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INCREASING THE SAFETY LEVEL CONSIDERING SOIL-STRUCTURE INTERACTION IN HIGH SEISMIC HAZARD-PRONE AREAS

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Abstract

The work describes assessments and public policies that would account for safety increase and duration in the exploitation of structures. The level at which the soil-structure interaction is approached in actual normative/codes is highlighted. Proposals for approaching different ways to rise the protection level of structures to be in seismic zones were examined, starting from their location and design; this implies the knowledge of the site seismicity, earthquakes-related parameters prediction, the importance of (extended) geotechnical studies, etc. The interaction wave-structure is studied by using the model of harmonic oscillator coupled to an elastic medium. This analysis is meant to be relevant for the effects of seismic motion upon localized structure. Also, the model of an elastic structural element embedded at one end is envisaged and the normal modes and the eigenfrequencies of this independent module are highlighted. The response to oscillating shocks is computed for various ground excitations applied to its base. The response of two coupled modules, viewed as simplified structures thereby harmonic oscillators as well, to an oscillating shock is calculated, and amplification factors are highlighted.

Key words: *soil-structure interaction, wave-oscillator coupling, localized structures, risk evaluation, public policies.*

INTRODUCTION

The buildings behaviour is influenced by the site characteristics and the way it acts under strong seismic shaking. For certain geophysical characteristics, such as deep sedimentary basins, soft layered soils, amplification, inhomogeneities, or non-linearities presence, the level of hazard is increased. Therefore, the assessment of the seismic risk level is a challenging task. For Bucharest city, the old buildings and various types of design add to this state of things. The employed analyses, proposed actions to be taken, provisions and public policies are meant to lead to safety increasing and exploitation duration for the objective of interest. Thus, the soil-structure interaction (SSI) was considered in the project for the normative act "Seismic design code - part I - Design provisions for buildings Indicator P 100-1/2025" (P100-1/2025) developed by the Technical University of Construction Bucharest in 2024 (currently being in the consultation stages); therein this issue was approached explicitly for the first time in a Romanian design code. The present work can also be taken as a guide for the general contractor to be aware of what elements to look for when making the choice for the location of a future building or an urban or industrial complex. In this sense, compliance with the legislation/norms in force must be taken with the obligation/recommendation to add a thorough assessment of the following elements:

1) Local hazard, seismicity maps (peak values for recorded parameters, estimated intensities, etc.), microzoning (if any);
2) Possible prediction of future earthquakes (characteristics, ground shake level, amplifications) at the chosen location;
3) Geotechnical engineering studies, standard (required by the laws/codes/norms in force) or more complex according to the future requirements of the objectives to be built on the chosen area;
4) History of landslides and the risk of future ones on the chosen site, and measures to prevent them (if applicable);
5) Checking the area where the future site was chosen for the potential of liquefaction and if this phenomenon exists, what measures should be taken to reduce/exclude the risk of liquefaction in the event of a strong earthquake;

6) Measures to improve the bearing capacity of the soil if the respective site does not meet the conditions required in the project;
7) In the case of future objectives enrolled in Class I (Buildings with essential functions for which the preservation of integrity during earthquakes is vital for civil protection), detailed knowledge of the geological stratification of the soil deposit from the bedrock to the surface, especially for areas known to be soft soils is of uttermost importance. This should be done because of the potential of the soil layers to amplify the local seismic input at the site, which in some cases can lead to significant structural damage.

The site-structures interaction systems performance is assessed and thereby applied as a contribution to the safety level improvement for the structures located in the seismic areas or characterised by a high hazard level. Some features of both seismological and earthquake engineering interest are discussed that account for the vulnerability mitigation of the constructed medium since its design stage. The research studies that are carried out in the work refer to needs that involve the development of advanced methods for foreseeing interaction effects, the development of practical computational methods for estimating and incorporating these effects into the building design.

MATERIALS AND METHODS

Reference to soil - structure interaction in current codes/norms

The following section outlines how soil-structure interaction is addressed in Romanian legislation and selected international standards.

In the national normative "Seismic design code – part I – design provisions for buildings, indicative P 100-1/2013" there is no explicit treatment of the soil-foundation-structure interaction phenomenon (P100-1/2013).

