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Effect of MetaFoundation on the Seismic Responses of Liquid Storage Tanks

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Abstract: Cylindrical liquid storage tanks are vital lifeline structures, playing a critical role in industry and human life. Damages to these structures during previous earthquakes indicate their vulnerability against seismic events. A novel strategy to reduce the seismic demands in the structures is the use of metamaterials, being periodically placed in the foundation, called MetaFoundation (MF). The periodic configuration of metamaterials can create a stop band, leading to a decrease in wave propagation in the foundation. The aim of this paper is to study the effect of MF on the dynamic behaviour of liquid storage tanks. To that end, the governing equations of motion of the liquid storage tank equipped with MF are derived and solved in the time domain to obtain the time history of the responses under a set of ground motions. Then, the peak responses of tanks, mounted on MF, are compared with the corresponding responses in the fixed base condition. Besides, a parametric study is performed to assess the effect of the predominant frequency of earthquakes, the number of layers of metamaterials, the thickness of soft material, and the damping ratios of soft material on the performance of the MF. The obtained results indicate that the MF improves the dynamic behaviour of the squat tank, in which the mean ratio of responses using MF to the ones in the fixed base conditions equals 0.551 for impulsive displacement, overturning moment, and base shear.

Keywords: liquid storage tank; MetaFoundation; time domain analysis; earthquake; passive control; stop band

1. Introduction

Cylindrical liquid storage tanks made of steel or concrete materials are strategic structures, having been employed to store water for drinking or firefighting, oil and chemical products in urban areas, and industrial plants. Damages to these structures may have catastrophic consequences such as economic losses, fire due to flammable materials, environmental pollution, and disruption of human lives. The reported failure modes of these structures during past earthquakes indicate their inappropriate seismic performance [1,2] and the need for a safeguard against seismic events. The seismic behaviour of liquid storage tanks has been studied extensively (e.g., [3–6]). Generally, two approaches can be followed to improve the performance of liquid containers against seismic events. The first approach is the strengthening of tanks by increasing their wall thickness. However, increasing the thickness of the wall will increase the input seismic energy. The second approach, aiming to decrease and dissipate the input seismic energy, is exploiting the advantages of control devices, such as base isolation systems, dampers, or other innovative control devices [7].

For more than four decades, a wide variety of studies have been conducted to develop various base isolation devices and to study their effects on the improvement of the seismic performance of steel tanks [8–14]. However, several factors influence the seismic responses of structures [15,16], and in the case of base-isolated liquid storage tanks, they may have adverse effects leading to an increase in seismic demands compared to the fixed base
condition [17–19]. For example, Bagheri and Farajian [17] showed that the base isolation may experience an excessive displacement when the system is subjected to near-fault excitations with severe pulses, resulting in a dramatic increase in the displacement of the impulsive mass and, consequently, base shear and overturning moment. The same results were observed through experimental tests conducted on the seismic response of scaled structures isolated by highly efficient, low-cost PVC-Rollers Sandwich seismic isolation [20,21]. Besides, the traditional base isolation devices are less capable of improving the seismic performance of structures built on soft soil and cannot isolate structures from the vertical component of ground motions. Therefore, it would be beneficial to mitigate the seismic demands through other control systems without the shortages mentioned above.

In recent years, the progress in the area of solid-state physics showed that the structures being placed periodically display distinctive properties called frequency stop band, which can be explained as a wave is blocked to propagate through a continuum model if its frequency falls in the stop band frequency and can propagate to the model for the frequencies other than the frequencies of stop band [22–24]. This fascinating feature attracted considerable attention, stimulating researchers to construct materials with periodic structures to block the propagation of waves. Locally resonant metamaterials (LRMs) and phononic crystals (PCs) have been known as two types of periodic structures which are employed to avoid the propagation of waves [25]. Compared to PCs, LRMs have a more suitable performance to diminish vibrations with low frequency because the local resonances have the ability to create the stop band. LRMs, made from heavy materials (metamaterials) coated with a soft layer in a stiff matrix [26] (usually concrete), have been employed as foundations and barriers to decrease the propagation of seismic waves into structures and to protect them against the harmful consequences of earthquakes. The benefits of such a foundation would be magnified in the case of different structures, such as liquid storage tanks as well as modular structures, in which their performance under seismic actions is still a big question [27,28]. Jia and Shi [29] investigated the effect of physical as well as geometrical properties of periodic foundation on the stop band. They concluded that a lower band gap can be achieved by considering a higher mass density for the core. Bao et al. [24] compared the seismic behaviour of a seven-story building mounted on a periodic foundation with the traditional foundation and base isolation system. They observed that the periodic foundation has a better performance compared to base isolation systems in attenuating the seismic responses when the predominant frequency of the wave incident lies in the stop band. Mitchell et al. [30] proposed metaconcrete in which spherical metal cores coated with soft material are used instead of standard concrete. The coated metal core behaved as a resonator, activating when a dynamic blast load is applied with the frequency at or near the resonator frequency. Hence, the overall system exhibits negative effective mass, leading to the reduction of the amplitude of the applied blast wave. Dertimanis et al. [31] used mass-in-mass barriers being placed periodically to investigate the effect of locally resonant metamaterials. They connected internal mass to the outer mass by tendons and found that the input energy is filtered if the frequency falls in the stop band. Maleki and Khodakarami [32] conducted numerical analyses to evaluate the effect of MetaSoil on the amplification of in-plane waves due to topography irregularities. More recently, Basone et al. [33] employed the concept of LRMs to alleviate the demand in liquid tanks due to seismic actions. The foundation was made of steel columns, and the concrete-type resonators were connected to these columns. They conducted an optimization procedure to obtain the optimized damping and frequency corresponding to the resonators. The obtained results demonstrated that the proposed system could decrease the base shear in a slender tank up to 30%. Aguzzi et al. [34] investigated the propagation of flexural waves in a thin reticulated plate augmented with two classes of metastructures for wave mitigation. Despite all the research on metamaterials, no study has been conducted on the performance of MetaFoundation, composed of concrete matrix and steel core, in liquid storage tanks. Moreover, it is vital to investigate the effect of various parameters influencing the performance of MF on the seismic behaviour of the superstructure. Particularly, due to
the fact that the MF works in a range of frequencies, it is essential to investigate the effect of earthquake frequency on the seismic behaviour of MF.

