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METAMATERIAL-BASED FOUNDATION SYSTEM FOR THE SEISMIC ISOLATION OF FUEL STORAGE TANKS

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ABSTRACT

Fluid-filled tanks in tank farms of industrial plants can experience severe damage and trigger cascading effects in neighbouring tanks due to the large vibrations induced by strong earthquakes. In order to reduce tank vibrations, we have explored an innovative type of foundation, designed by metamaterial-based concepts. Metamaterials are generally regarded as manmade structures that exhibit unusual responses not readily observed in natural materials. Due to their exceptional properties and advancements in recent years, they have entered the field of seismic engineering, and therefore, offer a novel approach for designing seismic shields. Of particular interest are the locally resonant metamaterials, which are able to attenuate waves at wavelengths much larger than their unit cell dimensions. Based on this concept, we conceived the so called Metafoundation for fuel storage tanks, which can effectively attenuate seismic excitations at varying fluid levels. The present work is dedicated to validation of the Metafoundation through analytical and numerical analyses in the frequency and in the time domain. As a result we found a significant reduction in the demand on the investigated tanks.

Keywords: Metamaterials; Seismic isolation; Fuel Storage Tanks; Band Gaps; Foundation design

1. INTRODUCTION

Natural hazards such as earthquakes can cause sever damages to the environment and the community. For example, in 1999 the Izmit earthquake damaged the largest Turkish petrochemical plant and set it on fire. The fire took five and a half days to extinguish and almost spread to other industrial sites (Barka, 1999). Such events can be described as natural technological events or NaTech events (Cruz and Steinberg, 2006) (Steinberg, et al., 2008). It is of critical importance for the community and the environment to prevent such incidents from happening. Fuel storage tanks in petrochemical plants need to be regarded as high risk structures, due to their fragility to earthquakes and their potential for cascading effects (Fabbrocino, et al., 2005). Their low impulsive frequencies can fall within the excitation frequencies of earthquakes and significant effort is required to isolate them against seismic vibrations. A very innovative solution for isolating tanks at low frequencies is constructing a foundation based on phononic crystals. These crystals can create stop bands, which stop waves from propagating in certain frequency regions (Sigalas, et al., 2009). Various applications could benefit from these properties, for example, noise protection (Liu, et al., 2000), seismic isolation (Shi & Huang, 2013) or coastal protection (Ha, et al., 2002). The present work is dedicated to the feasibility of such metamaterial-based structures for the seismic isolation of fuel storage tanks.

Three- and two-component foundations were conceived by (Cheng & Zhifei, 2013). A two-dimensional (2D) array of steel cylinders coated with rubber and embedded in a reinforced concrete matrix constituted the three-component foundation. Conversely, the two-component design was based on the same geometry, but replacing the steel cylinders inside the rubber with homogeneous rubber inclusions. By comparing these two designs, they showed that a three-component periodic foundation

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can generate useful band gaps for seismic vibration isolation. Furthermore, they concluded that the reinforcement of the concrete matrix has a negligible influence on the band gaps. However, it is important to underline the two-dimensional nature of their proposed designs, which would have to be improved for an omnidirectional wave. Another 2D approach was studied by (Gaofeng & Zhifei, 2010), while a three-dimensional (3D) approach for a phononic crystal-based structure was proposed by Cheng, et al., (2013). The latter design showed the possibility for a 3D foundation to generate stop bands in the low frequency region. Furthermore, they carried out a parametric study on the structural components and their influence on the band gaps. The mass of the resonator core, the thickness of the rubber coating as well as the stiffness of the rubber have proven to be of special importance for the frequency range of the stop bands. In order to validate the effects of stop bands in periodic structures, Yan, et al., (2014) conducted field experiments on scaled 2D periodic foundations. The comparison between experimental outcomes and numerical results showed that periodic foundations are able to mitigate seismic waves. Furthermore, they found good agreement between experimental tests and dispersion analysis. The work by (Achaoui, et al., 2016) provides additional insight on filtering waves propagating through a foundation made of inertial resonators. The recent work by (Carta, et al., 2016) has addressed the suppression of vibrations in fuel tanks via specially tuned systems of many multi-scale resonators attached to the tanks.
In the present paper, we introduce the Metafoundation. It is based on metamaterial concepts that can attenuate elastic waves, and therefore, is able to protect a superstructure. More precisely, the foundation is capable of attenuating waves in targeted frequency ranges, caused by a variable liquid level in fuel storage tanks. A broad as well as a slender tank, which pose significant threats to the community and the environment, were considered as case studies for the present design. The materials employed in the foundation are concrete and steel springs, which are commonly used in the construction industry. Based on these materials we designed a unit cell comprising columns, as the primary load bearing system, and a resonator, which is located between them. When assembling these cells in an array with multiple layers, a foundation can be conceived. The entailed foundation system has been analyzed on its metamaterial like properties as well as its seismic behavior when coupled with a fuel storage tank. The results show that the foundation works for seismic signals and that it can be applied to various tank systems.

2. CASE STUDY OF A BROAD AND A SLENDER FUEL STORAGE TANK

2.1 Materials

The proposed model for the foundation consists of two components: the concrete resonator cubes and the reinforced concrete framework. For the concrete parts the strength grade was assumed to be C30/37 in agreement with Eurocode 1992, while the fuel storage tanks were considered to be made of welded construction steel. For all models, the materials were considered homogeneous and linear elastic, and their main mechanical properties are collected in Table 1.

