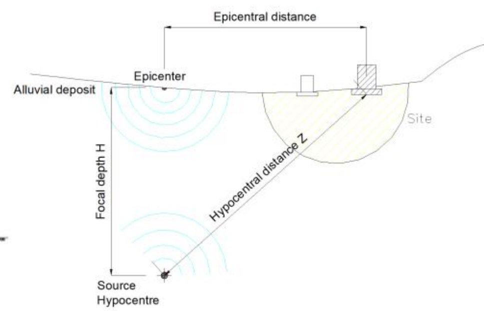


Loss of Containment can lead to significant damages due to Domino-Effects
The investigated broad tank has a diameter around 50m and a Fluid level of 15m
Resulting in Impulsive frequencies of approximately 3,9Hz for a filled Tank and 5Hz for a fluid level of 12m

Nuclear Power Plants

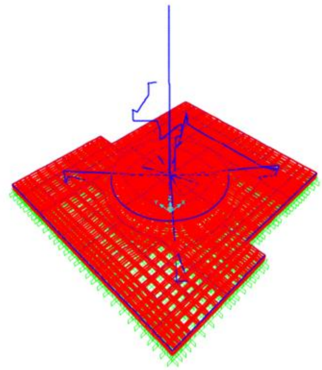
- Reduction of Isolators
- Vertical component isolation





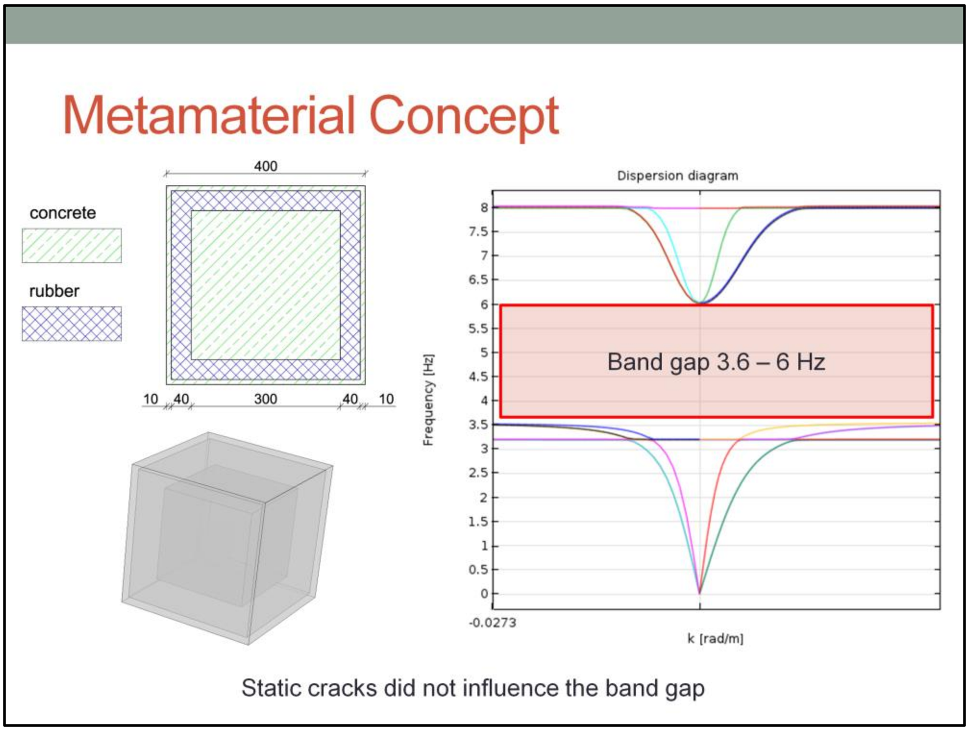
The Isolation of NPPs is very complex and requires many different devices.
The vertical component of a large structure can interact with a horizontal mode.
A low focal depth results in a higher possibility of receiving primary waves at the surface level, which in terms results in a vertical excitation.

Earthquake excitation



Mode Number Unitless	Frequency Hz	Modal Mass x %	Modal Mass y %	Modal Mass z %
1	**3,71**	06,14	0	0
3	**5,65**	01,27	43,3	0,01
14	**14,6**	01,23	0,0331	36,3

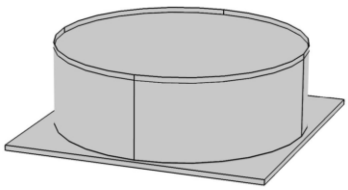
The 14th mode shows an interaction between vertical excitation and horizontal response.
The modal masses for the first modes are low because 3 structures were analyzed in one model, while the modal mass was calculated corresponding to the total mass.



A Unit Cell with dimensions as depicted was found under the aid of the Floquet-Bloch boundary conditions and COMSOL Multiphysics.
The band gap was chosen according to the needs of a broad fuel storage tank.
An analysis whether cracks due to static loading would affect the band gaps turned out negative. The cracks have no influence.