This paper aims to investigate the efficiency of a foundation made by concrete and locally resonant materials coated with a soft layer called MetaFoundation (MF) on the dynamic behaviour of cylindrical tanks made from steel materials. To that end, the theory and background of the MF based on Bloch’s theorem are studied, and a simplified mass–spring model is suggested for the dynamic analysis of the coupled MF–tank system. Then, the governing equations of motion of the system are derived and solved in the time domain. For the numerical study, two types of tanks, namely squat and slender, are subjected to a set of ground motions with far-field characteristics to compare the seismic responses of the tanks mounted on MF with corresponding responses in the fixed base condition. Besides, a parametric study is performed to investigate the influence of different parameters on seismic responses of considered tanks with MF. These parameters are the predominant frequency of ground motions, the number of layers of metamaterials, the thickness of the soft material, and the damping of the soft material.

2. Simplified Model of MF

The 3D view of an MF is illustrated in Figure 1. Compared to the traditional foundation, which is made of concrete and longitudinal and transversal rebars, the MF contains heavy cores with cubic shapes that are coated with soft material in addition to the concrete and rebars. It is assumed that the MF is subjected to dynamic excitations in X and Y directions. Therefore, it can be divided into N unit cells in X, Y, and N-layers in Z directions.

![Figure 1. Three-dimensional view of the proposed MetaFoundation.](image)

Assuming that the model is continuous, isotropic, made by materials with perfectly plastic behaviour, small deformation and insignificant damping, the governing equation of an inhomogeneous solid is written as [35]:

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

(1)

where \( \rho \) is the mass density, \( \mathbf{u} = (u_x, u_y, u_z) \) is the displacement vector, \( t \) is the time parameter, \( \mathbf{r} = (x, y, z) \) the coordinate vector, \( \lambda \) and \( \mu \) are Lamé’s constants and \( \nabla \) is the Laplace operator. Decoupling the out-of-plane modes from those of in-plane ones, Equation (1) is rewritten as [35]:

$$
\rho(\mathbf{r}) \frac{\partial^2 u_j}{\partial t^2} = \frac{\partial}{\partial x_j} \left[ \lambda(\mathbf{r}) \frac{\partial u_l}{\partial x_l} \right] + \frac{\partial}{\partial x_l} \left[ \mu(\mathbf{r}) \left( \frac{\partial u_l}{\partial x_j} + \frac{\partial u_j}{\partial x_l} \right) \right]
$$

(2)
where \( u_j = u_j(x, y) \) is the in-plane displacement vector, \( j, l = 1, 2 \) and \( r = (x, y) \). Using the Floquet–Bloch theorem for the periodic configuration of unit cells in uniaxial direction, the solution of Equation (2) is given as:

\[
u(x, t) = e^{i(qx - \omega t)}u
\]  

(3)

where \( q \) is the wave vector in reciprocal space, \( \omega \) is the circular frequency. The wave amplitude is shown by \( u \), which is a periodic function and is expressed as:

\[
u(x) = u(x + A)
\]  

(4)

where \( A \) is the unit cell size (shown in Figure 1). The stop band can be calculated through the dispersion analysis of the periodic structure. Two different approaches can be employed to conduct the dispersion analysis and obtain the stop band. The first approach is the 3D finite element modelling of the MF, which requires potential workload and high computational effort due to the complexity in modelling. The second approach is the use of the simple model of MF, which is represented by a set of masses and springs. Since the unit cells of each layer operate in parallel under seismic excitation, they can be represented by an equivalent unit cell through dynamic condensation. Figure 2 shows the simplified mass–spring model of an MF with \( N \)-layers in the \( Z \) direction.

![Figure 2. Simplified mass–spring model of an MF.](image)

The total mass of the concrete in each layer is shown by the external mass \( (m_1) \), and the total mass of the metamaterials in each layer is shown by the internal mass \( (m_2) \). The stiffness corresponding to each layer of foundation and soft material is represented by springs whose stiffnesses are shown by \( k_1 \) and \( k_2 \), respectively. The stiffness corresponding to the soft material for each unit cell is obtained by:

\[
k_2 = \frac{E_{SM}A_{SM}}{t_{SM} - (|u_2 - u_1|)}
\]  

(5)

where \( E_{SM} \) and \( t_{SM} \) are the modulus of elasticity and thickness of the soft material, respectively. The area of the soft material perpendicular to the applied wave direction is represented by \( A_{SM} \); \( u_1 \) and \( u_2 \) are displacements of external and internal masses. Note that, in this study, the stiffness corresponding to the soft material will be updated during the analysis based on the relative displacement of the internal and external masses. Therefore, more accurate seismic responses will be obtained. The damping associated with the external and internal masses are shown by \( c_1 \) and \( c_2 \) and expressed by

\[
c_1 = 2\xi_{con}\sqrt{k_1(m_1 + m_2)}
\]  

(6)

\[
c_2 = 2\xi_{SM}\sqrt{k_2m_2}
\]  

(7)

where \( \xi_{con} \) and \( \xi_{SM} \) are the damping ratios of concrete and soft material, respectively. Due to the periodicity, it is possible to reduce the dispersion analysis of the infinite structure to the dispersion analysis of a single unit cell with the same boundary condition. The response of boundary conditions is calculated by substituting Equation (4) into Equation (3) as follows:

\[
u(x + A, t) = e^{iA}u(x, t)
\]  

