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NOVEL METAMATERIAL-BASED FOUNDATION CONCEPT APPLIED TO A COUPLED TANK-PIPELINE SYSTEM

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ABSTRACT

The recent advance of seismic metamaterials has led to various concepts for the attenuation of seismic waves. A particularly promising type of material is the locally resonant metamaterial, which is capable of attenuating seismic waves at wave lengths much greater than the dimensions of its unit cells. Based on this concept, the so called Metafoundation has been design. It is able to protect a fuel storage tank from ground motions at various fluid levels. In order to show the effectiveness of the proposed design, the response of the Metafoundation is compared to the response of a tank on a traditional concrete foundation. The design process of conceiving the Metafoundation, optimizing it for a specific tank, and its seismic response are described herein. Furthermore, the response of a tank during a seismic event can cause severe damages to pipelines connected to the tank. This phenomenon can be of critical importance for the design of a seismic tank protection and must be treated with care. Since the coupled structure (tank+foundation+pipeline) exerts highly non-linear behavior, due to the complexity of the piping system, a laboratory experiment has been conducted. More precisely, a hybrid simulation that uses the Metafoundation and a tank as a numerical substructure (NS) and a piping system as a physical substructure (PS) was employed. In order to make the results relatable to the current state of the art, additional experiments were performed with concave spherical bearing devices (CSBs) as an isolation system in the NS. While the Metafoundation performed better than the CSB isolated structure for some records, a clear advantage could not be concluded. However, the Metafoundation offers a clear attenuation of tank stresses and may potentially mitigate also piping stresses when tuned to the right frequency in the future.

INTRODUCTION

Natural hazards such as earthquakes can cause significant damages to the environment and the community. Of special

interest to many studies on natural hazards are NaTech events (natural technological events) [1-3], which can be caused by the interaction of a seismic incident with the failure of critical technical components. These events include Loss Of Containment (LOC) of fuel storage tanks, pipelines and other components of e.g. petrochemical plants and nuclear power plants. LOC events of such critical infrastructures need to be avoided at the highest priority, as past NaTech disasters have displayed their potential in causing substantial damage to the community and the environment [4,5].

In order to protect structures from seismic effects, various strategies have found application in the field of earthquake engineering. The standard form of seismic isolation uses lead-rubber bearings [6] or spherical bearing devices [7]. This type of seismic protection is able to isolate a structure of interest from the ground motion, and hence, reduce the stresses appearing in the structure induced by seismic waves at a wide range of frequencies. It has been shown by Jadhav and Jangid [8] that these types of Isolation devices can effectively reduce the stresses in fuel storage tanks. In the present work, we investigate a new type of seismic protection based on metamaterial concepts that may offer an alternative to classical isolators in the future.

Many different types of Metamaterials exist with interesting wave propagation properties for elastic as well as optical waves [9]. Only recently it has been discovered that a particular type of metamaterial, namely phononic crystals, may be feasible to construct at a reasonable size for the isolation of structures against seismic waves. These phononic crystals exhibit so called band gaps that prohibit waves from propagating through the material when their frequency falls within that gap [10]. Several studies tried to harvest this property for the design of a foundation for the seismic isolation of a superstructure, but none have taken the feedback coming from the structure into account [11-15]. In this work a foundation is developed and optimized, based on the

aforementioned concept, for the dynamic protection of a fuel storage tank, while considering realistic feedback from a superstructure. The developed system shows promising results for the reduction of the demand on the tank in the frequency and time domain and will be referred to as Metafoundation. Furthermore, this work evaluates the effect that the proposed foundation may have on a connected piping system and compares the system to a system endowed with classical isolators. Due to the high non-linearity of the studied piping system, the evaluation has been carried out under the aid of a hybrid simulation, which can capture the interaction of the coupled system in a realistic manner [16,17]. In particular, the piping system will be constructed in a laboratory as the PS of the system, while the tank and the foundation are modelled as NSs that are coupled to the experimental setup. In summary, the Metafoundation reduces stresses in a tank as a superstructure, while exhibiting a similar demand as a standard isolator on a connected piping system.

MATERIALS

The Metafoundation consists of two components, namely the structural matrix and the internal resonators. Both parts are made of concrete of strength grade C30/37 with material parameters given by Eurocode 2 [18], and are connected to each other with ideal steel springs. Furthermore, a fuel storage tank was chosen as a superstructure for the system and is considered to be made of common welded construction steel with a strength grade of S235. For the laboratory experiments a welded piping system with a strength grade of S355 and a yield strain limit at 0.2 % has been used. Table 1 shows the material parameters for density, elastic modulus, bulk modulus, Poisson ratio, and yield strength, for all components used in the present work. Note that linear elasticity was assumed for all calculations.

Table 1. Material parameters.

Material	Density [kg/m ³]	E [N/mm ²]	Bulk mod [N/mm ²]	Poisson [-]	Strength [N/mm ²]
Concrete C30/37	2500	30000	-	0.2	30
Steel S235	7860	210000	-	0.3	235
Liquid	1000	-	2200	-	-
Steel S355	7860	210000	-	0.3	355

FUEL STORAGE TANK MODELLING

Fuel storage tanks can be reduced to two fundamental modes, which are the impulsive and the convective mode. More precisely, the impulsive mode represents that part of the liquid that resonates in phase with the tank walls and appears to move mainly in the horizontal direction, while the convective mode embodies the sloshing motion of the liquid, and moves mainly in the vertical direction. A simplified procedure for the modelling of storage tanks has been proposed by Malhotra et al. [19], where the tank is reduced to these two main modes under the aid of design coefficients dependent on the height to radius

ratio. When applying the equations below to typical fuel storage tanks, it can be found that the impulsive frequency is commonly situated between 3-7 Hz, while the convective mode embodies a much lower frequency around 0.3 Hz. However, for the tank under investigation, the impulsive mode takes up a value of 6.84 Hz, while the sloshing mode resonates at 0.338 Hz. Figure 1 (left) displays a sketch of storage tank with H, R and t denoting the height, radius and wall thickness of the tank, respectively. The two S-DoFs that simulate the impulsive and convective modes can be seen in Figure 1 (right), where they are connected to a rigid frame that contains the remaining mass of the tank.

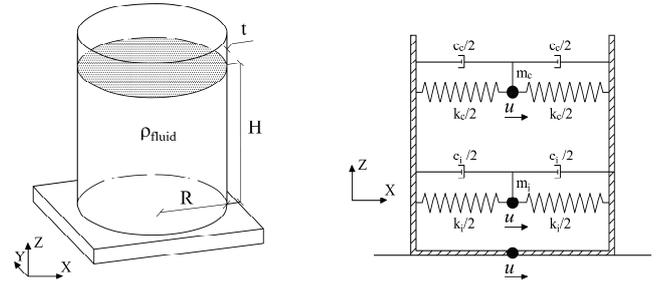


Figure 1. (left): Drawing of a generic fuel storage tank; (right): Representation of a fuel storage tank with two SDOFs for the impulsive and convective modes.