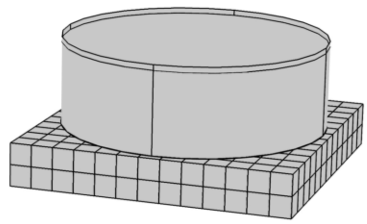
Foundation Design

Traditional Foundation

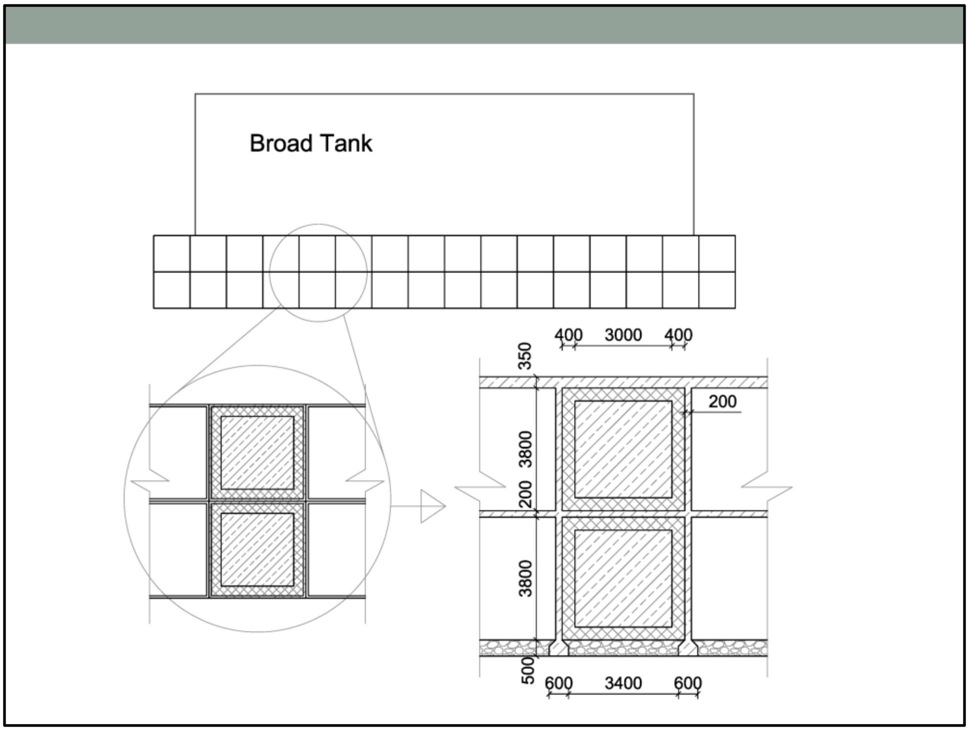


- Concrete baseplate
- Compacted ground
- Usually no isolation

Smart Foundation



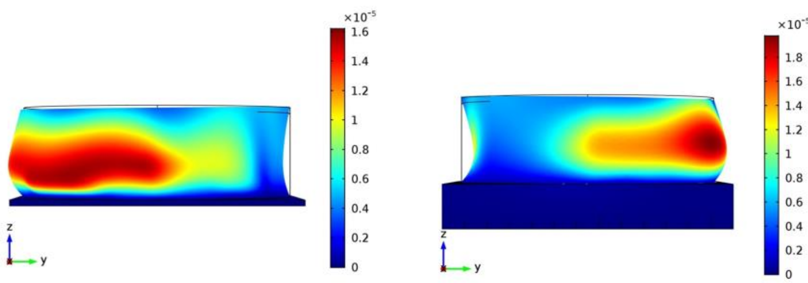
- Lattice of unit cells
- Seismic Isolation
- Concrete and rubber components



A static evaluation was carried out for the designed structure and resulted in the design shown in this slide.
A reinforcement grid will be necessary in order to maintain the static viability.

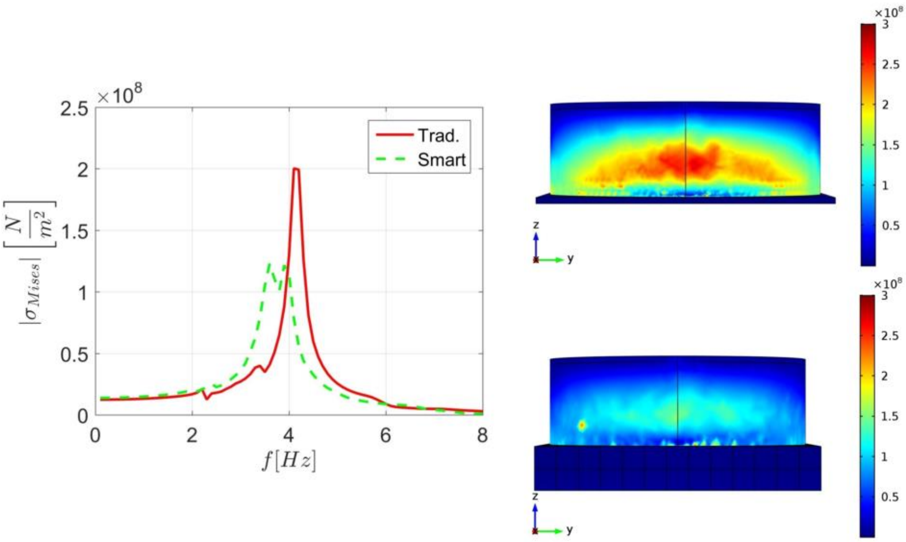
Functionality evaluation

- Finite structure performance
- Modelling of the complete structure in COMSOL Multiphysics
- Harmonic excitation at base
- Frequency response analysis

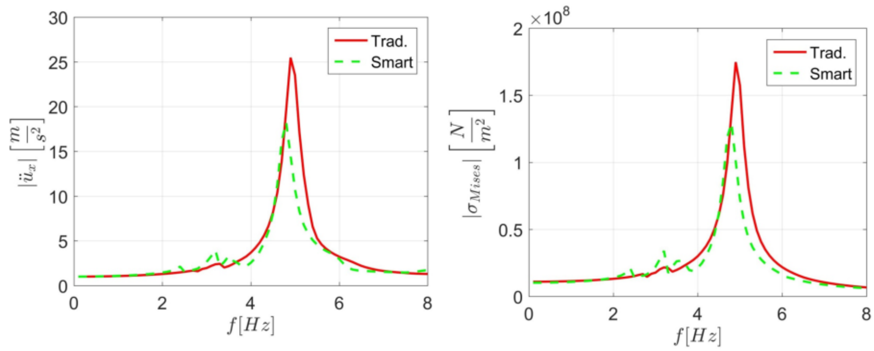


All Frequency Response Functions were achieved by imposing a time harmonic excitation of 1m/s² at the base of the foundation.