(8)
The stop band is estimated by conducting the Eigen-frequency analysis of an undamped unit cell for a considered Bloch wave vector \( \mathbf{q} \). The governing equations of motion of \( j \)-th unit cell are written as:

\[
\begin{align*}
m_j^1 \ddot{u}_j^1 + k_1 (2u_j^1 - u_{j-1}^1 - u_{j+1}^1) + k_2 (u_j^1 - u_j^2) &= 0 \quad (9) \\
m_j^1 \ddot{u}_j^1 + k_2 (u_j^2 - u_j^1) &= 0 \quad (10)
\end{align*}
\]

Equations (9) and (10) are rewritten by substituting Equation (8) into Equation (9) and under the consideration of the trigonometric relationship of \( e^{i\mathbf{q}A} = \cos (\mathbf{q}A) + i \sin (\mathbf{q}A) \), as follows:

\[
\begin{align*}
m_j^1 \ddot{u}_j^1 + (2k_1 - 2k_1 \cos (\mathbf{q}A)) u_j^1 - k_2 u_j^1 &= 0 \quad (11) \\
m_j^2 \ddot{u}_j^2 - k_2 u_j^1 + k_2 u_j^1 &= 0 \quad (12)
\end{align*}
\]

Equations (11) and (12) are formulated by Equation (13) to obtain the dispersion relation of the considered MetaFoundation.

\[
[K(q) - \omega^2 M]u = 0 \quad (13)
\]

where \( K(q) \) and \( M \) are the stiffness and mass matrices of the unit cell, respectively. Equation (13) shows that the stiffness of the unit cell is dependent on the Bloch wave vector \( \mathbf{q} \). The nontrivial solution of the eigenvalue problem is

\[
m_1 m_2 \omega^4 - [(m_1 + m_2) k_2 + 2m_2 k_1 (1 - \cos (\mathbf{q}A))] \omega^2 + 2k_1 k_2 (1 - \cos (\mathbf{q}A)) = 0 \quad (14)
\]

Equation (14) has two responses corresponding to two dispersion curves, known as acoustic and optical. The lower response is related to the acoustic branch, and the higher response is associated with the optical branch. The stop band gap falls between these two dispersion curves.

3. Structural Model of the Liquid Storage Tank

The three-dimensional finite element modelling and analysis of a cylindrical liquid tank is a complicated process and requires computational effort mainly due to the interaction of tank and fluid. Besides, the MF, which is made of different materials, increases its modelling and analysing complexity. Therefore, the use of a simple and accurate model with the capability to determine the response of a liquid storage tank under seismic ground motions is of interest. As an alternative approach of finite element modelling, the simplified mass–spring model, which is accepted by standard codes such as API 650 [36], ASCE 7-16 [37], and Eurocode 8 [38] can be employed to model and analyse of tank containers. This simplified mass–spring model is generally based on the work conducted by Housner [39]. He evaluated the effect of hydrodynamic actions in liquid storage tanks, assuming that the tank wall has a rigid behaviour. According to Housner’s model, the hydrodynamic response of a fluid tank system is determined by the superposition of two components, namely convective and impulsive components. The convective component is generated by convective mass \( m_c \), and the impulsive component is produced by impulsive mass \( m_i \). The convective mass refers to the portion of the liquid in the upper part of the tank near the free surface, which experiences a long period of sloshing motion during dynamic loading. Conversely, the portion of the filling liquid near the base of the liquid storage tank accelerating in unison with the tank wall is represented by impulsive mass \( m_i \). Haroun and Housner [40] modified the simplified mass–spring model of Housner to consider the tank wall flexibility. Malhotra et al. [41] offered a simple and accurate procedure to assess the seismic responses of liquid storage tanks. They combined the first impulsive modal mass with the higher impulsive modal mass and the first convective modal mass with the higher convective modal mass. As a result of such a combination, the tank liquid system was represented by two modes only. Figure 3 demonstrates a cylindrical liquid tank mounted
on an $N$-layer MF. The geometrical properties of the tank are the height of the liquid ($H$), the thickness of the wall of the tank ($t_w$) and the radius of the tank ($R$).

Figure 3. A liquid storage tank mounted on an MF.

In this paper, the mass-spring model suggested by Malhotra et al. is used for the dynamic time history analysis of the liquid storage tank (Figure 4).

Figure 4. Simplified model of the liquid storage tank.

The impulsive and convective masses ($m_i$ and $m_c$) are connected to the wall of the tank by linear springs whose stiffnesses are $k_i$ and $k_c$, respectively. The stiffness of springs is influenced by the properties of the filling fluid, the tank material, and the geometric properties of the tank. The damping coefficients corresponding to the impulsive and convective masses are shown by $c_i$ and $c_c$, respectively.

The damping coefficient and stiffness corresponding to impulsive and convective masses are expressed as follows:

$$c_i = 2\zeta_i m_i \times \frac{2\pi}{T_i}$$  \hspace{1cm} (15)  

$$c_c = 2\zeta_c m_c \times \frac{2\pi}{T_c}$$  \hspace{1cm} (16)
\[ k_i = m_i \times \frac{4\pi^2}{T_i^2} \]  
\[ k_c = m_c \times \frac{4\pi^2}{T_c^2} \]

where \( \zeta_i \) and \( \zeta_c \) are the damping ratios of the impulsive and convective masses. \( T_i \) and \( T_c \) are natural periods corresponding to impulsive and convective responses, given by [41]:

\[ T_i = C_i \frac{H \sqrt{R}}{\sqrt{t_w / R} \times \sqrt{E_s}} \]  
\[ T_c = C_c \sqrt{R} \]

where \( E_s \) is the modulus of elasticity of the tank material and \( \rho_w \) is the mass density of filling fluid, respectively. The ratio of impulsive and convective masses to the total mass \( (m_i/m) \) and \( (m_c/m) \), relative heights of impulsive and convective masses \( (h_i/H) \) and \( (h_c/H) \), and the coefficients \( C_i \) and \( C_c \) are suggested by Malhotra et al. [41]. The filling fluid mass \( (m) \) equals to \( \pi R^2 H \rho_w \).