According to the procedure proposed by Malhotra et al. the vibration periods T_i and T_c , and modal masses m_i and m_c can be calculated with,

$$T_i = C_i H \sqrt{\frac{\rho r}{E t}}, \quad T_c = C_c \sqrt{r} \quad (1)$$

$$m_i = \gamma_i m_l, \quad m_c = \gamma_c m_l \quad (2)$$

here, E , ρ , and m_l denote the elastic modulus of the tank wall, the density of the liquid, and the total mass of the liquid respectively, while the parameters C_i , C_c , γ_i and γ_c have to be determined accordingly to the slenderness of the tank H/R . Based on these values the stiffness coefficients can be evaluated as,

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

It has been shown by Belakroum et al. [20] and Maleki et al. [21] how baffles can increase the damping on the convective mode. Due to the possibility of using such baffles against resonance in the convective mode and the fact that the impulsive mode contains the highest participant mass, especially for slender tanks, the Metafoundation has been designed for the attenuation of the latter. Furthermore, a storage tank can experience varying fluid levels, thus, changing its impulsive mode. More precisely, the impulsive frequency increases when the liquid level decreases. In order to address this peculiarity, the band gap like properties of a locally resonant metamaterial are exploited. By tuning the lower bound

of the band gap to the frequency of the full tank and the upper bound to a frequency a bit higher than the impulsive frequency of a $\frac{3}{4}$ filled tank, an attenuation of both frequencies can be achieved. This will be discussed in more detail in the following Subsection. As mentioned in the Introduction section, it is necessary to take the feedback from the superstructure into account. One of the major impacts that this feedback has is the alteration of the modes of the tank. Due to the softening of the overall dynamic system for the coupled case, the new eigenfrequency, at which the impulsive mode gets excited most, appears to be smaller than for the tank alone. For all analyses in this work a tank with height H , radius R and tank wall thickness t of 12 m, 4 m, and 6 mm, respectively has been used. Furthermore, Table 2 depicts the various impulsive frequencies caused by a liquid level of 12 m and 9 m for a tank placed on the Metafoundation and compares them to a tank set on a traditional concrete slab. Based on these results a band gap with a lower bound of 1.1 Hz is desired, while the upper bound was found at 2.2 Hz for the proposed design.

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

Foundation typology	Tank type	Liquid height [m]	Impulsive frequency [Hz]
Traditional	Slender	12	6.84
		9	10.05
Meta-foundation	Slender	12	1.26
		9	1.48

METAMATERIAL-BASED SEISMIC DESIGN

Band gaps can be found in periodic structures under the aid of the Floquet-Bloch theorem [22]. These gaps represent frequency regions where elastic waves cannot propagate through the material, and therefore, shall be used to attenuate the response of a superstructure that exerts a varying frequency.

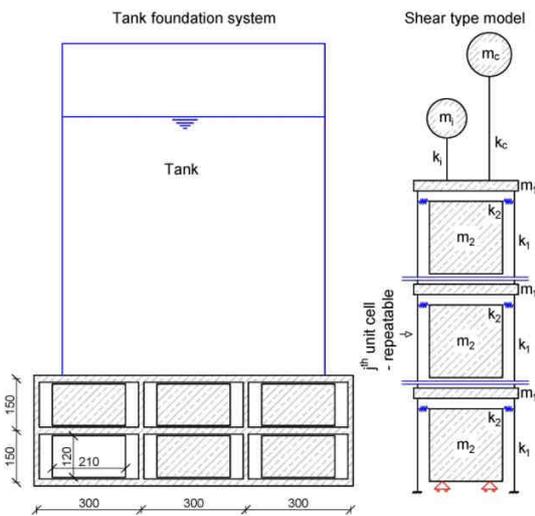


Figure 2. (left): Schematic of tank and Metafoundation; (right): Simplified shear type model (dimensions in cm).

For the design of the foundation unit cells are applied that consist of slabs that differentiate the layers, while columns provide the vertical stability. Inside the unit cell a resonator core will be attached to the columns via steel springs and is assumed to slide on a friction less surface. The unit cells are then assembled to a foundation with a tank placed on top as a superstructure, see Figure 2 (left). When assuming that the horizontal displacement is governed by the flexibility of the columns, while the slabs move as rigid bodies, the system can be simplified to a 1D model that propagates only shear type waves in the vertical direction (Figure 2 (right)). This model can now be described with analytical equations and will be analyzed in the following chapters. In particular, the system will be analyzed with and without a tank for its behavior in the frequency and time domain, while a dispersion analysis will demonstrate the band gap of the system. For these analyses it is necessary to formulate the equations of motion in a general form, so that the unit cell can be repeated in the vertical direction. This can be achieved by formulating the equations for the j^{th} unit cell as,

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

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

here, the mass of the columns is lumped to the slabs and is denoted with m_1 ; the mass of the resonators is described with m_2 ; two columns per unit cell provide the equivalent horizontal stiffness for one cell, which is denoted with k_1 ; the stiffness of the steel springs that provides the resonators with their resonance frequency is denoted with k_2 ; while the horizontal displacement is described with u . Since the j^{th} unit cell is connected to the previous $(j-1)^{\text{th}}$ and subsequent $(j+1)^{\text{th}}$ unit cell, it is necessary to include the displacements of these cells in the equations. This is taken into account by the superscript $(j-1, j, j+1)$ for u , while the subscript $(1, 2)$ determines the corresponding mass. In principal, these equations are sufficient for analyzing the uncoupled structure. However, since the coupled response of the system is also of interest, the tank will be modeled with 2DoFs according to the Malhotra procedure. As discussed in Subsection fuel storage tank modelling, these constitute the impulsive and the convective mode. The impulsive and convective modes will be attached as SDoF systems to the last layer of the foundation, while the remaining mass is simply lumped to the last slab of the foundation.

In order to find the metamaterial like properties of the unit cell under study, it is necessary to extend the system to an infinite stack of unit cells. According to the Floquet-Bloch theorem, the study of an infinite lattice of cells can be reduced to the study of a single cell with Floquet-Bloch quasi

periodicity conditions. In line with this, $\mathbf{u}(\mathbf{x}, t)$ can be expressed as,

$$\mathbf{u}(\mathbf{x}, t) = \mathbf{u}_{\mathbf{k}} e^{i(\mathbf{q} \cdot \mathbf{x} - \omega t)} \quad (6)$$

where the frequency is represented by ω , while $\mathbf{q} = [q_x, q_y, q_z]^T$ denotes the wave vector in (6). As a consequence,

$$\mathbf{u}(\mathbf{x} + \mathbf{R}) = \mathbf{u}(\mathbf{x}) e^{i\mathbf{q} \cdot \mathbf{R}} \quad (7)$$

with \mathbf{R} being the lattice vector. Furthermore, the eigenvalue problem for a dynamic system can be formulated as:

$$(\mathbf{K} - \omega^2 \mathbf{M})\mathbf{u} = 0 \quad (8)$$

here, mass and stiffness matrix are denoted by \mathbf{K} and \mathbf{M} . In order to achieve the dispersion relation, it is necessary to apply the boundary condition (7) to equations (4) and (5), and successively solve the eigenvalue problem as described in (8). When searching for non-trivial solutions for this problem, the dispersion relation can be found as,

$$m_1 m_2 \omega^4 - [(m_1 + m_2)k_2 + 2m_2 k_1 (1 - \cos(q))] \omega^2 + 2k_1 k_2 (1 - \cos(q)) = 0 \quad (9)$$

where the dimensionless wave number is denoted with q , while ω describes the circular frequency. Another research group has found a similar solution for an acoustic metamaterial when investigating the negative effective mass phenomenon [23].