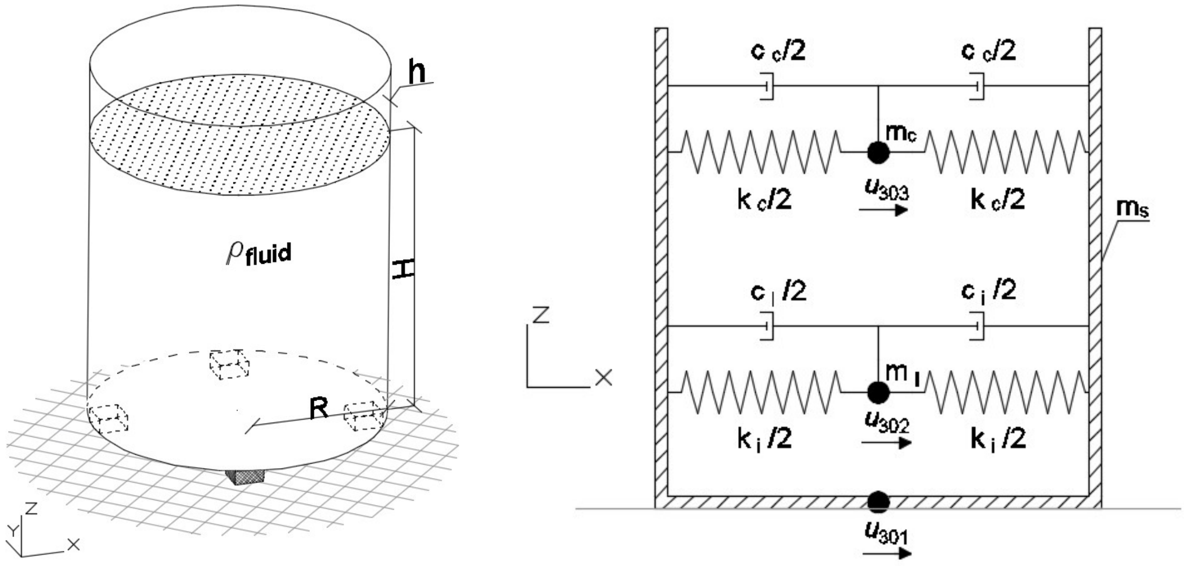
Table 1. Material Properties.

Material	**Density [kg/m³]**	**Elastic modulus [N/mm²]**	**Bulk modulus [N/mm²]**	**Poisson ratio [-]**	**Strength [N/mm²]**
Concrete C30/37	2500	30000	-	0.35	30
Steel	7860	210000	-	0.3	235
Liquid	1000	-	2200	-	-

2.2 Fuel Storage Tank modelling

From a dynamic viewpoint, storage tanks like the one under study can be thought of being composed of an impulsive mass that vibrates in phase with the tank walls at a higher frequency (e.g. 3-5 Hz) and a sloshing mass that vibrates not in phase with the tank walls at a lower frequency (i.e. about 0.3 Hz).

In order to simulate the response of the liquid storage tank the 3-DoFs linear model proposed by Malhotra et al. (2000) was adopted. The model accounts for fluid-structure interaction in a simplified yet accurate manner. A schematic of the liquid storage tank model is illustrated in Figure 1 (A). In detail, H and r define height and radius of the tank, while h is the equivalent uniform thickness of the tank wall.



a b

Figure 1. Sliding liquid storage tank; **(A):** schematic; **(B)**: numerical model.

As depicted in Figure 1 (B), two S-DoF damped oscillators emulate impulsive and convective vibration modes of the sloshing fluid. In this regard, natural vibration periods T_i and T_c and masses m_i and m_c associated with impulsive and convective fluid oscillation modes are respectively calculated as,

$$T_i = C_i H \sqrt{\frac{\rho r}{Eh}}, T_c = C_c \sqrt{r} \tag{1}$$

$$m_i = \gamma_i m_l, m_c = \gamma_c m_l \tag{2}$$

where, ρ is the mass density of liquid, E is the modulus of elasticity of the tank material; C_i, C_c, γ and γ_c are four coefficients depending on the tank slenderness *H/r*; m_l is the total mass of the liquid. Values of stiffness parameters k_c and k_i were calibrated to match the tank properties according to its dimensions with,

$$k_i = m_i \left(\frac{2\pi}{T_i}\right)^2, k_c = m_c \left(\frac{2\pi}{T_c}\right)^2 \tag{3}$$

The Metafoundation is conceived for the higher frequency, since sloshing frequencies can be easily suppressed or mitigated with baffles (Belakroum, et al., 2010). Therefore, the design of the unit cell focused on the first impulsive frequency of the fully filled tank. In fact, this is the eigenfrequency with the largest participant mass in the radial direction. A horizontal excitation at this frequency results in both the largest stresses and accelerations in the tank walls, and thus governs the requirements for the seismic resilience. Since the fluid level height is not a constant parameter in a storage tank, the impulsive frequency of the structure changes accordingly. In particular, the impulsive frequency of the structure increases as the fluid level decreases, thus, necessitating an isolation device that can cover a frequency region. For this reason, a variation of the liquid level from full to ¾ full was also studied. Furthermore, since the Metafoundation has an influence on the eigenfrequencies of the tank, the coupled structure must be taken into account when conducting a modal analysis and determining the desired band gaps. Relevant outcomes of the modal analysis for the tank configurations on different foundation systems are reported in Table 2, where R, H and h denote the tank radius, height and wall thickness of the tank, respectively. On the basis of these results, a frequency region that covers both frequencies for each tank would be desirable. Due to the fact that the fluid level can drop below ¾ full, band gaps that stretch even beyond the increased impulsive frequency were chosen for all the designs.

Table 2. First impulsive eigenfrequencies of tank-foundation systems with various liquid levels.

Foundation typology	**Tank type**	**Liquid height [m]**	**Impulsive frequency [Hz]**
Traditional	Broad	15	3.95
	(R=24m, H=15m, h=20mm)	12	4.63
	Slender	12	6.84
	(R=4m, H=12m, h=6mm)	9	10.05
Metafoundation	Broad	15	1.46
	(R=24m, H=15m, h=20mm)	12	1.73
	Slender	12	1.26
	(R=4m, H=12m, h=6mm)	9	1.48

3. METAMAERIALS AND METAMATERIAL-BASED SEISMIC DESIGN

3.1 Foundation design through analytical modelling

Periodic structures can be designed in order to suppress the propagation of seismic waves in certain frequency regions. These regions are called band gaps and can be determined with the Floquet-Bloch theorem (Phani, et al., 2006). The aim of our Metamaterial-based seismic design is to find a unit cell that provides these band gaps and can be used in a foundation for the mitigation of seismic signals.