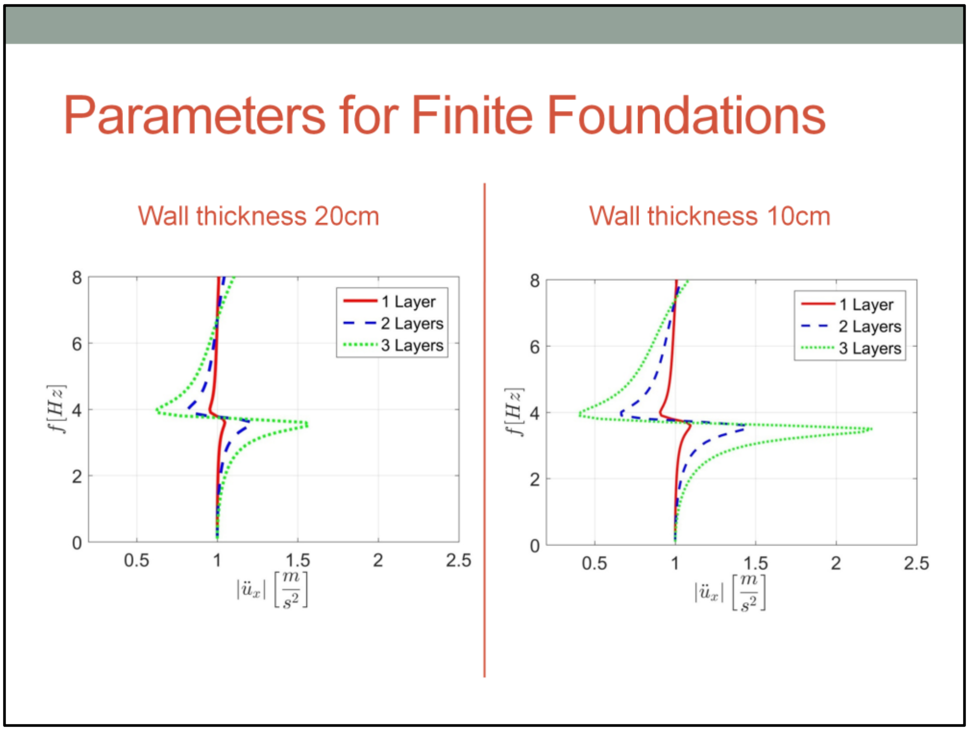
Functionality evaluation



12m Liquid Height



Paper submitted to Frontiers in Materials Journal:
Static and Dynamic Protection of Fuel Storage Tanks by means of 3D Structured Foundation

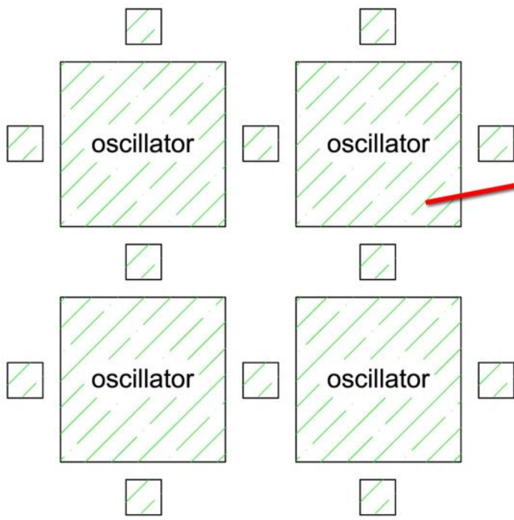


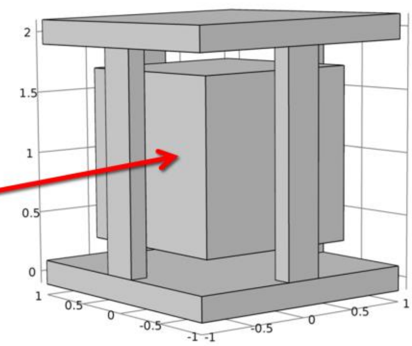
The shear stiffness of the structure seems to have a major impact on the Attenuation zone. In particular, the lower the stiffness the better the attenuation. Besides this, the amount of layers has a clear influence on the attenuation. The shear stiffness governs the propagation of a shear wave in vertical direction. For the vertical attenuation, however, the vertical stiffness has the biggest effect on the propagation behavior.