RESULTS FOR THE UNCOUPLED FOUNDATION

When considering the foundation as a metamaterial, its main property is its capability to attenuate elastic waves. In particular, the transmission of an imposed signal will be measured in the frequency domain and the results will be compared to the dispersion relation of the unit cell.

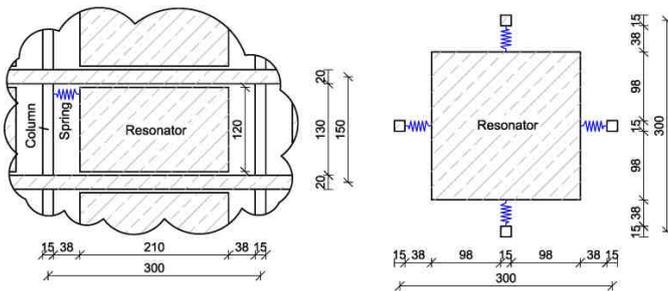


Figure 3. Geometry of the unit cell as part of the concrete matrix; (left) cross section of the foundation; (right) layout of one unit cell (dimensions in cm).

A cross section of 15x15 cm was used for the columns, which are being spaced apart 3 m in a cubic grid. The slabs on

the other hand were fixed to 20 cm thickness and 150 cm of vertical spacing, while the resonators consist of cuboids that are 210x210 cm wide and 120 cm high. For the exact geometry see Figure 3. This configuration resulted in values for m_1 , m_2 , and k_1 , of 4838 kg, 13230 kg, and 7.5e6 N/m, respectively. Note that these values are given by the geometric design of the foundation, thus leaving only k_2 , the stiffness of the steel springs, for tuning the system. For a slender fuel storage tank a band gap with a lower bound of approximately 1.1 Hz was chosen resulting in k_2 equal to 6.22e6 N/m and an upper bound for the band gap of 2.2 Hz.

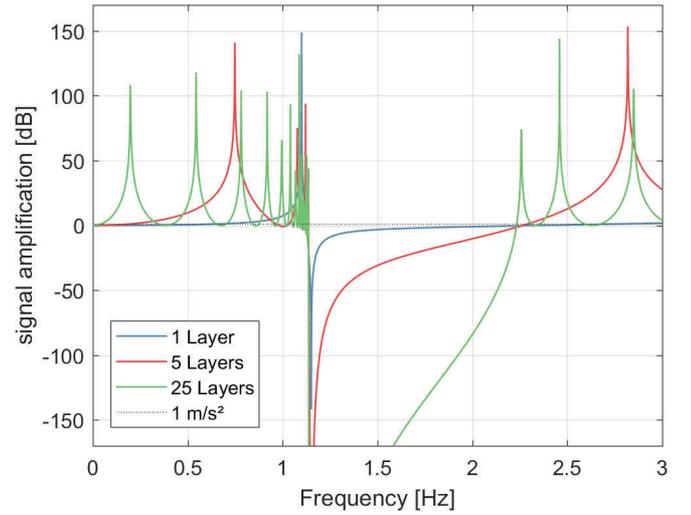


Figure 4. Frequency response function for a foundation with 1, 5, and 25 layers without any damping.

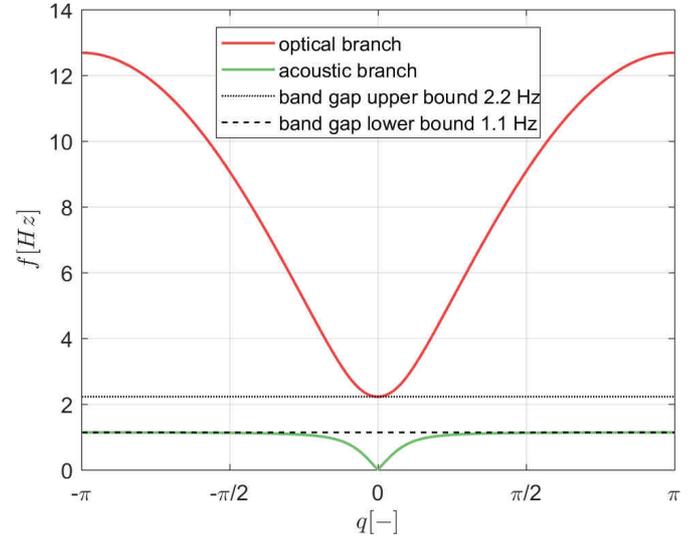


Figure 5. Dispersion relation of the unit cell.

After establishing the geometry and fixing the parameters of the system, the following analyses were carried out on the foundation and the unit cell: (i) A frequency response analysis

of a stack of unit cells with 1, 3, and 25 layers without any type of damping (Figure 4); (ii) The dispersion relation of the unit cell as part of an infinite lattice (Figure 5). Furthermore, the frequency response analysis was carried out by imposing a base excitation of $\ddot{u}_{in}=1\text{m/s}^2$ and measuring the output acceleration \ddot{u}_{out} . In particular, Figure 4 displays the signal amplification in dB, where the output acceleration is compared to the input acceleration with $(20*\log(\ddot{u}_{out}/\ddot{u}_{in}))$. When observing Figure 4, a clear attenuation zone becomes apparent between 1.1 Hz and 2.2 Hz. Here the signal amplification drops to the negative dB regime, resulting in a decreased output at the top of the foundation. The dispersion relation (Figure 5) yields a band gap between 1.1 Hz and 2.2 Hz, which is in line with the predicted attenuation zone of Figure 4. These results imply that, indeed, an attenuation zone is present in the foundation when regarded as an uncoupled system. However, in order to make a judgement on the viability of this concept, it is necessary to conduct analyses on the coupled system, as discussed in the following chapters.

ANALYTICAL RESULTS FOR THE METAFUNDATION-TANK SYSTEM

In order to evaluate the performance of the Metafoundation, two different types of analyses were carried out on the coupled system (tank clamped to the Metafoundation) as well as on the tank clamped to a concrete plate.

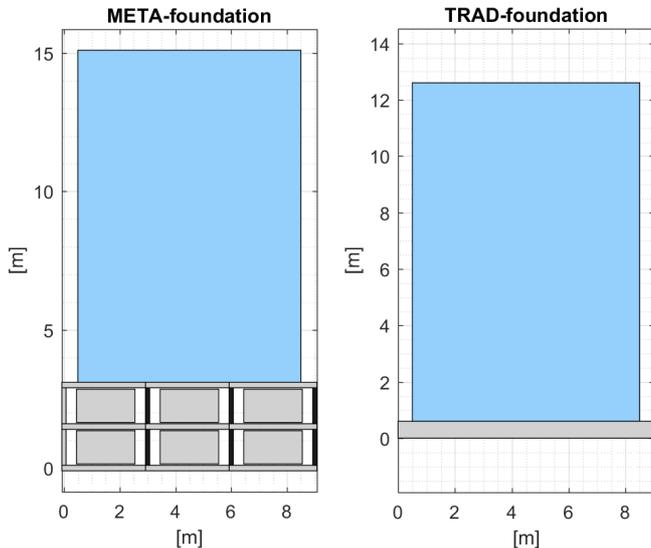


Figure 6. Geometrical characteristics: (left) slender tank including the Metafoundation META; (right) slender tank on a traditional foundation TRAD (dimensions in m).