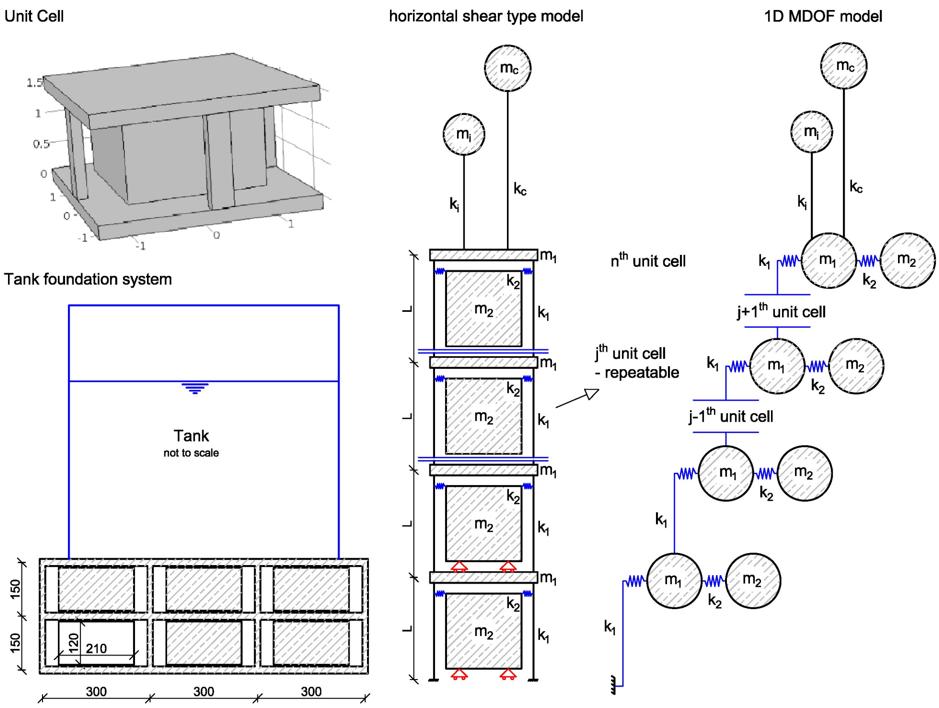


Figure 2 **(A)**: Unit cell and assembly of unit cells with a fuel storage tank on top; **(B)**: Simplified shear type model including 2 DoFs for the representation of the tank; **(C)**: 1D MDoF model for the analysis of the system.

The Principal design of the unit cell is based on columns as the vertical load bearing system, and resonators that will be attached to the columns with steel springs. Figure 2 (A) depicts the unit cell and an assembly of unit cells with a Tank on top. Note that the depiction of the tank including the resonators is not to scale. This figure has the purpose to show the principal arrangement of the coupled tank-foundation system, while in fact, the tank size will be much larger compared to the foundation. Since multiple tanks have been studied, the specific geometries of the systems will be shown together with the results in Subsection 4.2. In principal, the unit cell dimension will be kept fixed, while only the number of horizontally aligned unit cells will be chosen accordingly to the tank size. However, in order to tune the resonators to the specific frequency needs of the tank, the steel springs that connect them to the columns will be varied. In order to investigate the metamaterial-like properties of the new design and to optimize the geometry of the system, we conceived an analytical model of the foundation and calculated the frequency response of the foundation without tank, the frequency response of the foundation with tank, and the dispersion analysis of the unit cell. The horizontal shear model and its 1D MDoF representation are depicted in Figure 2 (B) and (C), respectively. This model allows only shear type waves that act in the horizontal and propagate in the vertical direction. As can be seen in Figure 2 (C), the jth unit cell can be repeated in order to achieve as many layers as desired. The equations of motion read,

$$m_1^j \frac{d^2 u_1^j}{dt^2} - k_1 u_1^{j-1} + k_1 u_1^j + k_2 u_1^j + k_1 u_1^j - k_2 u_2^j - k_1 u_1^{j+1} = 0 \tag{4}$$

$$m_2^j \frac{d^2 u_2^j}{dt^2} - k_2 u_1^j + k_2 u_2^j = 0 \tag{5}$$

where, m_1 denotes the mass of a slab between two layers of foundation including half the columns of the layer below and half the columns of the layer above; m_2 denotes the mass of the resonator; k_1 denotes the horizontal stiffness of two columns, which represents the equivalent stiffness of the columns pertaining to each resonator; k_2 represents the equivalent stiffness of the steel springs holding the resonator; and u describes the horizontal displacement. In order to relate the state variables across the system, the equations of motion must contain the displacement of the *j-1th* and *j+1th* unit cell. Therefore, u is endowed with a subscript (1, 2) that describes the corresponding mass, while the unit cell is determined by the superscript (*j-1, j, j+1*). For a finite system these equations can be written in matrix form. Furthermore, a tank can be represented with 3 additional DoFs, namely the convective, the impulsive mode, and the residual mass mode. The 3rd DoF (residual mass mode) of the Malhotra procedure is introduced to the system as a lumped mass (m_s) that will be added to the last layer of the foundation. Note that its contribution to the system under study is extremely small, about two orders of magnitude smaller than the impulsive mass of the tank. The remaining 2 DoFs are simply connected to the top layer of the foundation, thus, resulting in a system sufficient for the analysis of the coupled problem. The generalized stiffness matrix for a system with *n* unit cells reads,

$$\boldsymbol{K} = \begin{array}{c|} 1 \\ 1 \\ \vdots \\ j^{th} \\ j^{th} \\ \vdots \\ n^{th} \\ n^{th} \\ con \\ imp \end{array} \begin{bmatrix} k_1+k_2+k_1 & -k_2 & -k_1 & \cdots & & & & & & \\ -k_2 & k_2 & 0 & \cdots & & & & & & \\ \vdots & \vdots & \ddots & & & & & & & \\ & -k_1 & 0 & k_1+k_2+k_1 & -k_2 & -k_1 & \cdots & & & \\ & \vdots & \vdots & -k_2 & k_2 & 0 & \cdots & & & \\ & & & \vdots & \vdots & \ddots & & & & \\ & & & & -k_1 & 0 & k_1+k_2+k_c+k_i & -k_2 & -k_c & -k_i \\ & & & & & & -k_2 & k_2 & 0 & 0 \\ & & & & & & -k_c & 0 & k_c & 0 \\ & & & & & & -k_i & 0 & 0 & k_i \end{bmatrix} \tag{6}$$