REDESIGN

Optimization of the unit cell

Columns replace Walls

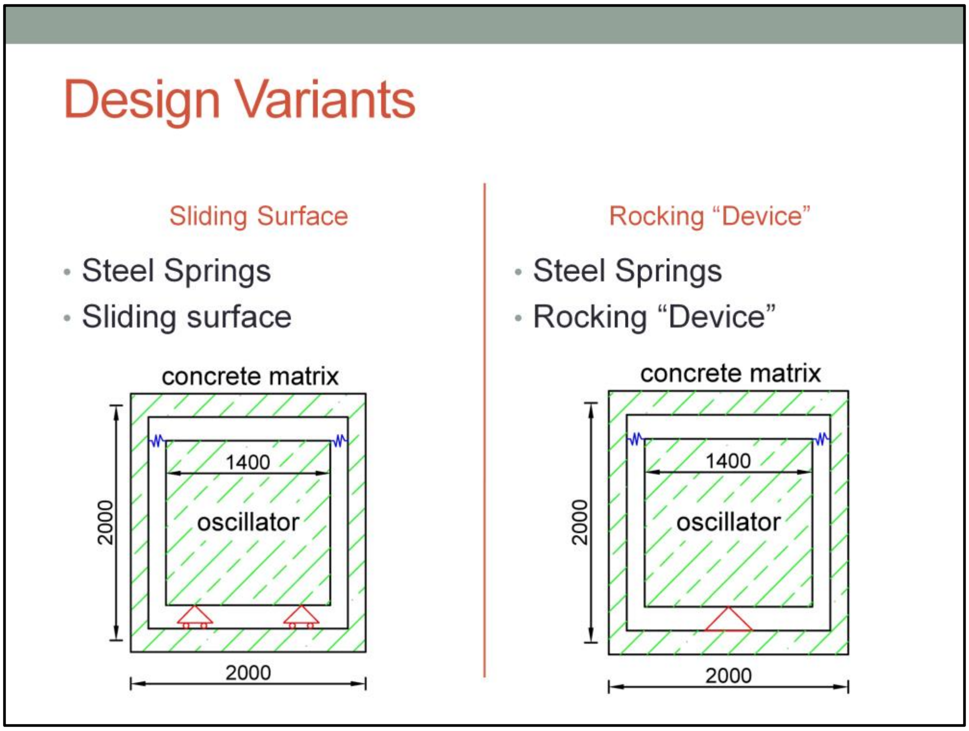




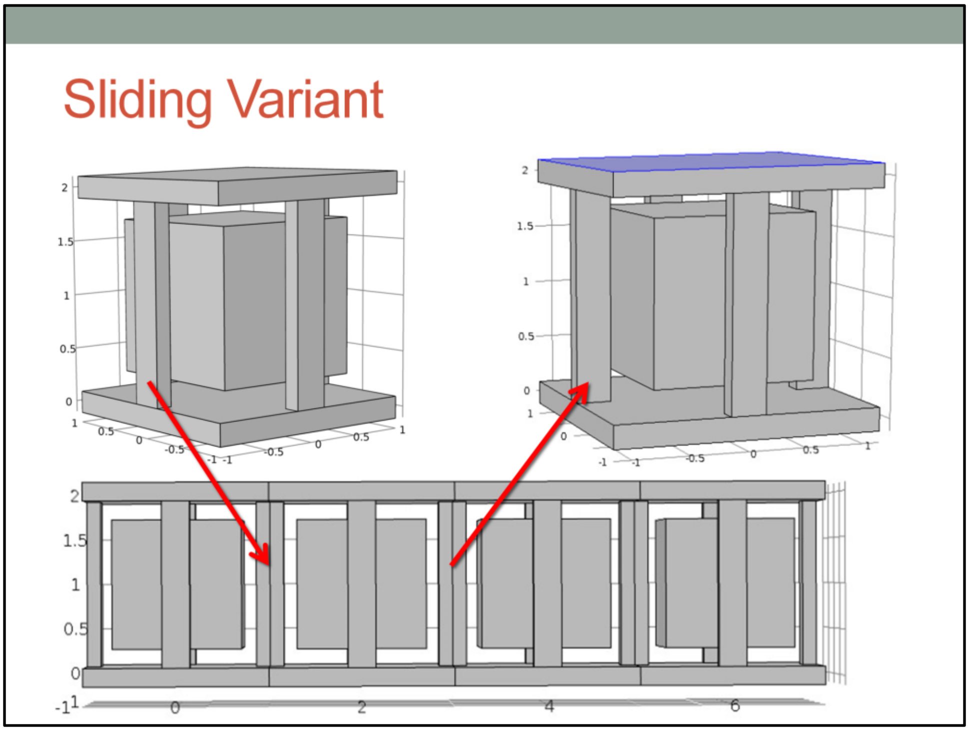
4x4x4 cell → 67.5 [to] oscillator
2x2x2 cell → 6.86 [to] oscillator

Significant size reduction

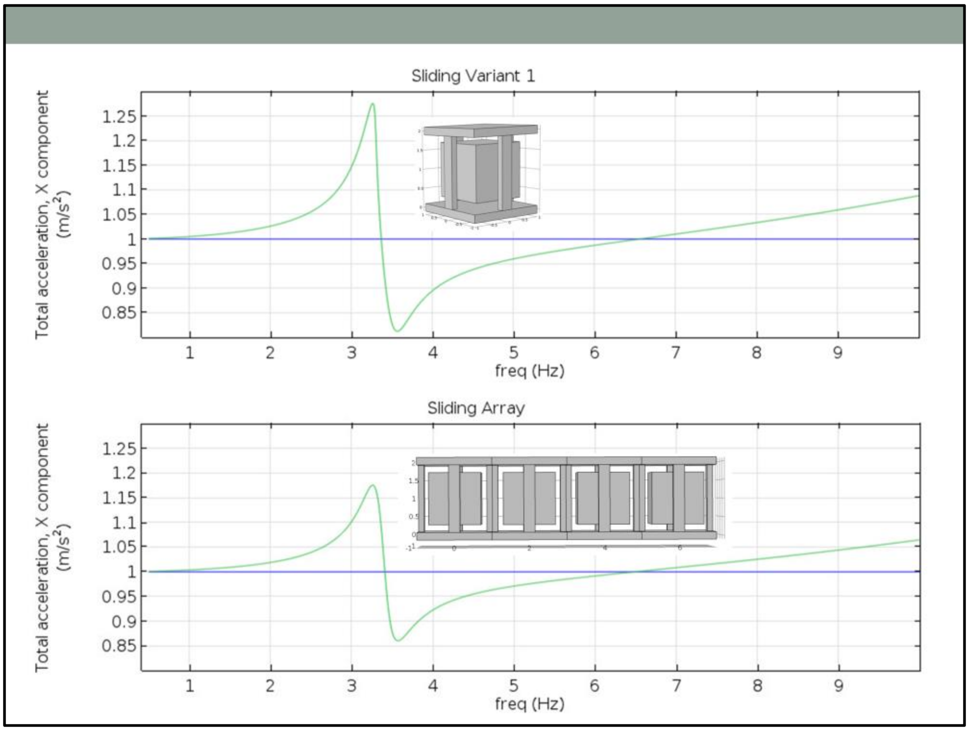
The Stiffness can be greatly reduced by replacing the walls with columns. Furthermore, the attenuation zone can be tune with steel springs instead of rubber.