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. Note that for all analysis from here on forth a Rayleigh damping model of 5 % between 1 Hz and 5 Hz

has been used. The system, designed for a slender tank with a diameter of 8 m and 12 m height, comprises 2 layers with 9 unit cells each. This system can have varying fluid levels, and therefore, was also studied for a decreased impulsive frequency. 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 tank, are represented in Table 3. Furthermore, the tank-foundation constellations are described by the acronyms STF, and STnF, which stand for: 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	m_2	k_1	k_2	m_i	m_c	k_i	k_c
[-]	[kg]	[kg]	[N/m]	[N/m]	[kg]	[kg]	[N/m]	[N/m]
STF	4.35	1.19	6.75	6.22	4.52	8.58	8.35	3.86
	E+4	E+5	E+7	E+6	E+5	E+4	E+8	E+5
STnF	4.35	1.19	6.75	6.22	3.16	8.69	1.26	3.92
	E+4	E+5	E+7	E+6	E+5	E+4	E+9	E+5

Figure 6 shows the configuration of the slender-tank-foundation system with the full liquid height (META) and the reference system of a tank with a solid concrete slab as a foundation (TRAD). Furthermore, Figure 7 and Figure 8 show the frequency response functions of the impulsive mode for the full and $\frac{3}{4}$ full tank, respectively.

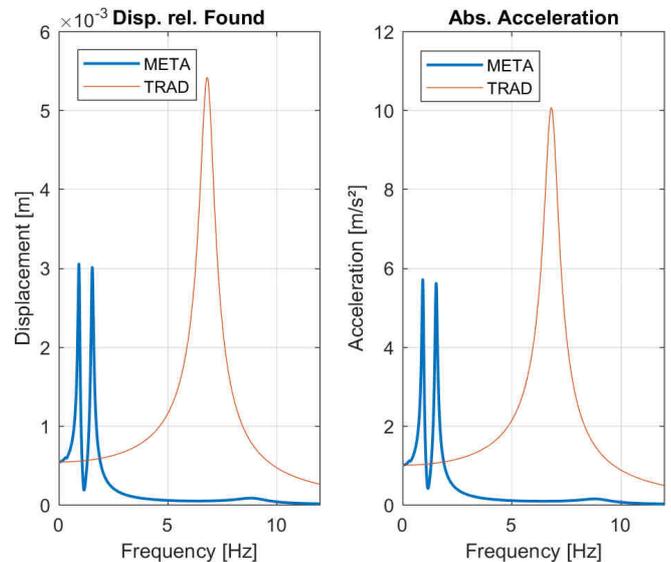


Figure 7. Frequency response function of the impulsive mode of a Slender tank with full liquid height; (left) displacement of impulsive mass compared to foundation; (right) Absolute acceleration of the impulsive mass.

The graphs depict the displacement response of the impulsive mode relative to its foundation and the absolute acceleration response of the impulsive mode. Clearly, the setup for the full tank shows the most effective attenuation in respect to the traditional foundation, while the tank with a reduced fluid level performs a little less efficient. However, it is worth noting

that in terms of magnitude of response the setup with a reduced fluid level still performs on a similar level as the version for the full tank does. Furthermore, the frequency of the resonator has been tuned to produce a lower bound of 1.1 Hz for the band gap, which also corresponds to the optimal tuning of the two spikes of the frequency response (see Figure 7 META curve). 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.

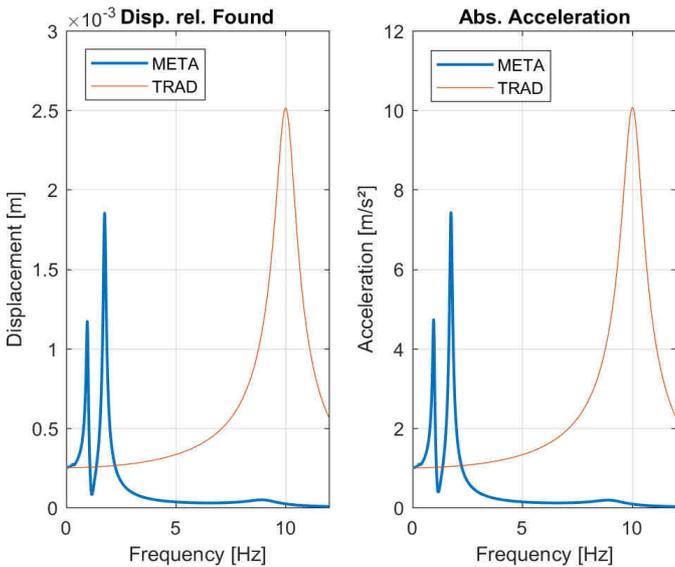


Figure 8. Frequency response of a slender tank foundation system for a reduced fluid level of $\frac{3}{4}$ fill; (left) displacement of impulsive mass compared to foundation; (right) Absolute acceleration of the impulsive mass.

For the assessment of the functionality of the structure it is not sufficient to consider only calculations in the frequency domain, therefore, additional analyses were carried out in the time domain for various earthquakes (Table 4).

Table 4. Set of EC 8 compatible ground motions for the site Priolo Gargallo (soil type B) with a return period of 2475 years.

Event (component)	Event ID	Magni.	Rjb [km]	PGA [m/s ²]
Erincan (X)	000535	6.6	13	3.81
South Iceland (X)	006263	6.5	7	6.23
South Iceland Aftersh. (Y)	006334	6.4	11	7.07
L'Aquila Mainshock (X)	IT0789	6.3	5	4.34
L'Aquila Mainshock (X)	IT0790	6.3	4	4.79
L'Aquila Mainshock (X)	IT0792	6.3	5	5.35

Note that the set of seismic records is compatible for a site in Priolo Gargallo in Sicily, Italy with soil type B and a return period of 2475 years (according to Eurocode 8 [24]). Figure 9

and Figure 10 present the response of the system for an earthquake that occurred in South Iceland on the 21st of June 2000 with a magnitude of 6.4 and a PGA of 7.07 m/s². In order to judge the results of the time history simulations, the base shear and overturning moment of the tank were considered as governing for the limit state. More precisely, Figure 9 depicts the absolute time evolution of the base shear and overturning moment for a full slender tank, while Figure 10 shows the results for a tank with $\frac{3}{4}$ liquid height. Clearly, the amplitudes of the base shear and the overturning moment are significantly smaller for the Metafoundation variant.