4. Governing Equations of Motion MF-Tank System

The simplified mass–spring model of an \( N \)-layer MF-tank system is depicted in Figure 5.

The whole system comprises \( 2N \) degrees of freedom representing the MetaFoundation and two degrees of freedom demonstrating the convective and impulsive masses, respectively.

The governing equations of motion of the MF tank system can be written in matrix form:

\[ M_T \ddot{u} + C_T \dot{u} + K_T u = -M_T \ddot{u}_g \]  

where \( M_T, K_T, \) and \( C_T \) are the mass, stiffness, and damping matrices of the coupled tank system mounted on the MetaFoundation, respectively expressed by

\[ M_T = \begin{bmatrix} M_{MF} & 0 \\ 0 & M_{Tank} \end{bmatrix} \]
Then, these equations are solved in each time step using the state-space representation for the vertical displacement of the surface of the fluid (\(\delta\)) of the liquid (\(\omega_x\)) break of the shell–roof connection. Because of lack of sufficient freeboard, the tank may experience a leak of fluid, tear of the shell or buckling or diamond shape buckling. Conversely, the vertical displacement of the free surface caused by the convective component controls the required freeboard. In the case of impulsive displacement, the vertical displacement of the free surface, the overturning moment at the top of the tank wall, which is proportional to the axial compressive force. The axial compressive force is the main reason of buckling of the tank walls, either in the form of elephant foot buckling or diamond shape buckling. Conversely, the vertical displacement of the free surface caused by the convective component controls the required freeboard. In the case of lack of sufficient freeboard, the tank may experience a leak of fluid, tear of the shell or buckling or diamond shape buckling.

The overturning moment determines the generated hydrodynamic forces in the tank wall, which is proportional to the axial compressive force. The overturning moment is calculated according to Equations (31)–(33), respectively [8]. The overturning moment determines the generated hydrodynamic forces in the tank wall, which is proportional to the axial compressive force.

The governing equations of motion for the tank are derived from the force balance and transferred to the first-order differential equations. These equations are solved in each time step using the state-space representation and ODE15s in MATLAB programming language. The response quantities of interest are the impulsive displacement (\(\delta_{imp}\)) and overturning moment on the tank (\(M_{tank}\)).

\[
C_T = \begin{bmatrix} C_{MF} + C_{Tank} & -C_{Tank} \\ -C_{Tank} & C_{Tank} \end{bmatrix}
\]

\[
K_T = \begin{bmatrix} K_{MF} + K_{Tank} & -K_{Tank} \\ -K_{Tank} & K_{Tank} \end{bmatrix}
\]

\[
M_{MF} = \text{diagonal} \left( m_1, m_2, \ldots, m_N \right)_{2N \times 2N}
\]

\[
M_{Tank} = \text{diagonal} \left( m_i \right)_{2 \times 2}
\]

\[
C_{MF} = \begin{bmatrix} 2 \omega_x^2 + c_2 & -c_2 & -c_1 & \cdots & 0 \\ -c_2 & c_2 & 0 & \cdots & 0 \\ -c_1 & 0 & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & c_1 + c_2 & -c_2 \\ 0 & 0 & \cdots & -c_2 & c_2 \end{bmatrix}
\]

\[
K_{MF} = \begin{bmatrix} 2 \omega_x^2 + k_2 & -k_2 & -k_1 & \cdots & 0 \\ -k_2 & k_2 & 0 & \cdots & 0 \\ -k_1 & 0 & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & k_1 + k_2 & -k_2 \\ 0 & 0 & \cdots & -k_2 & k_2 \end{bmatrix}
\]

\[
C_{Tank} = \text{diagonal} \left( c_i, c_i \right)_{2 \times 2}
\]

\[
K_{Tank} = \text{diagonal} \left( k_i, k_i \right)_{2 \times 2}
\]

\[
u = [u_1, u_2, \ldots, u_{12}, u_i, u_c]^{T}
\]

The superscript \(MF\) and \(Tank\) stand for MetaFoundation and tank system, respectively; \(u\) is the displacement of the system relative to the ground; \(x_2 = (u_2 - u_1)\), \(x_1 = (u_1 - u_i)\), \(x_c = (u_c - u_1)\) are displacement of internal, impulsive, and convective masses relative to the external mass, respectively. In Equation (21), the earthquake acceleration is shown by \(\ddot{u}_g\), and \(r\) is a column vector of one.

To obtain the time history of responses of the liquid storage tanks with MF, the governing equations of motion are derived and transferred to the first-order differential equations. Then, these equations are solved in each time step using the state-space representation and ODE15s in MATLAB programming language. The response quantities of interest are vertical displacement of the surface of the fluid (\(\delta\)), impulsive displacement (\(\chi_i\)), overturning moment (\(M\)) at the top of the MF, and structural base shear of the tank (\(F_s\)). While the impulsive displacement can be obtained directly through the solving of equations of motion, the vertical displacement of the free surface, the overturning moment at the top of the foundation, and structural base shear are calculated according to Equations (31)–(33), respectively [8]. The overturning moment determines the generated hydrodynamic forces in the tank wall, which is proportional to the axial compressive force. The overturning moment is calculated according to Equations (31)–(33), respectively [8]. The overturning moment determines the generated hydrodynamic forces in the tank wall, which is proportional to the axial compressive force. The overturning moment is calculated according to Equations (31)–(33), respectively [8].