where the indices of the unit cell is indicated in the left column. Furthermore, the mass matrix, including all the lumped masses of the system, can be written as,

$$
\boldsymbol{M}=\begin{array}{l} 1 \\ 1 \\ \vdots \\ j^{th} \\ j^{th} \\ \vdots \\ n^{th} \\ n^{th} \\ con \\ imp \end{array}\begin{bmatrix}
m_1 & & & \cdots & & & & & & \\
& m_2 & & \cdots & & & & & & \\
\vdots & \vdots & \ddots & & & & & & & \\
& & & m_1 & & & \cdots & & & \\
& & & & m_2 & & \cdots & & & \\
& & & \vdots & \vdots & \ddots & & & & \\
& & & & & & m_1+m_s & & & \\
& & & & & & & m_2 & & \cdots \\
& & & & & & & & m_c & \\
& & & & & & & \vdots & & m_i
\end{bmatrix} \tag{7}
$$

As mentioned before, the unit cell can be repeated in order to create a foundation with as many layers as desired. When extending this approach to an infinite stack of unit cells, the system can be described as a lattice that potentially offers metamaterial like properties (i.e. band gaps). Under the aid of the Floquet-Bloch theorem, it becomes possible to reduce the study of an infinite lattice to the analysis of a single unit cell with Floquet-Bloch quasi-periodicity conditions. After imposing these conditions, a frequency dispersion analysis can be carried out and the band gaps of the system can be found. According to the Floquet-Bloch theorem the solution $\boldsymbol{u}(\boldsymbol{x},t)$ for a periodic system can be expressed as:

$$\boldsymbol{u}(\boldsymbol{x},t)=\boldsymbol{u_k}e^{i(\boldsymbol{q}\cdot\boldsymbol{x}-\omega t)} \tag{8}$$

where $\boldsymbol{q}=[q_x,q_y,q_z]^T$ represents the wave vector in (8), while ω denotes the corresponding frequency in rad/s. As a consequence,

$$\boldsymbol{u}(\boldsymbol{x}+\boldsymbol{R})=\boldsymbol{u}(\boldsymbol{x})e^{i\boldsymbol{q}\cdot\boldsymbol{R}} \tag{9}$$

with $\boldsymbol{R}$ being the lattice vector. By imposing these boundary conditions on a system and solving the discrete eigenvalue problem of a typical cell, which takes on the following form:

$$(\boldsymbol{K}-\omega^2\boldsymbol{M})\boldsymbol{u}=0 \tag{10}$$

it becomes possible to calculate the frequency dispersion curves. In Equation (10), $\boldsymbol{K}$ and $\boldsymbol{M}$ are the stiffness and mass matrix, respectively. When imposing equation (9) on the equations (4) and (5), formulating the eigenproblem as in equation (10) and looking for non-trivial solutions, the dispersion relation is given by:

$$m_1m_2\omega^4-[(m_1+m_2)k_2+2m_2k_1(1-\cos(q))]\omega^2+2k_1k_2(1-\cos(q))=0 \tag{11}$$

A similar solution has been found by (H.H. Huang et al. 2009), who analyzed the negative effective mass peculiarity in an acoustic metamaterial. Here, ω denotes the circular frequency; and q the wave number with dimension 1/m.

4. METAFOUNDATION ANALYIS FOR THE UNCOUPLED AND COUPLED CASE

4.1 Analytical results for the uncoupled foundation

In order to investigate the metamaterial like properties of our foundation, we carried out various analyses on the foundation without any superstructure. The values for m_1, m_2, and k_1, are 4838 kg, 13230 kg, and 7.5e6 N/m, respectively. Note that these values stay the same for all foundation variations, thus the only remaining variable for tuning the system is k_2, the stiffness of the steel springs. For a broad fuel storage tank a band gap with a lower bound of 1.34 Hz was chosen resulting in k_2 equal to 9.24e5 N/m. In the interest of brevity the metamaterial properties of the unit cell are exclusively shown for the variant optimized for a broad tank, since the results for a slender tank are very similar.