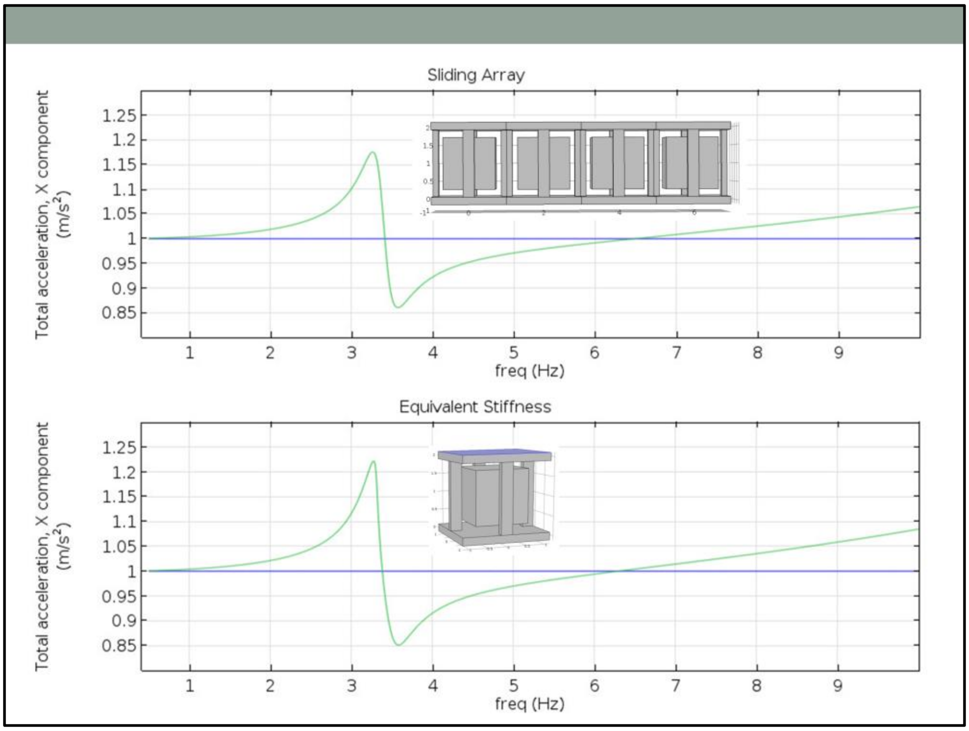
The horizontal movement of the sliding variant results in a high participant mass. The rocking variant will have a reduce effectiveness due to a lower participant mass, but can be designed so that it will also dampen out vertical waves.



A stiffness equivalent unit cell can be achieved by aligning the split columns to the excitation direction and applying a roller to the top slab of the unit cell.



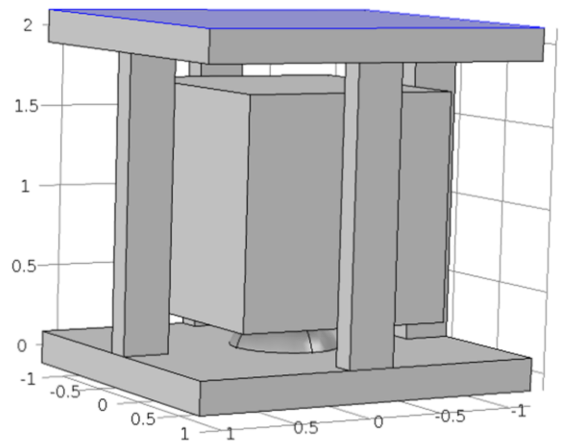
The results show a significant discrepancy.