In the draft "Seismic Design Code – Part I – Design Provisions for Buildings, Indicative P 100-1/2025" developed by the Technical University of Construction Bucharest in 2024, (P100-1/2025) (currently in the consultation stages at various professional levels) the notion of soil-structure interaction appears in several paragraphs as an additional calculation method in certain design situations.

Some examples of how this type of interaction was addressed in several international design codes are given below.

In Eurocode 8 (EUR 25204 EN – 2012), Seismic Design of Buildings soil-structure interaction appears in Chapter 4, "Introduction to the RC building example. Modelling and analysis of the design example"; 4.9. "Soil Structure Interaction". This subchapter presents qualitative/introductory elements about the phenomenon. Throughout Chapter 4, reference is also made to the soil-structure interaction phenomenon, and it is recommended that it be considered in certain practical situations.

National Institute of Standards and Technology (NIST, USA) has published guidelines on soil-structure interaction for building structures (Gcr, N. 2012; Stewart et al., 2012).

Techniques for simulating SSI phenomena in engineering practice are described. The recommendations are specifically addressed to the modelling of the effect of seismic soil-structure interaction on buildings. Realistic building examples are used to illustrate and test these recommendations.

One of the codes in Japan that specifically addresses soil-structure interaction is ISO 23469 (ISO 23469/2005). It provides guidelines for seismic actions in the design, including various types of structures that interact with the soil. This standard recognizes the importance of considering the effects of soil-structure interaction in seismic engineering. It complements ISO 3010, which focuses on seismic actions for superstructures of buildings and bridges. Designers use ISO 23469 to evaluate seismic loads on geotechnical works, considering factors such as soil displacement and the dynamic behaviour of buried structures.

Tasks to be accomplished for safety level increase

The features that need to be assessed within the oversight process of the soil-structure interaction are described; they may support the increase of the protection level of the buildings located in seismically dangerous areas.

1. Seismicity of the area. Studying the seismicity of the future site by complying with the legislation/norms in force is essential, and if the objective is of particular importance, additional local/regional seismic hazard studies will be carried out (Welsh-Huggins & Liel, 2018; Joyner & Sasani, 2020).

2. Prediction of the earthquake's parameters. Predicting strong ground motion for future earthquakes is currently accomplished primarily by applying attenuation laws or parametric scaling relationship (Manea et al., 2022; Manea et al., 2025; Ardeleanu et al., 2005). These relationships related parameters describing the seismic source, such as the magnitude, to the location of a site relative to that source, to ground motion datasets (for example maximum (damped) spectral acceleration and the corresponding oscillation period). The current lack of recorded data, for some sites, at shorter or longer distances from the epicentres of strong earthquakes means that there is not enough hazard data to represent the presumed hazard of the most dangerous events. Dedicated computing programs and computational simulation, using various methods, offer a way to fill this data gap, for which structural engineers need histories of future ground motion.

3. Importance of Geotechnical Engineering Studies. The properties of the soil at a construction site substantially affect the performance of the construction and its associated facilities during earthquakes. However, these materials (soils) are usually the most variable in properties, the least investigated, and the least controlled of all materials in the built environment.

Knowledge of soil behaviour is key for a high-level structural design. Constructions and associated facilities (of all kinds) built in seismic regions on saturated sands, reclaimed land, and deep deposits of soft clays are vulnerable to damage from strong earthquakes. (Basu et al., 2014). Soils of the aforementioned types are common in marine environments and alluvial deposits, where large cities are often founded. For example, Mexico City is located on deep alluvial land (Beresnev et al., 1998). The Los Angeles Basin, consisting of unconsolidated sediments (Rukos, 1988) and Kobe city also are among these areas. The latter, comprises few not too deep different layers, was experienced liquefaction phenomenon occurred during strong Hyogoken-Nanbu earthquake (Ishihara et al., 1996). Damage to structures is worsened by soil liquefaction which causes the loss of foundation support and contributes to dramatic settlement of large buildings. Bucharest is crossed by 2 rivers (Dâmbovița with a length of 22 km and Colentina) and has several lakes on its territory, being located on an alluvial plain, formed by thick layers of sediments (sands, loess, etc.), with a preponderance of soft soils. Deep deposits of soft clays are particularly prone to amplifying the amplitude of seismic movement and decreasing the frequency content in the event of a strong earthquake, a situation that often leads to major damage to a structure, especially if resonance occurs between the soil and the structure.