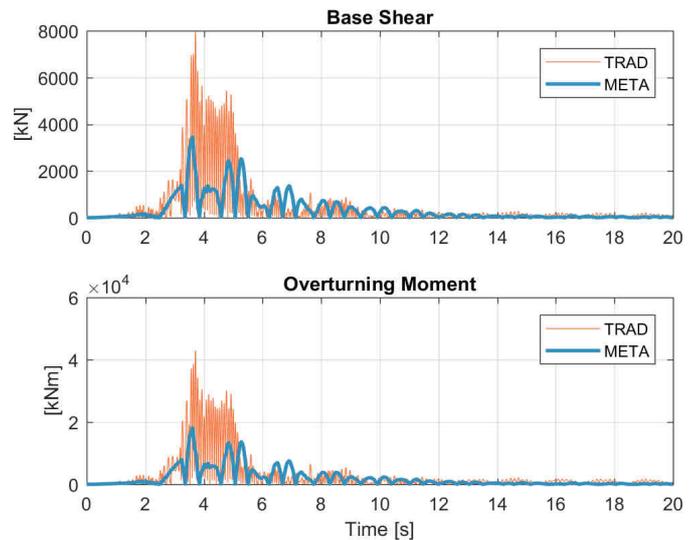


Figure 9. Absolute time evolution of the base shear and the overturning moment of a full slender tank.

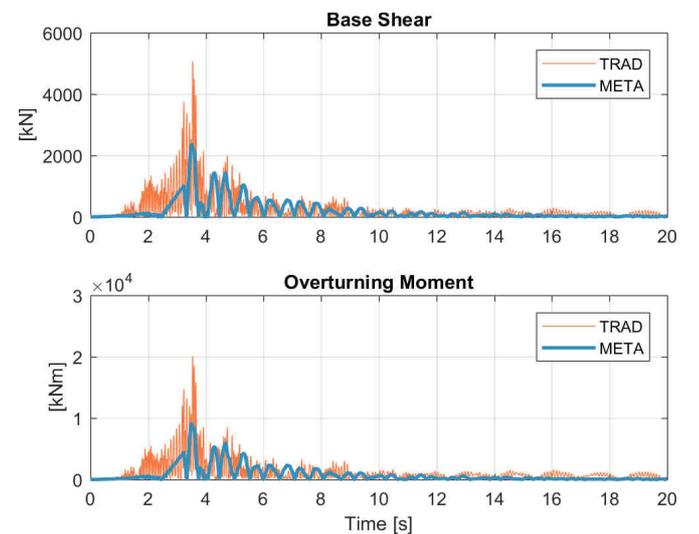


Figure 10. Absolute time evolution of the base shear and the overturning moment of a slender tank with 9 m liquid height.

For the sake of brevity, only the maximum values of the base shear and overturning moment are presented for the rest of

the ground motions ordered by PGA (Figure 11). Note that the time history analysis was carried out for particularly strong ground motions, in order to estimate the performance of the foundation in extreme scenarios. When comparing the maximum values of base shear and overturning moment of the two tank setups, it becomes apparent that the Metafoundation greatly attenuates the forces in the tank with respect to a traditional concrete base plate.

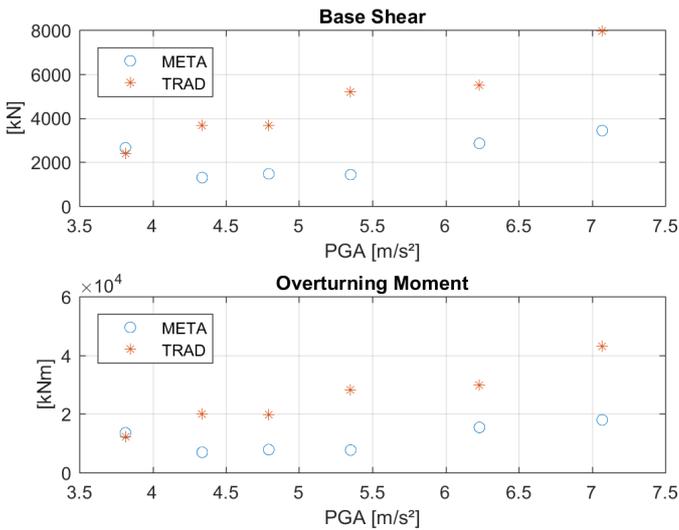


Figure 11. Maximum values of base shear and overturning moment in a full slender tank for all studied ground motions.

VALIDATION OF THE 1D MODEL THROUGH FE-MODELLING

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 Figures 2, 3, and 6 and contains the Metafoundation with resonators as lumped masses and a slender fuel storage tank. In particular, the columns were modelled with beam elements, while the slabs and tank shells were modelled as shell elements. The liquid inside the tank, on the other hand, was modeled as an acoustic medium with 3D elements, since this represents an accurate representation when sloshing motions are neglected [25,26]. All components were considered to be linear elastic and endowed with 5% Rayleigh damping between 1 and 5 Hz, which is equivalent to the damping used in the 1D model. Figure 12 shows the FE-model of the coupled system. Analogous to the procedure for the analytical model, the coupled tank-foundation system has been studied in the frequency domain and compared to the response of a tank modeled with a traditional foundation (Figure 13). When comparing Figure 13 to Figure 7, it becomes clear that the 1D model shows a very similar response with respect to the finite element model. Therefore, the 1D model is considered to be a good approximation for the evaluation of the Metafoundation and may serve as a basis for optimization procedures.

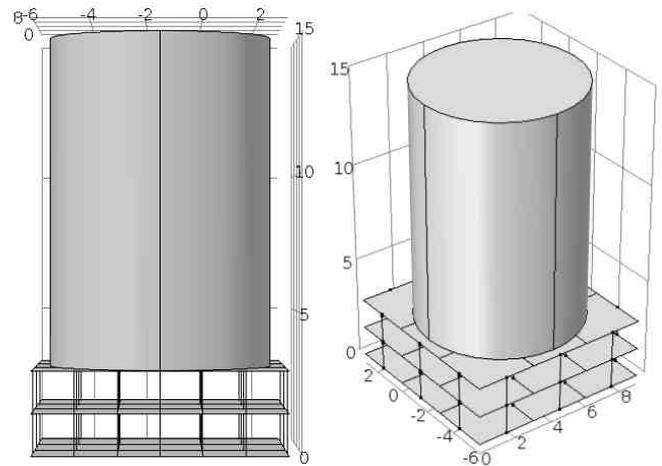


Figure 12. (left): Side view of FE-model; (right): Isometric view of FE-model.

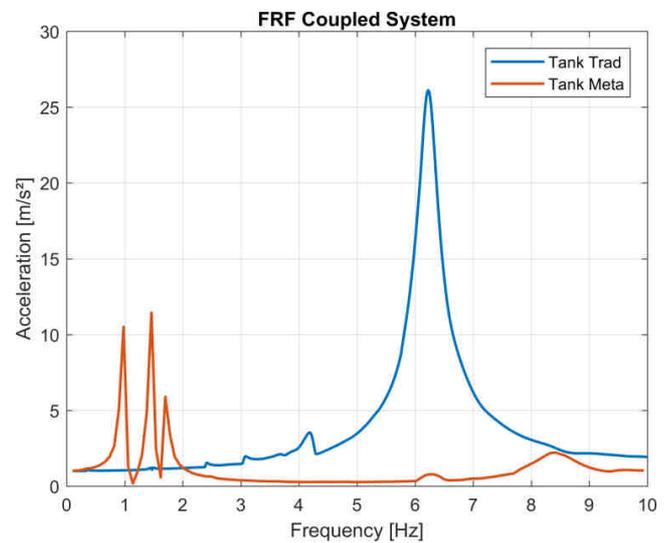


Figure 13. (left): FE-Model of the tank-foundation system; (right): Frequency response function of the coupled system.