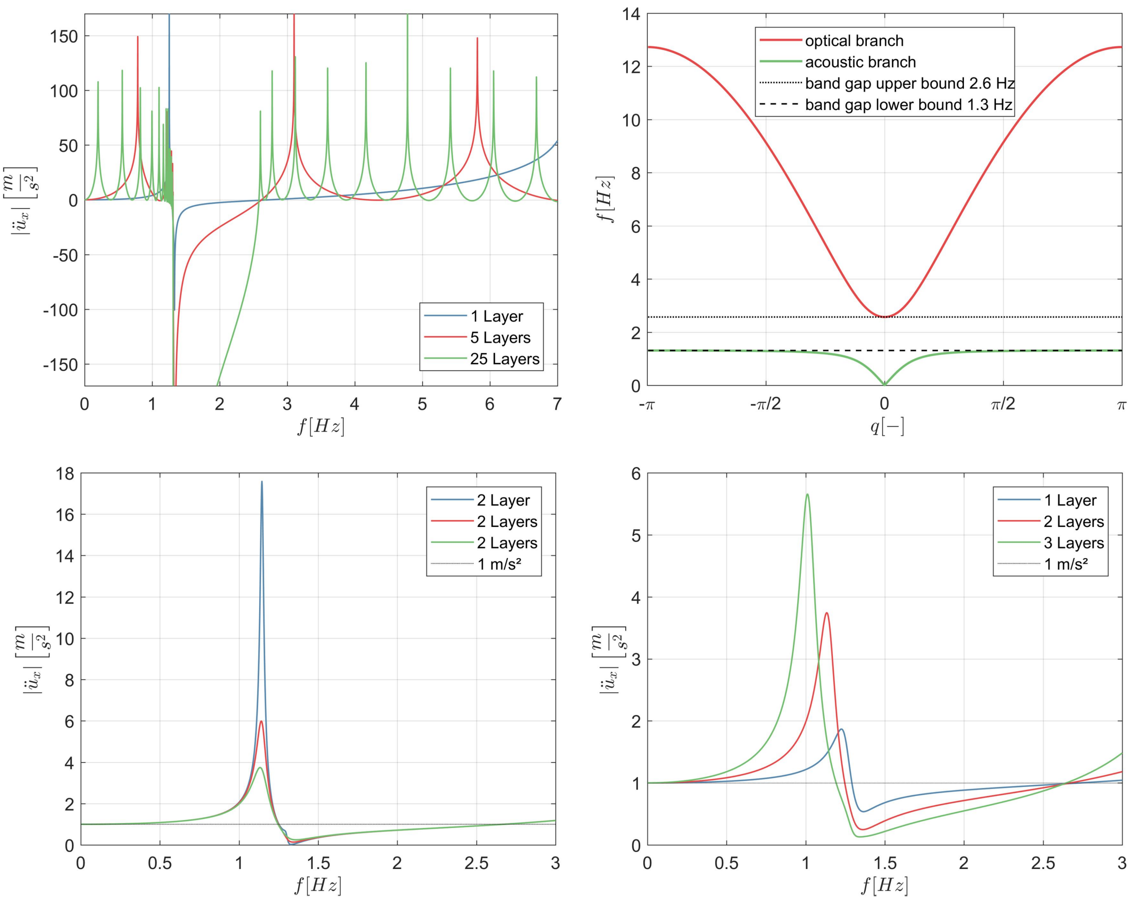


Figure 3 **(A)**: Undamped frequency response function for 1, 5, and 25 layers of foundation for a base excitation of 1 m/s²; **(B)**: Dispersion relations for the optimized unit cell; **(C)**: Frequency response function of the analytical model for two layers and Rayleigh damping of 1, 3, and 5 %; **(D)**: Frequency response function of the analytical model with 5 % Rayleigh damping and 1, 2, and 3 layers.

Firstly, we performed a frequency response analysis on the model with 1, 5, and 25 layers. A base excitation $\ddot{u}_{\text{in}}$ of amplitude 1 m/s² was selected and compared to the output $\ddot{u}_{\text{out}}$ at the top of the foundation. As shown in Figure 3 (A), the foundation exhibits a distinctive attenuation zone that increases with the number of layers. This calculation was carried out without damping and is depicted in decibel dB (20*log($\ddot{u}_{\text{out}}/\ddot{u}_{\text{in}}$)). Furthermore, we were interested whether a dispersion analysis of the system would yield a band gap in the predicted attenuation zone. Figure 3 (B) shows the dispersion relation and the corresponding band gap of an infinite stack of unit cells, calculated with (11). In particular, the band gap for a system designed for a broad fuel storage tank stretches from 1.34 Hz to 2.6 Hz, while a system designed for a slender tank offers a band gap between 1.15 Hz and 2.3 Hz. Additionally, a Rayleigh damping model was employed and ratios of 1, 3, and 5 % were investigated between 1 and 5 Hz, while on the other hand a model with 1, 2, and 3 layers with damping of 5 % between 1 and 5 Hz was analyzed as well. Relevant results are shown in Figure 3 (C) and 3 (D), respectively. The results of the foundation without superstructure show that an harmonic signal is attenuated through the foundation when it falls in the right frequency range. However, for a statement on the viability of the foundation as a seismic shield, it is necessary to carry out analyses on the coupled foundation-tank system.

4.2 Analytical results for the coupled system

Two different tanks were considered for the coupled system, namely a broad and a slender fuel storage tank. For both systems the unit cells were kept with fixed dimensions, while only the number of horizontally aligned unit cells was changed according to the tank size. In order to evaluate the

performance of the systems, two different types of analyses were carried out on the coupled system as well as on the tank alone. In particular, a frequency response analysis showed the performance of the structure for an harmonic excitation, while a time history analysis gave insight in the performance for realistic seismic events.
The first system was designed for a broad tank and constitutes 2 layers with 289 unit cells each and a broad tank with diameter and height of 48 m and 15 m, respectively. The second system, designed for a slender tank with a diameter of 8 m and 12 m height, constitutes 2 layers with only 9 unit cells each. These systems can have varying fluid levels, and therefore, were also studied for decreased impusive frequencies. The relevant parameters, m_1, m_2, k_1, and k_2 for the foundation and m_i, m_c, k_i, and k_c for the impulsive and convective modes of the tanks, are represented in Table 3. Furthermore, the tank-foundation constellations are described by the acronyms BTF, BTnF, STF, and STnF, which stand for: Broad Tank Full, Broad Tank not Full, Slender Tank Full, and Slender Tank not Full, respectively.

Table 3. Parameter values for the analysis of two tank-foundation systems with various fluid levels.

System [-]	m_1 [kg]	m_2 [kg]	k_1 [N/m]	k_2 [N/m]	m_i [kg]	m_c [kg]	k_i [N/m]	k_c [N/m]
BTF	1.40E+6	3.82E+6	2.17E+9	2.47E+8	8.83E+6	1.54E+7	5.44E+9	9.26E+6
BTnF	1.40E+6	3.82E+6	2.17E+9	2.47E+8	5.67E+6	1.37E+7	4.80E+9	7.43E+6
STF	4.35E+4	1.19E+5	6.75E+7	6.22E+6	4.52E+5	8.58E+4	8.35E+8	3.86E+5
STnF	4.35E+4	1.19E+5	6.75E+7	6.22E+6	3.16E+5	8.69E+4	1.26E+9	3.92E+5

Figure 4 shows the configuration of the tank-foundation system with the full liquid height, while figure 5 depicts the frequency response analysis of the impulsive mode of the tanks. The graphs depict the response of the impulsive mode of a tank on the Metafoundation and compare it to the response of a tank clamped to the ground. Clearly, the setups with full tanks show the most effective attenuation in the frequency domain, while the tanks with reduced fluid level perform a little less efficient. However, it is worth noting that in terms of absolute response the setup with a reduced fluid level still performs on a similar level as the full tank does. This becomes apparent when comparing the maximum peak of the frequency responses of the ¾ full tanks to the frequency responses of the full tanks. These results were expected, since firstly, the attenuation zone for a finite foundation has different levels of effectiveness in its frequency range, and secondly, a tank with a reduced fluid level experiences less demand due to the reduced mass.