The expression for \(\delta\), the displacement of internal, impulsive, and convective masses relative to the external mass, is as follows:

\[
\delta = \frac{R \omega_x^2 \chi_{c}}{8}
\]

\[
M = -\left\{ m_c \delta_c (\ddot{u}_c + \ddot{u}_g) + m_i \delta_i (\ddot{u}_i + \ddot{u}_g) \right\}
\]

\[
F_s = -\left\{ m_c \delta_c + m_i (\ddot{u}_i + \ddot{u}_g) \right\}
\]

where \(\omega_x\) is the frequency of the convective mass (\(\omega_x = \frac{2 \pi}{T_c}\)). For simplicity and better comparison of the results, the performance index of vertical displacement of the surface of the liquid (\(PI_{\delta}\)), the displacement of impulsive mass (\(PI_{\delta_i}\)), overturning moment on
the foundation (PI \( M \)), and structural base shear (PI \( F_s \)) are defined as the ratio of seismic responses of the liquid storage tank mounted on the MF (\( d_{v}^{MF}, x_{i}^{MF}, M^{MF} \) and \( F_s^{MF} \)) to the corresponding responses of the tank in fixed base condition (\( d_{v}^{F}, x_{i}^{F}, M^{F} \) and \( F_s^{F} \)), according to Equations (34)–(37). Therefore, a PI of less than one indicates that the MF is an efficient solution to improve the dynamic behaviour of liquid storage tanks. However, the performance index of more than one shows that the response is amplified due to the implementation of MF. Therefore, the MF has an adverse effect.

\[
\text{PI } d_v = \frac{d_{v}^{MF}}{d_{v}^{F}} \tag{34}
\]

\[
\text{PI } x_i = \frac{x_{i}^{MF}}{x_{i}^{F}} \tag{35}
\]

\[
\text{PI } M = \frac{M^{MF}}{M^{F}} \tag{36}
\]

\[
\text{PI } F_s = \frac{F_s^{MF}}{F_s^{F}} \tag{37}
\]

In addition to the time history of responses, it is interesting to evaluate the efficiency of the proposed MetaFoundation in the frequency domain through the transmission ratio (TR) of displacement above the MF against different frequencies (\( f \)). The transmission ratio is expressed as

\[
TR(f) = 20 \log_{10} \left( \frac{u_t(f)}{u_0(f)} \right) \tag{38}
\]

In Equation (38), the amplitude of the input displacement at the bottom of the MF is shown by \( u_0(f) \), and the amplitude of the displacement measured at the top of the MF is shown by \( u_t(f) \), respectively. In detail, in order to obtain the displacement transmission ratio, a harmonic displacement at various frequencies is imposed at the bottom of the foundation with amplitude \( u_0 \), and the displacement response \( u_t \) on the top of the foundation is observed.

5. Numerical Study

For practical applications, the periodic MetaFoundation must be constructed by available materials. In this paper, it is assumed that the foundation is made of concrete, and the heavy cores are made of steel coated by rubber. The material properties of different parts of unit cells, including modulus of elasticity and density, are listed in Table 1.

| Part Name | Material | Modulus of Elasticity, \( E \) (GPa) | Density, \( \rho \) (kg/m\(^3\)) |
|-----------|----------|------------------------------------|-----------------|
| matrix    | concrete | 24.85                              | 2400            |
| soft material | rubber   | 0.000137                           | 1300            |
| core      | steel    | 210                                | 7850            |

For the preliminary time history analysis, it is assumed that the MetaFoundation comprises unit cells with dimensions of \( 0.305 \times 0.305 \times 2.0 \) m corresponding to the length, width, and height, respectively. In addition, the cores of unit cells have a dimension of \( 0.10 \) m. The thickness of the rubber is assumed to be \( 0.05 \) m. The damping ratios corresponding to concrete and rubber are assumed to be 5% and 30%, respectively. A dispersion analysis has been conducted to calculate the dispersion relation and stop band corresponding to an infinite unit cell. The optical and acoustic branches obtained from the dispersion analysis are illustrated in Figure 6.
The results show that the stop band forms in the frequency range of 18.733 to 18.984 Hz, where the elastic waves cannot propagate through the MF according to the Floquet–Bloch theory. However, the obtained stop band is valid for an infinite number of unit cells. For the case of the foundation comprising finite unit cells, additional modal analysis is required to calculate the stop band.

Two different types of cylindrical tanks have been considered as case studies from [8]. The considered tanks have different aspect ratios (height to radius). The ratio of height to the radius of the assumed tanks \((S = H/R)\) is 0.6 and 1.85, corresponding to squat and slender tanks, respectively. The filling fluid is assumed to be water, with a mass density of \(\rho_w = 1000 \text{ kg/m}^3\). Table 2 shows the geometrical properties of considered tanks. A foundation that has a square shape is considered for both squat and slender tanks. The dimension of the MF for the squat tank is assumed to be \(50.0 \times 50.0 \text{ m}\), corresponding to its width and length, respectively; for the slender tank, a MetaFoundation with \(15.0 \text{ m}\) length and width is considered. As mentioned above, the height of each layer of MF is assumed to be \(2.0 \text{ m}\).

### Table 2. Geometrical properties of the selected tanks used as case studies.

| Tank Type | \(H\) (m) | \(R\) (m) | \(t_w\) (m) |
|-----------|-----------|-----------|------------|
| Squat     | 14.6      | 24.4      | 0.0203     |
| Slender   | 11.3      | 6.1       | 0.0058     |

The natural period, relative masses, and relative heights of the simplified mass–spring model depend on the geometrical properties of the cylindrical tanks. The parameters of the equivalent mechanical model of the tank have been calculated and tabulated in Table 3. The damping ratios of the convective \((\zeta_c)\) and impulsive masses \((\zeta_i)\) are assumed to be 0.5% and 2%, respectively, as suggested by [8].