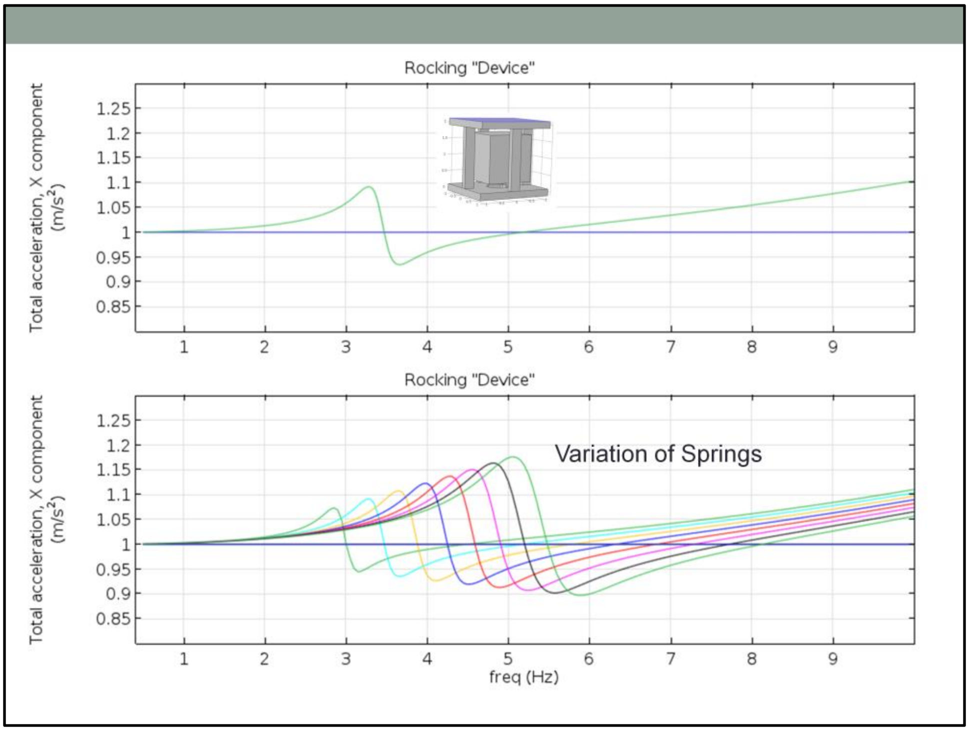
The results show a good correspondence.

Rocking Device

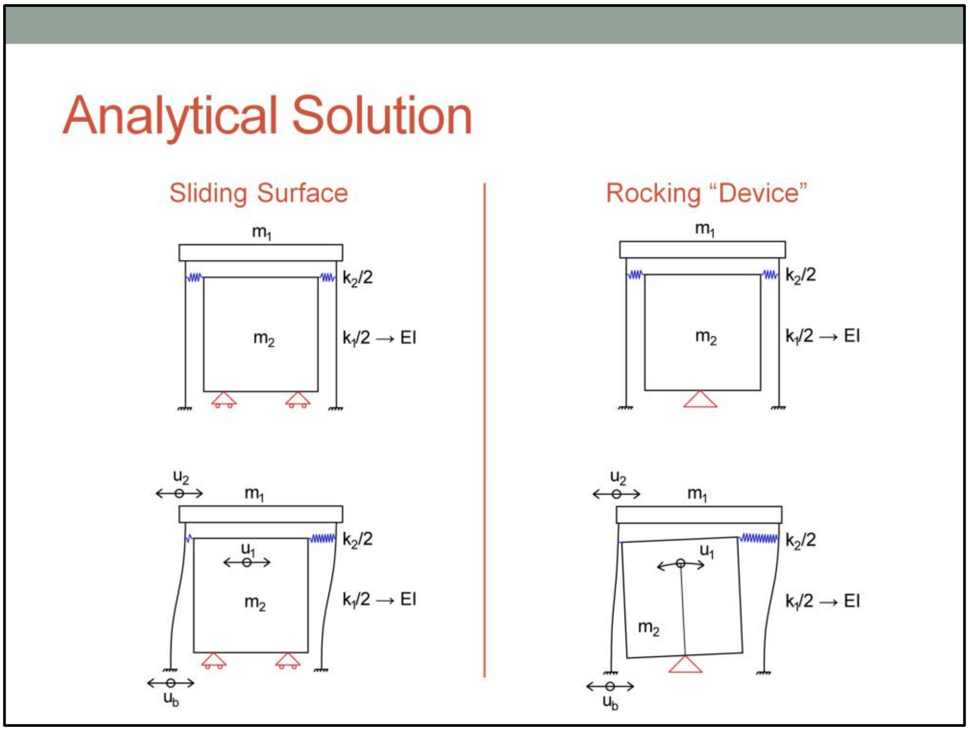
- Rocking motion
- Stiffness equivalent
- Vertical component
- Reduced effect



A ball bearing was modeled in COMSOL Multiphysics.



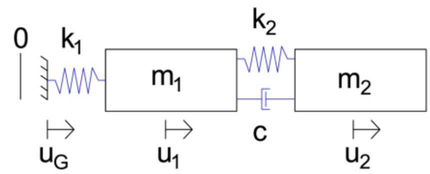
The reduced effectiveness is clearly visible in the top graph.
The bottom graph shows a variation of the spring stiffness. This helped finding the factor of 0.4 that describes the relation of the effectiveness between rocking an sliding variants.



The basic assumptions are: The spring is placed so close to the top slab that it can be assumed to be attached to the top slab.
The columns are replace with linear springs are neglected . This means that shear deformations as well as contributions from second order terms of the differential equations of the beam theory. The resonator system for the rocking variant is considered to be equal to the sliding variant, but with a factor of 0.4 applied to the resonating parts (springs and oscillating mass).