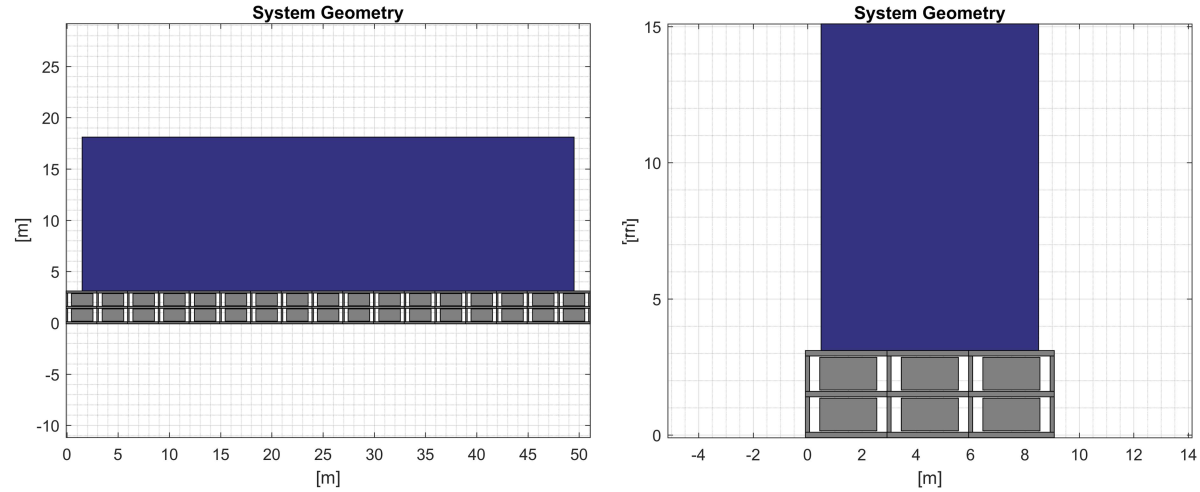


Figure 4 **(left)**: System geometry of a broad including the Metafoundation; **(right)**: System geometry of a slender including the Metafoundation.

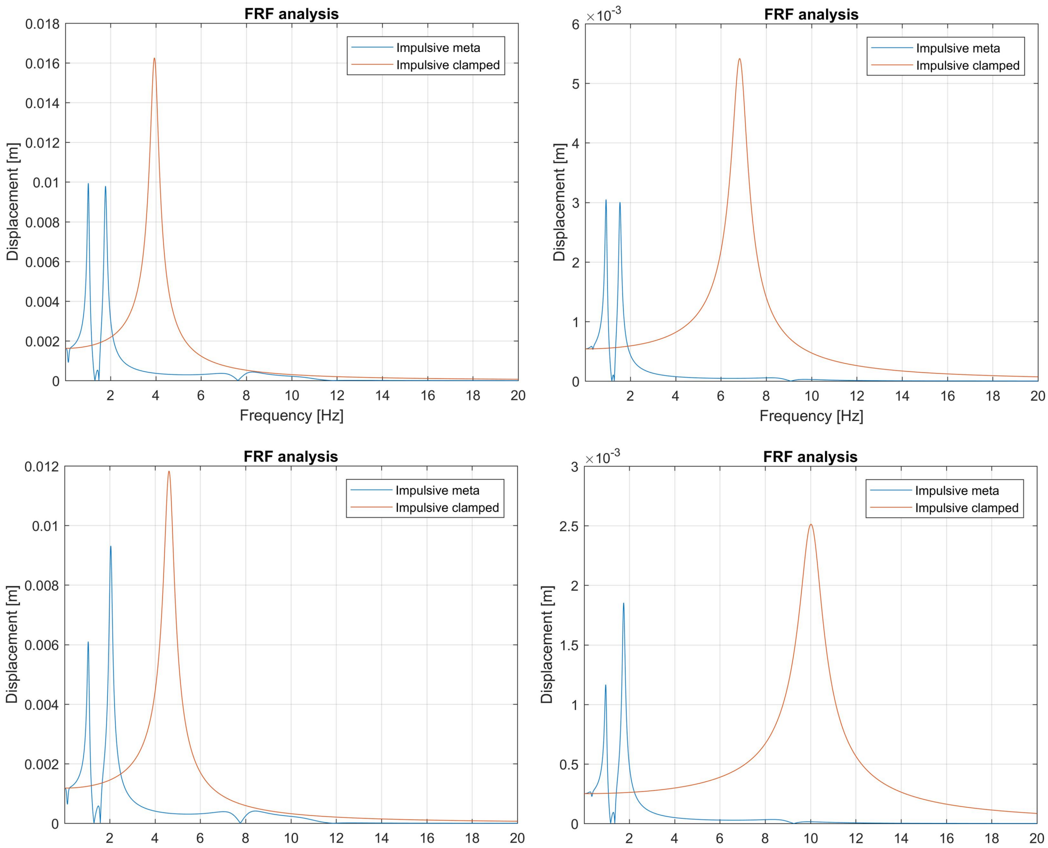


Figure 5 **(top)**: Frequency response function of the impulsive mode of a Broad (left) and Slender (right) tank with full liquid height; **(bottom)**: Frequency response of the same system for a reduced fluid level of approximately ¾ fill.

For the assessment of the functionality of the structure it is not sufficient to consider only calculations in the frequency domain, therefore, we carried out additional analyses in the time domain for various earthquakes. The results presented in Figure 6 and 7 were calculated for an earthquake that occurred in Erzincan, Turkey on the 13th of March 1992 with a magnitude of 6.6 at a fault distance (Rjb) of 13 km. In order to judge the results of these simulations, we considered the base shear and overturning moment of the tanks as governing for their limit states and compared the results for a tank on the Metafoundation to a tank clamped to a traditional foundation. The relevant results are presented in Figure 6 and 7, and show a clear attenuation of the demand on the structure.