SEISMIC PERFORMANCE OF COUPLED TANK-FOUNDATION-PIPELINE SYSTEM

Pipelines are critical components of petrochemical plants and can be subjected to extreme loading conditions during earthquakes. Their potential to cause LOC events, and thus, trigger cascading effects has to be treated with care. Furthermore, due to their slender nature, complicated geometry and complex boundary conditions, they are difficult to model in a realistic manner and often exert highly non-linear behavior. As a consequence it becomes reasonable to carry out experiments for the verification of their performance. In the present work, the interaction of a tank+foundation structure coupled with a realistic piping system is investigated. This type of coupling for laboratory experiments can be achieved with a hybrid simulation (HS), where the tank and the foundation are

modeled as NS, while a piping setup in a laboratory represents the PS. The setup for the studied experiment is based on the theoretical work of Abbiati et al. [27], where m substructures are coupled with localized Lagrange multipliers resulting in the following set of differential algebraic equations:

$$\begin{aligned} \mathbf{M}^{(l)}\ddot{\mathbf{u}}^{(l)} + \mathbf{C}^{(l)}\dot{\mathbf{u}}^{(l)} + \mathbf{K}^{(l)}\mathbf{u}^{(l)} \\ = \mathbf{L}^{(l)T}\boldsymbol{\Lambda}^{(l)} - \mathbf{M}^{(l)}\mathbf{T}^{(l)}\mathbf{a}_g(t) \\ \forall l \in \{1, \dots, m\} \end{aligned} \quad (10)$$

$$\mathbf{L}^{(l)}\dot{\mathbf{u}}^{(l)} + \bar{\mathbf{L}}^{(l)}\dot{\mathbf{u}}_g^{(l)} = 0 \quad (11)$$

$$\sum_{l=1}^m \bar{\mathbf{L}}^{(l)T}\boldsymbol{\Lambda}^{(l)} = 0 \quad (12)$$

Here, $\mathbf{M}^{(l)}$, $\mathbf{C}^{(l)}$, and $\mathbf{K}^{(l)}$ are the mass, damping and stiffness matrix of the l^{th} substructure, respectively, while $\ddot{\mathbf{u}}^{(l)}$, $\dot{\mathbf{u}}^{(l)}$, and $\mathbf{u}^{(l)}$ denote acceleration, velocity and displacement of the l^{th} substructure. Moreover, the interface DoFs are collocated by the signed Boolean matrices $\mathbf{L}^{(l)}$ and $\bar{\mathbf{L}}^{(l)}$ to the substructure DoFs $\dot{\mathbf{u}}^{(l)}$ and the generalized interface DoFs $\dot{\mathbf{u}}_g^{(l)}$. In order to enforce compatibility between multiple substructures, localized Lagrange multiplier vectors $\boldsymbol{\Lambda}^{(l)}$ are used in (10) and (12) [28]. For more details on this procedure refer to [27]. Note that this technique is able to couple several numerical and/or physical substructures. Furthermore, In order to make the results relatable to the current state of the art, the Metafoundation will be compared to a system protected with concave sliding bearings (CSBs). Note that this system is different to the tank clamped to a traditional foundation. This change of reference system is necessary, since a tank subjected to very strong ground motions is unlikely to sustain its integrity when clamped to a concrete slab, while at the same time exhibiting very small deformations to a possible connected piping system. Therefore, a more realistic comparison was aspired by using a tank isolated with CSBs.

PHYSICAL SUBSTRUCTURE

The PS consists of a piping system with its main line having a diameter of 8 in (outer diameter: 219.08 mm, thickness: 8.18 mm) and its secondary line showing a diameter of 6 in (outer diameter: 168.28 mm, thickness: 7.11 mm). Furthermore, the system comprises two elbow elements, one t-joint, and one bolted flange joint, and is based on the U.S.NRC report from 2008 [29]. Here, a large scale shaking table test was carried out on a piping system common for the nuclear industry. As discussed in the report, masses have to be added to the structure at specified positions, in order to take valves and other components into account.

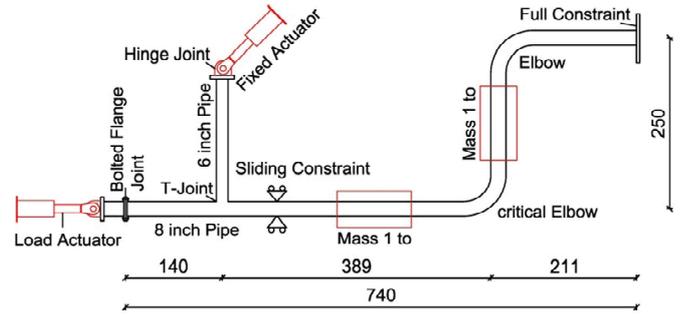


Figure 14. Schematic of the piping system (dimensions in cm).

The exact geometry of our system is depicted in Figure 14, while the actual specimen is represented in Figure 15. When observing these figures, it becomes clear that the real boundary conditions of the system are rather complex and that the dynamic response may be difficult to predict with an FE model.



Figure 15. Experimental setup of the piping system.

Additionally, the piping system was filled with pressurized water (32 bar), in order to represent a scenario as realistic as possible.

Of particular interest for the present study are the strains in the critical elbow element, since, as shown by Bursi et al. [30], elbow elements are highly vulnerable to seismic excitations and may lead to LOC events when damaged. Therefore, the strains in the critical elbow (Figure 14) are measured with strain gauges, and considered governing for the following experimental verification.

NUMERICAL SUBSTRUCTURE

The NS consists of the tank and Metafoundation equal to the configuration of the slender tank full (STF), where two layers of foundation were used.

Pipes of petrochemical plants are often connected to tanks close to the tank base plate. When assuming that the relative tank deformation between ground and piping connection is very small, the pipe can be assumed to be connected to the bottom of the tank. This simplifies the numerical model, since the interface node can now be placed on the last layer of the

foundation where tank, foundation and pipe coincide. Figure 16 shows a representation of the coupling of the NS with the PS.

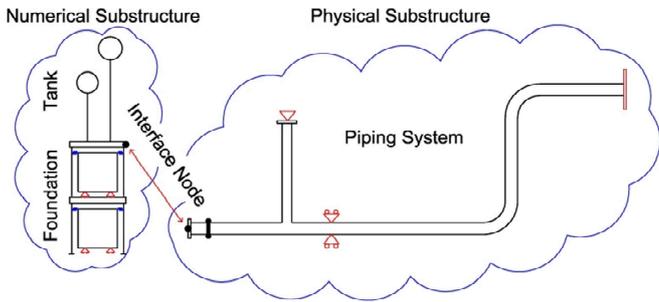


Figure 16. Coupling of the numerical and physical substructure.

Furthermore, in order to draw a comparison to conventional isolation systems, an additional NS has been investigated. In particular, four CSBs (concave sliding bearings) were considered as an isolation variant for the slender tank and modeled as an alternative NS. A common approach for modeling a CSB is to use the piece-wise linear Mostaghel model as it is represented in Figure 17. This model is well described in [31], with its governing parameters δ_{MST} , α_{MST} , and k_{MST} being equal to $5e-4$ m, $1.3e-3$, and $2.18e8$ N/m, respectively.