Equations of Motion

- Dynamic System



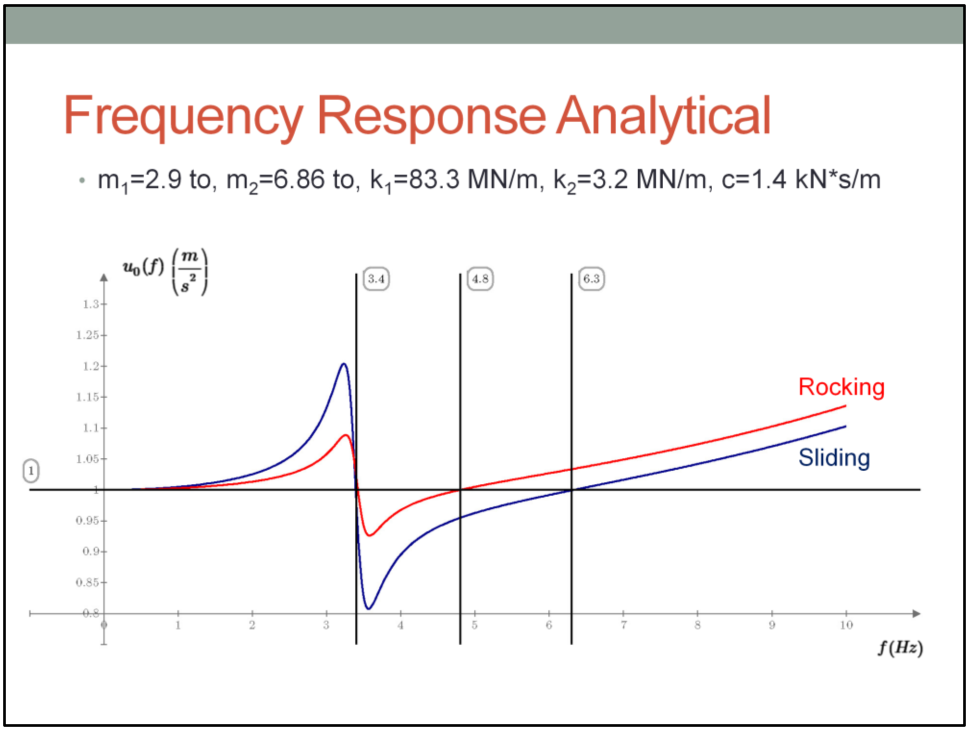
- Matrix form

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\cdot\frac{d^2}{dt^2}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}+\begin{bmatrix} c & -c \\ -c & c \end{bmatrix}\cdot\frac{d}{dt}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}+\begin{bmatrix} k_1+k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}\cdot\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}=\begin{bmatrix} k_1\cdot u_G \\ 0 \end{bmatrix}$$

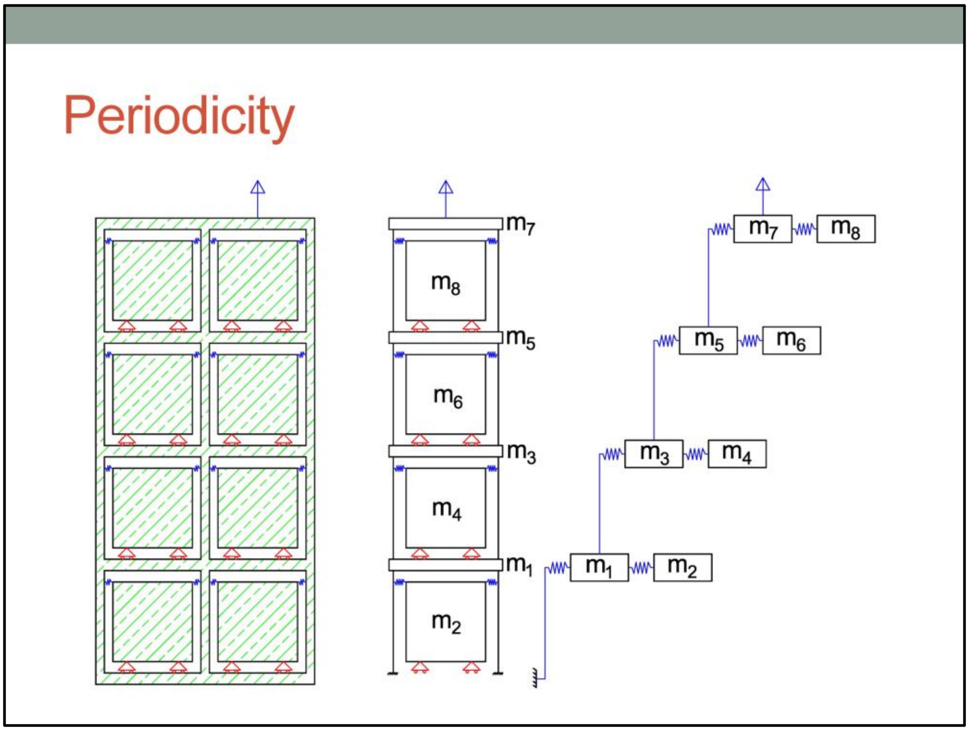
- Frequency Response Function

$$u_0(\omega):=\left|\frac{u_g\cdot k_1}{\left(k_1+k_2-\omega^2\cdot m_1+c\cdot i\cdot\omega-\frac{k_2\cdot(k_2+c\cdot i\cdot\omega)-c\cdot i\cdot\omega\cdot(k_2+c\cdot i\cdot\omega)}{c\cdot i\cdot\omega-m_2\cdot\omega^2+k_2}\right)}\right|$$

The excitation consists of a base motion of $1 m/s^2$.
The damping is a linear dashpot damping which was applied to all the COMSOL Models with a damping ratio of c=4.7%.
This damping was also introduced into the analytical solution.



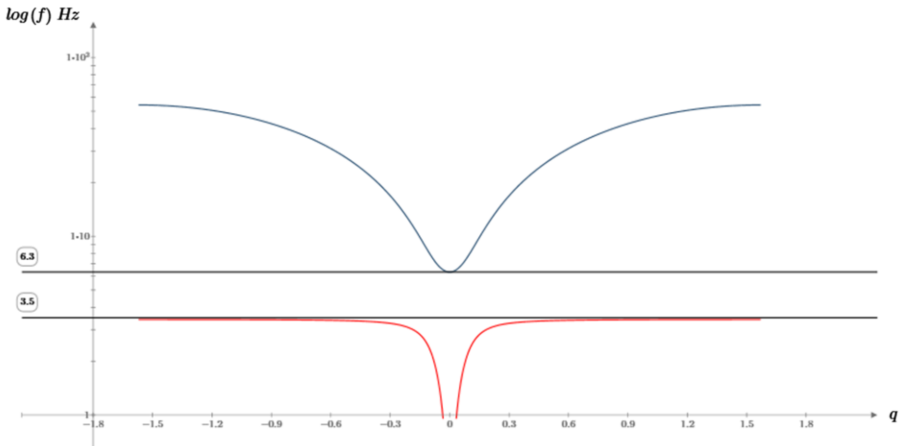
The graphs show good correspondence to the FEM solutions. The enhanced attenuation effectiveness can be explained by the assumption of the springs being connected to the top slab. This results in a better attenuation in the analytical model.