### Table 3. Resultant parameters of the equivalent mechanical model for the selected squat and slender tanks.

| Tank Type | \(m_c/m\) | \(m_i/m\) | \(h_i/H\) | \(h_c/H\) | \(C_e\) (s/m\(^{0.5}\)) | \(C_i\) | \(T_c\) (s) | \(T_i\) (s) |
|-----------|-----------|-----------|-----------|-----------|-----------------|--------|-----------|-----------|
| Squat     | 0.608     | 0.392     | 0.557     | 0.400     | 1.65            | 7.08   | 8.15      | 0.253     |
| Slender   | 0.245     | 0.755     | 0.727     | 0.444     | 1.48            | 6.07   | 3.66      | 0.157     |

An adequate number of earthquakes should be considered for the required time history analysis to assess the efficacy of the proposed MF on the seismic responses of liquid storage tanks. Federal Emergency Management Agency (FEMA) [42] suggested three sets of ground motions for quantifying seismic performance factors of buildings. The three sets
include far-field (FF), near-fault without pulse (NF-WO Pulse), and near-fault with pulse (NF-W Pulse) ground motions. In this paper, the FF set, which comprises twenty-two pairs of records with an average moment magnitude of \( M_w = 7.0 \), has been used. Each record has two horizontal components; therefore, the system is subjected to forty-four ground motions. All of the considered earthquakes with a distance from the fault rupture of more than 10 km were recorded on site classes C or D based on the NEHRP classification, and they do not reveal any pulse in their velocity time history. Besides, the selected excitations cover different intensities in terms of their PGA. The ground motions were downloaded from the strong ground motion database of the PEER NGA-West2 (pacific earthquake engineering research) centre. The properties of the considered earthquakes, including the station name, \( M_w \), PGA, and PGV, have been listed in detail in Table 4. Figure 7 a,b depicts the pseudo-acceleration and spectral displacement of the selected earthquake ground motions for 2% and 0.5% damping ratios corresponding to the impulsive and convective masses, along with median as well as 2.5% and 97.5% percentile.

Table 4. Selected earthquakes for time history analysis.

| Record Pair | Earthquake              | Year  | Station                  | \( M_w \) | Component 1  | Component 2  | PGA (g) | PGV (cm/s) |
|-------------|-------------------------|-------|--------------------------|-----------|--------------|--------------|---------|------------|
| 1           | Northridge              | 1994  | Beverly Hills-Mulhol     | 6.7       | MUL009       | MUL279       | 0.52    | 63         |
| 2           | Northridge              | 1994  | Canyon Country-WLC       | 6.7       | LOS000       | LOS270       | 0.48    | 45         |
| 3           | Duzce, Turkey           | 1999  | Bolu                     | 7.1       | BOL000       | BOL090       | 0.82    | 62         |
| 4           | Hector Mine             | 1999  | Hector                   | 7.1       | HEC000       | HEC090       | 0.34    | 42         |
| 5           | Imperial Valley         | 1979  | Delta                    | 6.5       | H-DLT262     | H-DLT352     | 0.35    | 33         |
| 6           | Imperial Valley         | 1979  | El Centro Array #11      | 6.5       | H-E11140     | H-E11230     | 0.38    | 42         |
| 7           | Kobe, Japan             | 1995  | Nishi-Akashi             | 6.9       | INIS000      | INIS090      | 0.51    | 37         |
| 8           | Kobe, Japan             | 1995  | Shin-Osaka               | 6.9       | SHI000       | SHI090       | 0.24    | 38         |
| 9           | Kocaeli, Turkey         | 1999  | Duzce                    | 7.5       | DZC180       | DZC270       | 0.36    | 59         |
| 10          | Kocaeli, Turkey         | 1999  | Acrelik                  | 7.5       | ARC000       | ARC090       | 0.22    | 40         |
| 11          | Landers                 | 1992  | Yermo Fire Station       | 7.3       | YER270       | YER360       | 0.24    | 52         |
| 12          | Landers                 | 1992  | Coolwater                | 7.3       | CLW-LN       | CLW-TR       | 0.42    | 42         |
| 13          | Loma Prieta             | 1989  | Capitola                 | 6.9       | CAP000       | CAP090       | 0.53    | 35         |
| 14          | Loma Prieta             | 1989  | Gilroy Array #3          | 6.9       | G03000       | G03090       | 0.56    | 45         |
| 15          | Manjil, Iran            | 1990  | Abbar                    | 7.4       | ABBAR-L      | ABBAR-T      | 0.51    | 65         |
| 16          | Superstition Hills      | 1987  | El Centro Imp. Co.       | 6.5       | B-ICC000     | B-ICCC090    | 0.36    | 46         |
| 17          | Superstition Hills      | 1987  | Poe Road (temp)          | 6.5       | B-POE270     | B-POE360     | 0.45    | 36         |
| 18          | Cape Mendocino          | 1992  | Rio Dell Overpass        | 7.0       | RIO270       | RIO360       | 0.55    | 44         |
| 19          | Chi-Chi, Taiwan         | 1999  | CHY101                   | 7.6       | CHY101-E     | CHY101-N     | 0.44    | 115        |
| 20          | Chi-Chi, Taiwan         | 1999  | TCU045                   | 7.6       | TCU045-E     | TCU045-N     | 0.51    | 39         |
| 21          | San Fernando            | 1971  | LA-Hollywood stor        | 6.6       | PEL090       | PEL180       | 0.21    | 19         |
| 22          | Friuli, Italy           | 1976  | Tolmezzo                 | 6.5       | A-TMZ000     | A-TMZ270     | 0.35    | 31         |
6. Verification

In order to verify the obtained governing equations of motion, the vertical displacement of free surface ($d_v$) and impulsive mass displacement ($x_i$) of both squat and slender tanks mounted on an MF with a small dimension of the core are compared with corresponding responses in fixed base conditions. To that end, it is assumed that the core has a dimension of 0.001, 0.001, and 0.001 m corresponding to width, length, and height, respectively, and the thickness of the soft layer is 0.001 m. These small dimensions have been assigned to the core and the soft layer to avoid difficulties during solving of the governing equations of motion. It is expected that this MetaFoundation behaves as a traditional foundation made by concrete, and the resonators have no significant influence on the seismic responses of tanks.