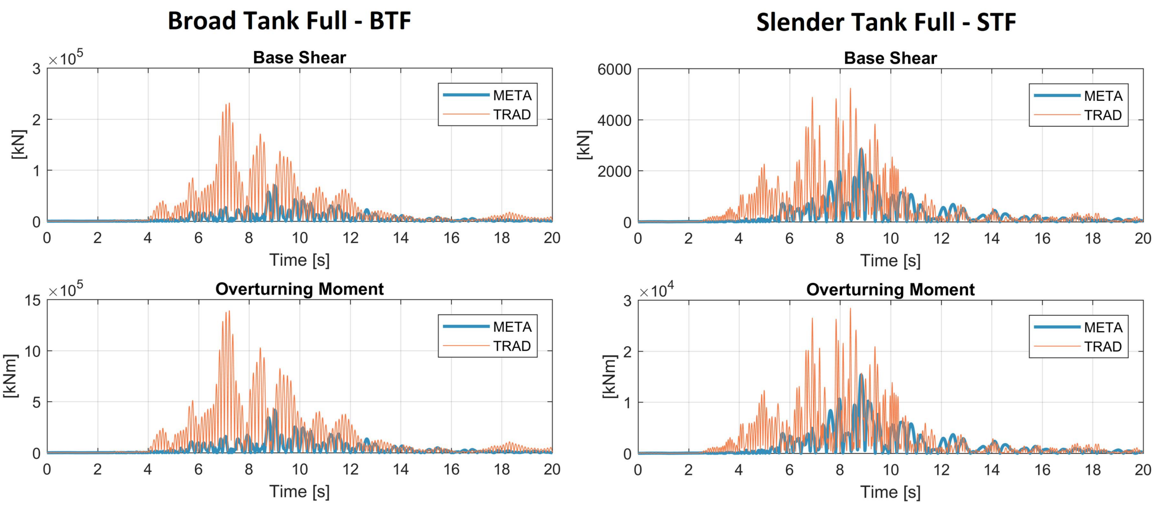


Figure 6 **(left)**: Time history response of a broad tank full BTF; **(right)**: Time history response of a slender tank full STF.

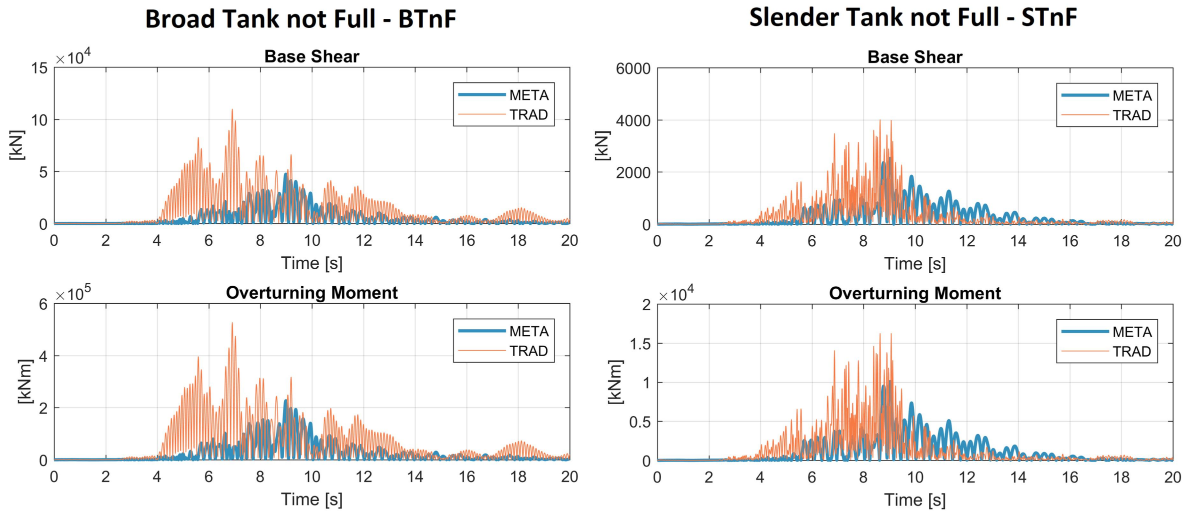


Figure 7 **(left)**: Time history response of a borad tank with 12 m liquid height; **(bottom right)**: Time history response of a slender tank with 9 m liquid height.

4.3 Numerical validation

In order to numerically validate our analytical model, we studied an FE-model of the Metafoundation coupled with a slender tank. The model was built according to the geometry shown in Figure 4 and contains the Metafoundation with lumped masses as resonators and a slender fuel storage tank. The liquid inside the tank was modeled as an acoustic medium, since this represents an accurate representation when sloshing motions are neglected (Carta, G., et al. 2016) (Ding, W., et al 2000).

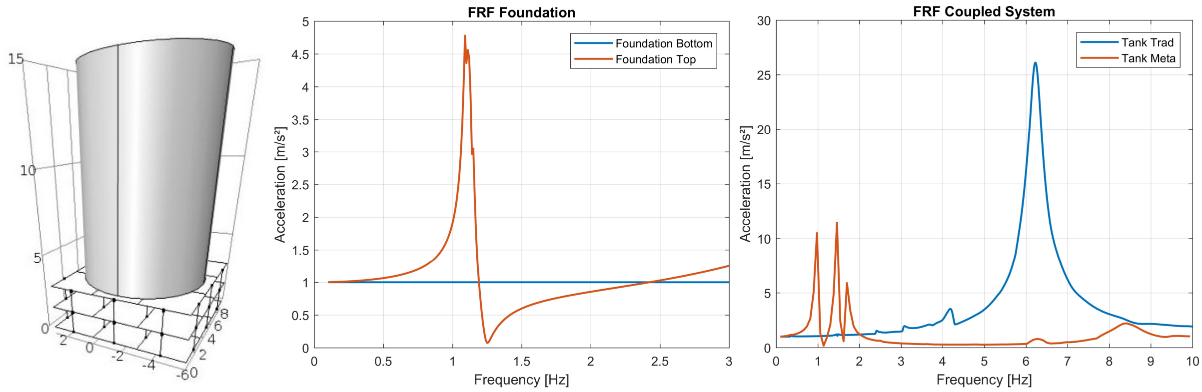


Figure 8 **(A)**: Model of the Tank coupled with the Metafoundation; **(B)**: Response of the Metafoundation without superstructure; **(C)**: Response of the full coupled system.