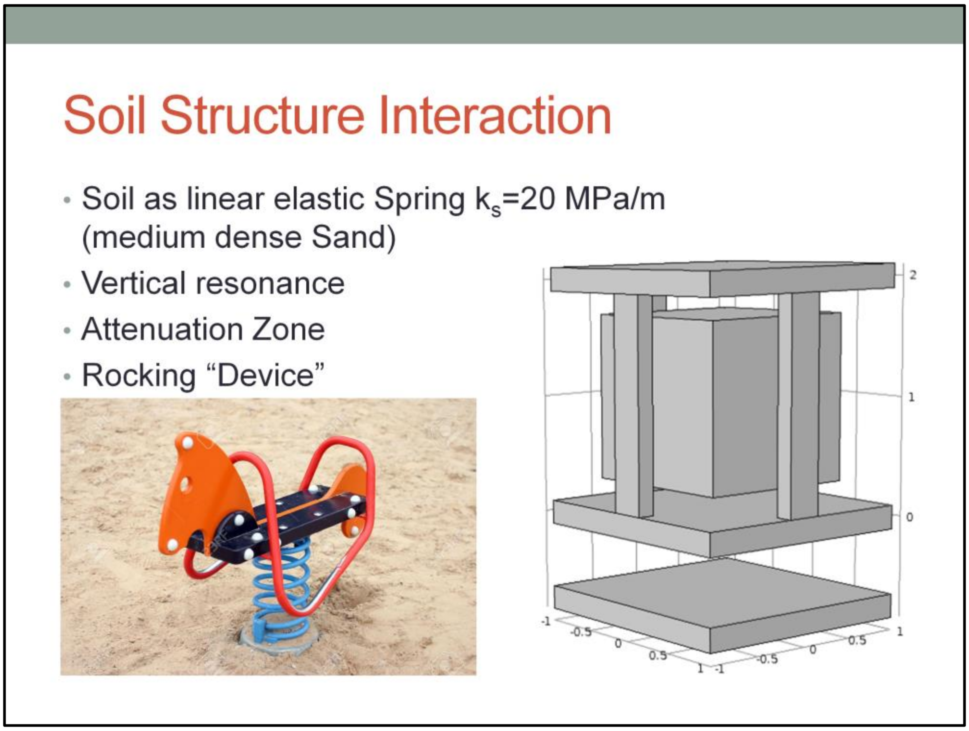
The matrix is reduced to a mass resonator chain.

Dispersion Diagram

$$m_1 \cdot m_2 \cdot \omega^4 - ((m_1+m_2) \cdot k_2 + 2 \cdot m_2 \cdot k_1 \cdot (1-\cos(q \cdot L))) \cdot \omega^2 + 2 \cdot k_1 \cdot k_2 \cdot (1-\cos(q \cdot L)) = 0$$



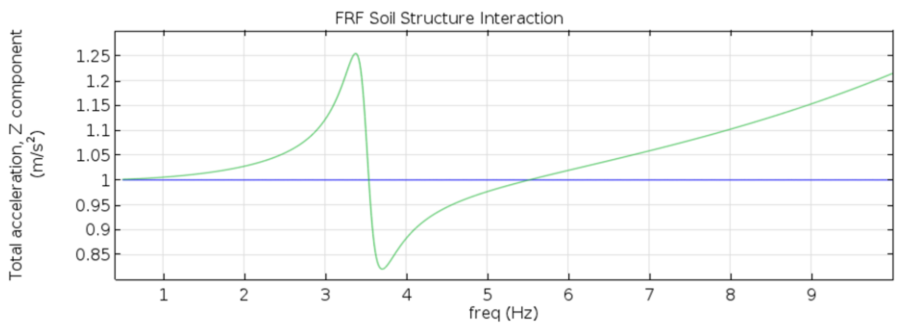
The equations are extracted from the literature and then solved for w (omega).



A vertical spring may be able to provide the rocking motion as well as a vertical vibration.
The Soil is assumed as linear elastic and will provide the softness that the vertical attenuation needs.

FRF for SSI

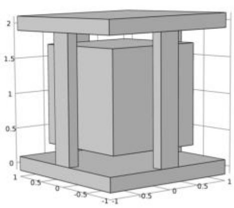
- Soil as Spring
- Softness → Attenuation
- Only One Layer “possible”

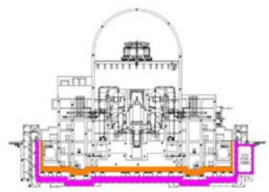


A clear attenuation is visible. Periodicity is hard to achieve, since the alteration of layers of soil and foundation does not seem like a valid approach.

Conclusion

- How small can the unit cell become?
- Nonlinear plastic Soil
- Reduction of the System
- Further improvements for the Vertical Component





The reduction of the system is especially interesting, since the interaction of the structure with the foundation influences the foundations performance.

Thank You

If you have any questions or comments, contact: moritz.wenzel@unitn.it