Figure 8 compares the time history of the vertical displacement of the free surface as well as the impulsive displacement of both squat and slender tanks subjected to the Friuli, A-TMZ270 earthquake. The obtained responses verify the governing equations of motion and the accuracy of responses of liquid storage tanks with MF. The maximum difference between the responses is found to be less than 1%.

7. Results and Discussions

7.1. Effect of MetaFoundation

To evaluate the influence of the proposed MetaFoundation in the time domain, the time transient analysis is performed under selected ground motions. The seismic responses of liquid storage tanks mounted on MF are compared with the corresponding responses in fixed base condition. The parameters of the MF are described in the previous section.
Figure 9 shows the time history of seismic responses of considered tanks under ABBAR—L, Manjil earthquake.

![Figure 9](image_url)  
*Figure 9. Time history of responses of squat and slender tank subjected to ABBAR—L, Manjil ground motion for w/o and w MF.*

The seismic responses are depicted for both squat and slender tanks in fixed base condition and mounted on MF, respectively. The performance index of seismic responses of the selected liquid storage tank tanks subjected to various ground motions is depicted in Figure 10. According to the obtained responses, two different trends were observed for the performance of the MF on the seismic responses of squat and slender tanks.

First, in the squat tanks, it is observed that the displacement of the impulsive mass, overturning moment on top of the foundation, and base shear have been reduced in most cases due to the implementation of the MF. The mean performance index of the displacement of impulsive mass, overturning moment on the foundation, and base shear are 0.551, 0.551, and 0.551, illustrating that the MF reduces the input excitation. Therefore, the use of the MF in the squat tank is an effective solution to improve its dynamic behaviour. The best performance of the MF was observed when the system was subjected to G03000, Loma Prieta ground motion in which the PI of the displacement of impulsive mass, overturning moment on the MF, and base shear equalled 0.091, 0.09, and 0.091, respectively. However, a performance index of more than one is seen in some cases. For example, a PI equal to 1.491, 1.480, and 1.476 for the displacement of impulsive mass, the overturning moment on the foundation and base shear was observed when the system was excited by HEC090, showing that the MF increases the responses compared to fixed base condition. This is attributed to the fact that the performance of MF highly depends on the frequency content of input earthquake ground motion as well as the stop band. According to Figure 11, it is seen that in some frequency ranges, the TR is magnified. This illustrates that the amplitude of the input wave will be intensified, and therefore, the responses of liquid storage tanks are increased compared to the fixed base condition. The reduction of the
overturning moment leads to a decrease in the axial demand in the tank wall, which is the main reason for the buckling of the tank wall. Hence, the more economical and reliable design of the tank is achievable by the use of MF.

![Performance index (PI) of various seismic responses of squat and slender tanks.](image1)

**Figure 10.** Performance index (PI) of various seismic responses of squat and slender tanks.

![TR of the displacement above the MF.](image2)

**Figure 11.** TR of the displacement above the MF.
Conversely, it is seen that the MF increases the vertical displacement of the free surface of the liquid. The mean performance index of the vertical free surface displacement is 1.5. Therefore, it is vital to consider a more freeboard to avoid the disrupting consequences corresponding to vertical displacement of the free surface.

Second, with reference to Figure 10, one can conclude that the displacement of impulsive mass, overturning moment on the foundation, and base shear in the slender tank are magnified in most cases. The mean PI of the impulsive displacement, overturning moment, and base shear in the slender tank are 1.315, 1.315, and 1.35, respectively. Therefore, it can be concluded that the MF has an adverse effect on the seismic responses of the slender liquid storage tank. The best performance of the MF is observed under the ABBAR—L, Manjil earthquake in which the PI corresponding to the displacement of impulsive mass, overturning moment on top of foundation, and base shear are 0.742, 0.742, and 0.740, respectively. In terms of the vertical displacement of the free surface, it is seen that the MF has no significant effect. As is seen in Figure 10, the PI of the vertical displacement of the free surface approximately equals one for all of the earthquake ground motions.

To demonstrate the filtering effect of the MF, the TR above the MF in the absence of the liquid storage tank is demonstrated in Figure 11.

A TF equal to zero implies that the displacement output on the top of the foundation equals the input displacement induced at the bottom of the foundation. After that, the TR corresponding to the regions of less than zero indicates that the amplitude of the output displacement is less than the amplitude of the input displacement. This is due to the fact that the incident wave is blocked and cannot pass through the MF. Conversely, when the amplitude of the input displacement increases, the value of TR becomes more than zero; hence, the MF has an adverse effect. With reference to Figure 11, an amplification area is seen for the frequency region below 18.733 Hz, followed by an attenuation region from 18.733 to 18.984 Hz where the wave cannot propagate throughout the MF. The second attenuation zone is seen for frequencies over 22.4 Hz. Based on the obtained responses, the MF reduces the amplitude of waves with frequencies falling in the stop band. Since an earthquake is a random phenomenon with a wide range of frequencies, and its frequency content cannot be predetermined, the effectiveness of MF is limited to those ranges of frequencies which it is designed for.

7.2. Effect of the Frequency Content of the Excitation

To evaluate the influence of the characteristics of the input excitation, the PI of the seismic responses of both squat and slender tanks are depicted in Figure 12 against the predominant frequency of the considered earthquake. The predominant frequency is determined through the signal processing of considered earthquake ground motions and by selecting the maximum spectral acceleration occurring in their acceleration response spectra.