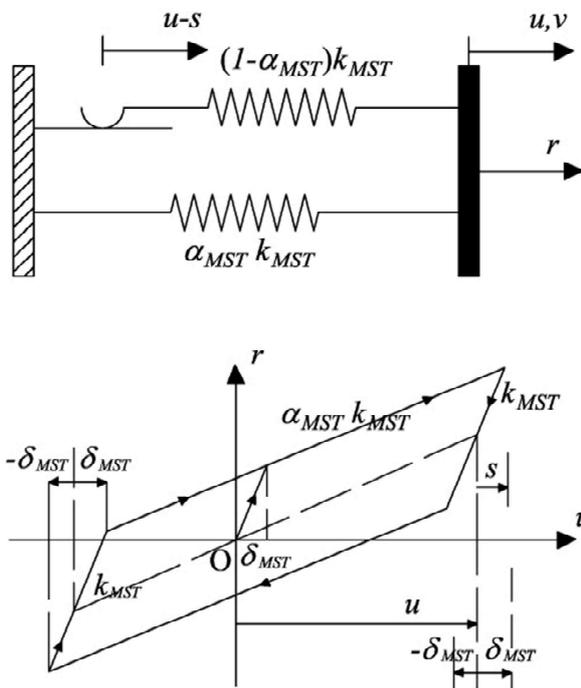


Figure 17. Generic Mostaghel model.

All four CSB devices work in parallel and therefore can be simulated by a single device with equivalent parameters. The resulting coupling of the PS and NS is represented in Figure 18.

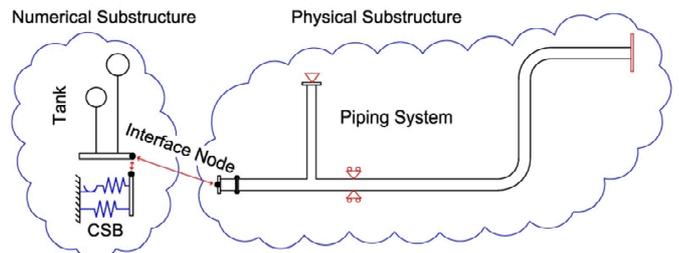


Figure 18. Numerical coupling of CSB, tank, and piping system.

RESULTS OF THE EXPERIMENTAL VERIFICATION

Table 5 lists the seismic records that have been used for the experiment. In particular, two sets of Eurocode 8 [24] compatible records have been used; (i) a set of three records compatible with a site situated in Priolo Gargallo with soil type B and a return period of 475 years; (ii) 2 records from the previous set as discussed in subsection analytical results for the coupled system (return period 2475 years).

Table 5. Seismic events for the experimental validation

T [yrs]	Event (component)	Event ID	Mag	Rjb [km]	PGA [m/s ²]
475	South Iceland (Y)	004673	6.5	15	4.68
	L'Aquila Mainshock (Y)	IT0791	6.3	9	3.24
	L'Aquila Mainshock (Y)	IT0792	6.3	5	6.44
2475	Erircan (X)	000535	6.6	13	3.81
	L'Aquila Mainshock (X)	IT0789	6.3	5	4.34

In Figure 19 the configuration of the strain gauges on the elbow is shown. Note that rose like strain gauges were applied on the inside and outside of the elbow, in order to capture the strain in radial and longitudinal direction of the pipe.

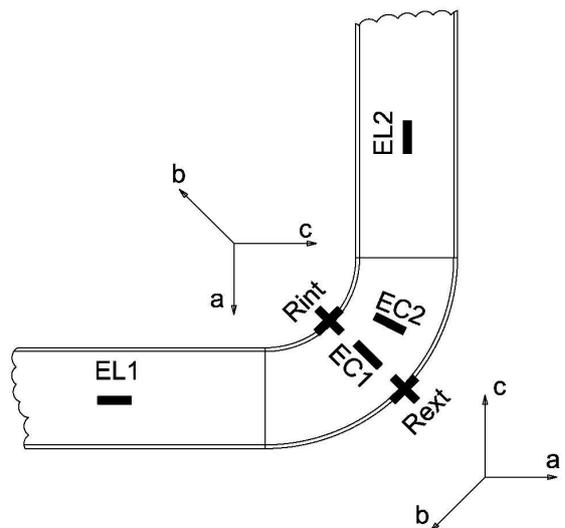


Figure 19. Configuration of strain gauges on the elbow element.

The nomenclature of the strains shall be explained on the example of the REC strain gauge, where R stands for Rose, E for external gauge, and C for the vertical strain or in this case hoop strain (as indicated by the a-b-c coordinate system in the bottom right corner of Figure 19). For the sake of clarity, only the results of the critical strain gauges for one of the seismic events, namely 000535, are depicted in Figure 20.

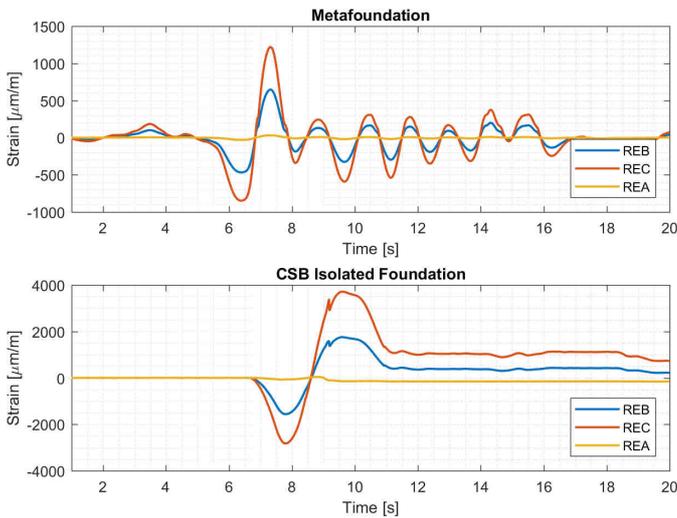


Figure 20. Strains in the critical elbow for the most sever seismic event

Clearly the piping system remains in the elastic range when connected to the Metafoundation, while the setup comprising the CSB array exhibits yielding in the REC strain gauge (hoop strain). However, when comparing this result with the maximum appearing hoop strains recorded for all seismic events shown in Table 6, it becomes apparent that a reduction of hoop strain cannot be assumed for any given earthquake. For a more reliable performance of the system, it may be necessary to take the piping system into account when tuning the foundation. This, on the other hand, is not within the scope of the present work.

Table 6. Maximum strains.