The model for the FE validation is shown in Figure 8 (A). Analogous to the procedure for the analytical model, we started with an analysis of a foundation only model (Figure 8 (B)), and subsequently studied the coupled tank-foundation system and compared it to the response of a tank modeled with a traditional foundation (Figure 8 (C)). Clearly, the results are quite similar to the analytical model, and therefore, confirm the foundations capability of attenuating seismic waves.

5. CONCLUSION

The Metafoundation was designed on the basis of metamaterial concepts and has been elaborated in the present paper. Through analytical and numerical analysis methods, we proved that the foundation can effectively shield fuel storage tanks from seismic excitations for varying fluid levels. These calculations have been carried out in the frequency as well as the time domain and show promising results for the protection of critical civil infrastructures. However, it is necessary to mention that an exhaustive statement on its effectiveness will require further studies that should include an analysis of its limit state behavior according to the Eurocodes and laboratory experiments. On the other hand, since the designed foundation is still in an early research state, we expect further improvements due to potential design improvements and optimized tuning of the resonators. Moreover, soil-structure interaction will be taken into account; especially for the benefit that soil flexibility can entail for vertical seismic excitations or vertical motions of the coupled (foundation+tank) system. Finally, given the main drawback of standard isolators, i.e. the inherent high vertical stiffness, we expect that the use of the investigated foundation for large structures characterized by rocking motion can reveal great innovative potential and undiscovered advantages.

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REFERENCES

Achaoui, Y., Ungureanu, B., Enoch, S., Brûlé, S., and Guenneau, S., (2016). Seismic waves damping with arrays of inertial resonators. Extreme Mechanics Letters 8, 30-37. http://dx.doi.org/10.1016/j.eml.2016.02.004

Barka, A., (1999). The 17 August 1999 Izmit Earthquake. Science 285:5435, 1858-1859. doi: 10.1126/science.285.5435.1858

Belakroum, R., Kadja, M., Mai, T., and Maalouf, C., (2010). An efficient passive technique for reducing sloshing in rectangular tanks partially filled with liquid. Mechanics Research Communications 37:3, 341-349. doi: 10.1016/mechrescom.2010.02.003

Carta, G., Movchan, A. B., Argani, L. P., and Bursi, O. S., (2016). Quasi-periodicity and multi-scale resonators for the reduction of seismic vibrations in fluid-solid systems. International Journal of Engineering Science 109, 216-239. doi: 10.1016/ijengsci.2016.09.010

Cheng, Z., Yan, Y. Q., Menq, F.-Y., Mo, Y. L., Xiang, H.J., Shi, Z. F., and Kenneth, H. S., (2013). 3D Periodic Foundation-based Structural Vibration Isolation. Proceedings of the World Congress on Engineering, 3-5 July.

Cheng, Z., and Zhifei, S., (2013). Novel composite periodic structures with attenuation zones. Engineering Structures 56, 1271-1282. http://dx.doi.org/10.1016/j.engstruct.2013.07.003

Cruz, A. M., Steinberg, L. J., 2006, Emerging Issues for Natech Disaster Risk Management in Europe, Journal of Risk Research, 9:5, 483-501. https://doi.org/10.1080/13669870600717657

Ding, W. P., and Chen, H. L., (2001). A symmetrical finite element model for structure-acoustic coupling analysis of an elastic, thin-walled cavity. Journal of Sound and Vibration 243:3, 547-559. https://doi.org/10.1006/jsvi.2000.3478

EN 1992-1-1, (2003). Eurocode 2 – Design of concrete structures – Part 1-1: General rules and rules for buildings, CEN:Bruxelles.

Fabbrocino, G., Irevolino, I., Orlando, F., and Salzano, E., (2005). Quantitative risk analysis of oil storage facilities in seismic areas. Journal of hazardous Materials 123, 61-69. http://dx.doi.org/10.1016/j.jhazmat.2005.04.015

Gaofeng, J., and Zhifei, S., (2010). A new seismic isolation system and its feasibility study. Earthquake Engineering and Engineering Vibration 9, 75-82. doi: 10.1007/s11803-010-8159-8

Ha, Y.-K., Kim, J.-E., Park, I.-W., and Lee, H. Y., (2002). Propagation of water waves through finite periodic arrays of vertical cylinders. Applied Physics Letters 81:7. doi: 10.1063/1.1499520

Huang, H.H., Sun, C.T., Huang, G.L., (2009). On the negative effective mass density in acoustic metamaterials. International Journal of Engineering Science 47:610-617. https://doi.org/10.1016/j.ijengsci.2008.12.007

Liu, Z., Zhang, X., Mao, Y., Zhu, Y. Y., Yang, Z., Chan, C. T., and Sheng, P., (2000). Locally Resonant Sonic Materials. Science 289:5485, 1734-1736. doi: 10.1126/science.289.5485.1734

Malhotra, K.P., Wenk, T., Wieland, M., (2000). Simple Procedure for Seismic Analysis of Liquid-Storage Tanks. Structural Engineering International 10:3, 197-201. https://doi.org/10.2749/101686600780481509

Phani, A. S., Woodhouse, J. & Fleck, N. A., 2006. Wave propagation in two-dimensional periodic lattices. Acoustical Society of America, April.

Shi, Z. and Huang. J., (2013). Feasibility of reducing three-dimensional wave energy by introducing periodic foundations. Soil Dynamics and Earthquake Engineering 50, 204-212. http://dx.doi.org/10.1016/j.soildyn.2013.03.009

Sigalas, M., Kushwaha, M. S., Economou, E. N., Kafesaki, M., Psarobas, I. E., and Steurer, W., (2009). Classical vibration modes in phononic lattices: theory and experiment. Zeitschrift für Kristallographie – Crystalline Materials 220:9-10. https://doi.org/10.1524/zkri.2005.220.9-10.765

Steinberg,L. J., Sengul, H., Cruz, A. M., 2008, Natech risk and management: an assessment of the state of the art, Natural Hazards, 46:2, 143-152. https://doi.org/10.1007/s11069-007-9205-3

Yan, Y., Laskar, A., Cheng, Z., Menq, F., and Tang, Y., (2014). Seismic isolation of two dimensional periodic foundations. Journal of Applied Physics 116:044908. http://dx.doi.org/10.1063/1.4891837