Besides, a linear regression line is plotted to observe the overall trend of the responses over the frequencies of the considered earthquake ground motions. Generally, it is seen that the PI of the displacement of the impulsive mass, overturning moment, and base shear of the squat tank is less than one for all of the ground motions with the predominant frequency higher than the frequency corresponding to impulsive mass. Conversely, both a PI of less and more than one were observed for the aforementioned responses when the system was subjected to ground motions with the predominant frequency lower than the frequency of the impulsive mass. In the case of the slender tank, the PI of more than one was observed for the impulsive displacement, overturning moment, and base shear when the system was subjected to excitations with the predominant frequency lower than the impulsive frequency. Besides, for those earthquakes with a predominant frequency higher than the impulsive mass frequency, a PI of less and more than one can be observed.
7.3. Effect of Number of Layers

In this section, the effect of the number of layers of MetaFoundation on the seismic responses of squat and slender liquid storage tanks is investigated. The height of each layer is kept constant at 2.0 m, and the properties of unit cells are the same as those mentioned in the previous sections. For the required analysis, five types of MF with one, two, three, four, and five layers are considered. For a better comparison of the obtained results, the numerical results provided in terms of performance index under various considered ground motions are shown in Figure 13.

In the case of the squat tank, one can see that the performance index of the displacement of impulsive mass, overturning moment on the foundation, and structural base shear decreases as the number of layers. Therefore, the more layers there are, the more reduction in the responses. Conversely, for the slender tank, it is seen that as the number of layers of MetaFoundation increases, the displacement of the impulsive mass, overturning moment on the MF, and base shear significantly increase. According to the TR shown in Figure 14, the boundary of the stop band becomes steeper when the number of layers of MF increases, leading to more attenuation of the input energy in this region. Conversely, for other regions other than the stop band, the TR increases, causing the intensify of the input energy. Therefore, the seismic responses of the squat tank are decreased, and those of the slender tank are magnified.
In terms of the vertical displacement of the free surface, it is observed that the mean PI of vertical displacement of the free surface remains constant for the different number of layers in the squat tank. However, a slight increase is observed in the slender tank.
7.4. Effect of Rubber Thickness ($t_r$)

The effect of rubber thickness on the seismic responses of liquid storage tanks is investigated here. Five different rubber thicknesses, $t_r = 0.01, 0.02, 0.03, 0.04, 0.05$ m were considered for the models. The dimension of the unit cell and the heavy core is the same with other sections. The obtained responses of squat and slender tanks subjected to various ground motions are illustrated in Figure 15.

From the obtained response, one can observe that the free vertical surface displacement ($d_v$) is not sensitive to rubber thickness ($t_r$), and these responses are almost constant for various values of rubber thickness. Conversely, other seismic responses are changed with the change in rubber thickness. The obtained results show that as the thickness of rubber increases, the displacement of the impulsive mass ($x_i$), overturning moment on the MF, and base shear ($M$ and $F_s$) decreases in the squat tank, leading to the improvement in the performance of the liquid storage tank. Conversely, a slight increase is observed in the impulsive mass displacement, overturning moment, and base shear of the slender tank. However, a fluctuation trend is seen for some earthquakes in both squat and slender tanks. This is attributed to the frequency content of earthquake ground motion, which affects the performance of MF.

**Figure 15.** Effect of thickness of rubber ($t_r$) on various seismic responses of squat and slender liquid storage tanks.
7.5. Effect of Damping of Soft Material

In this section, the effect of damping of soft material on the seismic response of considered liquid storage tanks is investigated. In order to study the effect of damping, five different damping ratios of $\zeta_{SM}$ are considered as 0.05, 0.1, 0.15, 0.2, 0.25 and 0.3, respectively. The dimension of unit cell, heavy core, and thickness of soft material are assumed to be the same with the previous sections. Figure 16 illustrates the effect of damping ratios on the maximum responses of both liquid storage tanks.

![Figure 16. Effect of soft material damping ratio on the seismic response of squat and slender liquid storage tanks.](image)

The results obtained from time history analysis indicate that the damping ratios of soft material affects the maximum responses of structures. The more damping ratios there are, the more the impulsive mass displacement ($x_i$) becomes reduced. As a result of such reduction, the overturning moment ($M$) recorded on the MF and the structural base shear ($F_s$) are decreased. However, it is seen that the damping ratio of soft material has no significant effect on the vertical displacement of free surface ($d_v$).

8. Conclusions

This paper evaluates the effectiveness of a novel foundation called MetaFoundation (MF) on the seismic response of liquid storage tanks. The MF comprises concrete and cubic shape steel coated with rubber as a soft layer. The concept of the MF is based on the finite
locally resonant metamaterials, which produce a stop band to avoid the propagation of waves. The obtained results indicate that the MF has the capability to reduce the seismic response of squat liquid storage tanks, such as displacement of the impulsive mass, overturning moment, and base shear. Conversely, the obtained performance indexes indicate that the use of MF will lead to an increase in the seismic responses of the slender tank.

The effects predominant frequency of earthquakes, the number of layers of metamaterial, rubber thickness, and damping ratios of soft material were studied. The results confirm that as the number of metamaterials increases, more reductions can be observed in the TR of the stop band; therefore, the displacement of the impulsive mass, overturning moment on the top of the foundation, and base shear of squat tank decreases. However, the displacement of free vertical surface displacement was not significantly affected. Besides, the obtained responses show that the rubber thickness has an insignificant effect on the vertical displacement of the free surface of the squat tank, while other responses such as impulsive mass displacement, overturning moment, and structural base shear reduce when the rubber thickness increases. Furthermore, it was observed that the use of MF amplified the seismic responses of the slender tank. The results indicated that as the number of layers of metamaterial increases, the results become more reduced.

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