T [yrs]	Event ID	META REC [$\mu\text{m/m}$]	CSB REC [$\mu\text{m/m}$]
475	004673	801.75	864.75
	IT0791	518.75	1085.25
	IT0792	1139.75	977.50
2475	IT0789	721.50	377.50
	000535	1219.75	3713.50

CONCLUSION

The proposed Metafoundation represents a novel type of seismic shield and has been designed to protect fuel storage tanks from ground motions. Through analyses in the frequency and time domain, we have demonstrated the effectiveness of the foundation at attenuating seismic effects. More precisely, a

slender fuel storage tank may profit greatly from the proposed foundation in terms of attenuation of base shear and overturning moment in respect to a traditional concrete foundation. Additionally, the conducted laboratory tests shed light on the interaction of the Metafoundation with the complete coupled structure (tank+foundation+pipeline) and made it comparable to standard isolation devices. The measured elbow strains show no plastification for the system coupled with the Metafoundation, while the configuration including the CSB array exceeds the critical yield strain for one of the investigated ground motions. However, since some seismic events showed a higher demand in the elbow when coupled to the Metafoundation, a clear statement on whether the foundation reduces stresses cannot be concluded yet. In future studies we aim to expand the tuning of the foundation to the complete coupled system and, consecutively, reduce stresses in a connected piping system more reliably. Besides the attenuation of horizontal excitations, we also intend to investigate soil-structure interaction and vertical component damping. We intend to take advantage of the soil flexibility and the subsequent interaction with the resonators for the attenuation of vertical vibrations.

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REFERENCES

- [1] Cruz, A. M., Steinberg, L. J., 2006, "Emerging Issues for Natech Disaster Risk Management in Europe", *Journal of Risk Research*, 9(5), 483-501. DOI: 10.1080/13669870600717657
- [2] 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. DOI: 10.1007/s11069-007-9205-3
- [3] Cozzani, V., Antonioni, G., Landucci, G., Tugnoli, A., Bonvicini, S., Spadoni, G., 2014, "Quantitative assessment of domino and NaTech scenarios in complex industrial areas", *Journal of Loss Prevention in the Process Industries*, 28, 10-22. DOI: 10.1016/j.jlp.2013.07.009
- [4] Barka, A., (1999). "The 17 August 1999 Izmit Earthquake". *Science* 285(5435), 1858-1859. DOI: 10.1126/science.285.5435.1858
- [5] Nakashima, M., Lavan, O., Kurata, M., Luo, Y., (2014), "Earthquake Engineering Research Needs in Light of Lessons Learned from the 2011 Tohoku Earthquake", *Earthquake Engineering and Engineering Vibration*, 13, 141-149. DOI: 10.1007/s11803-014-0244-y
- [6] Kelley, J. M., Konstantinidis, 2011, *Mechanics of rubber bearings for seismic and vibration isolation*, John

Wiley & Sons, Ltd, ISBN: 9781119994015

- [7] Mokha, A., Constantinou, C., Reinhorn, A. M., Zayas, V. A., 1991, "Experimental Study of Friction-Pendulum Isolation System", *Journal of Structural Engineering*, 117(4), 1201-2117. DOI: 10.1061/(ASCE)0733-9445(1991)117:4(1201)
- [8] Jadhav, M. B., Jangid, R. S., 2004, "Response of base-isolated liquid storage tanks", *Shock and Vibration* 11, 33-45. DOI:10.12989/sem.2006.23.6.615
- [9] Solymar, L., Shamonina, E., 2009, *Waves in Metamaterials*, Oxford University Press, Oxford, UK, Chap. 2. ISBN: 978-0-19-921533-1
- [10] Sigalas, M., Kushwaha, M. S., Economou, E. N., Kafesaki, M., Psarobas, I. E., Steurer, W., 2009. "Classical vibration modes in phononic lattices: theory and experiment.", *Zeitschrift für Kristallographie – Crystalline Materials* 220(9-10). DOI:10.1524/zkri.2005.220.9-10.765
- [11] Cheng, Z., Shi, Z. F., 2017. "Composite periodic foundation and its application for seismic isolation". *Earthquake Engineering and Structural Dynamics*, 1–20. DOI: 10.1002/eqe.2999
- [12] Cheng, Z., and Zhifei, S., 2013. "Novel composite periodic structures with attenuation zones." *Engineering Structures* 56, 1271-1282. DOI: 10.1016/j.engstruct.2013.07.003
- [13] 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
- [14] 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
- [15] 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). DOI: 10.1063/1.4891837
- [16] Bursi, O. S., Abbiati, G., Reza, Md S., 2014, "A novel testing approach for piping systems of industrial plants", *Smart Structures and Systems* 14(6). DOI: <http://dx.doi.org/10.12989/sss.2014.14.6.000>
- [17] Bursi, O. S., Reza, Md S., Abbiati, G., Paolacci, F., 2015, "Performance-based earthquake evaluation of a full-scale petrochemical piping system", *Journal of Loss Prevention in the Process Industries* 33, 10-22. DOI: <http://dx.doi.org/10.1016/j.jlp.2014.11.004>
- [18] EN 1992-1-1. (2003). *Eurocode 2: Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings*. CEN: Bruxelles.
- [19] Malhotra, K. P., Wenk, T., and Wieland, M., 2000. "Simple procedure for seismic analysis of liquid-storage tanks.", *Struct. Eng. Int.* 10, 197–201. DOI:10.2749/101686600780481509
- [20] Belakroum, R., Kadja, M., Mai, T., and Maalouf, C., 2010., "An efficient passive technique for reducing sloshing in rectangular tanks partially filled with liquid.", *Mech. Res. Commun.* 37, 341–349. DOI:10.1016/j.mechrescom.2010.02.003
- [21] Maleki, A., Ziyaeifar, M., 2008, "Sloshing damping in cylindrical liquid storage tanks with baffles", *Journal of Sound and Vibration* 311, 372-385, DOI:10.1016/j.jsv.2007.09.031
- [22] Phani, A. S., Woodhouse, J., and Fleck, N. A., 2006, "Wave propagation in two-dimensional periodic lattices", *J. Acoust. Soc. Am.* 119, 1995–2005. DOI:10.1121/1.2179748
- [23] Huang, H. H., Sun, C. T., and Huang, G. L., 2009; "On the negative effective mass density in acoustic metamaterials.", *Int. J. Eng. Sci.* 47, 610–617. DOI:10.1016/j.ijengsci.2008.12.007
- [24] EN 1998-1-1. (2005). *Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings*. CEN: Bruxelles.
- [25] 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/j.ijengsci.2016.09.010
- [26] 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>
- [27] Abbiati, G., La Salandra, V., Bursi, O. S., Caracoglia, L., 2017, "A composite experimental dynamic substructuring method based on partitioned algorithms and localized Lagrange multipliers", *Mechanical Systems and Signal Processing* 100, 85-112. DOI: 10.1016/j.ymsp.2017.07.020
- [28] Park, K. C., Felippa, C. A., Gumaste, U. A., 2000," A localized version of the method of Lagrange multipliers and its applications", *Computational Mechanics* 24(5), 476-490. DOI: <https://doi.org/10.1007/s004660050007>
- [29] U.S.NRC, 2008, "Seismic Analysis of Large-Scale Piping Systems for the JNES-NUPEC Ultimate Strength Piping Test Program", Office of Nuclear Regulatory Research.

- [30] Bursi, O. S., Di Filippo, R., La Salandra, V., Pedot., M., Reza, S., 2017, “Probabilistic seismic analysis of an LNG subplant”, *Journal of Loss Prevention in the Process Industries*, in press.
DOI:10.1016/j.jlp.2017.10.009
- [31] Mostaghel, N., 1999, “Analytical Description of Pinching, Degrading Hysteretic Systems”, *Journal of Engineering Mechanics*, 125(2), 216-224.
DOI:10.1061/(ASCE)0733-9399