4. Ground motion amplification. In addition to their tendency to cause structural damage, poor soil conditions are often associated with damage due to their tendency to amplify ground motions and/or to resonance with above infrastructure during strong earthquakes.

A spectacular example of ground motion amplification occurred during the 1985 Mexico City earthquake (M_W = 8.0, depth =20 km). The earthquake epicentre was over 400 km from the city, and the shaking amplitude at bedrock level in Mexico City was almost negligible (Anderson et al., 1986; Stone et al., 1987). However, since much of the city is built on soft soils that extend to considerable depths, these generated a seismic response that led to ground motion amplifications at frequencies close to those built structures. The structures display a strong resonance and were subjected to movements well above their design loads. Significant damage occurred, followed by the collapse of buildings, producing over 8,000 victims, and leaving over 50,000 people homeless. The significant increase in the potential for damage due to soft soil requires a better understanding of how local soil conditions modify seismic action and how these conditions can be identified, designed, and/or modified.

5. Considerations upon buildings. The 1994 Northridge (M_W = 6.7, depth = 18.2 km) (Mahin et al., 1998; Arboleda-Monsalve, 2020), 1995 Kobe (M_W = 6.9, depth = 21.9 km)

(Scawthorn et al., 1995; Aguirre & Irikura, 1997), and numerous other major earthquakes around the world illustrate that, despite advances in seismic design over the past decades, we need to develop a better understanding of the behaviour of built systems to ensure that new buildings are designed and old buildings are retrofitted to reduce their vulnerability to excessive damage and large economic losses during earthquakes.

5.1. ***Predicting the seismic capacity and performance of existing and new buildings***. Certain types of buildings are particularly vulnerable to major earthquakes: unreinforced masonry buildings, concrete frame buildings, precast concrete buildings etc. and many structures built before 1977 (the case of Romania) (Balan et al., 1982). Depending on their age, storage tanks, buried and above ground pipelines, and bridges may also be vulnerable.

Therefore, it is imperative to develop tools to identify buildings in this category, the facilities and supply lines (electricity, water etc.) that are vulnerable to cost-effective rehabilitation. Historic buildings present a particular challenge for seismic rehabilitation due to the limitations imposed on physical modification of the structure and the difficulty of structurally testing equivalent systems and components.

5.2. ***Assessment of non-structural building systems***. Most direct economic losses in buildings result from damage to non-structural systems, as opposed to structural systems (Balan et al., 1982). Even in earthquakes with minimal structural damage, non-structural damage can be substantial. The behaviour of non-structural components, such as architectural cladding, interior walls, and utility distribution systems, and their interactions with buildings, during earthquakes are complex phenomena. To adequately and better understand these interactions, they should be modelled (with accurate representation of both the structure and the non-structural components), at natural or smaller scale. Actions taken to protect non-structural elements from degradation during an earthquake must also consider a detailed cost-benefit analysis.

6. Performance of soil-foundation-structure interaction systems. Soil-foundation-structure interaction can have a significant effect on the seismic performance of building structures during strong earthquakes. Testing should be performed on representative structures and foundation systems to adequately represent the interaction on both the building and the foundation.

Currently, data on the response of soil-foundation-structure systems are quite scarce, and research needs include the development of advanced methods for predicting the effects of interaction, performing large-scale shake table tests and, where required, centrifuge testing of interaction mechanisms, developing practical computational methods for estimating the effects of interaction, and incorporating these effects into building design.

This issue will be particularly addressed in the next section.

7. Determining the performance of innovative materials and structures. Innovative materials and structures will include new intelligent uses and configurations of conventional materials and new “smart” developments of materials and structures. The use of smart materials and structures is an emerging concept in mechanical, aeronautical, and civil engineering.

Smart structures (“self-adaptive” or “intelligent”) have the ability to respond to internal and/or external stimuli by varying their shape or mechanical properties. Smart materials can be used in sensors or actuators.

Examples of “smart” sensing materials include: optical fibre, piezoelectric ceramics, magnetorheological, electrorheological fluids and microelectromechanical systems (MEMS). The integration of these materials with sensing-actuating capabilities into conventional materials or structural systems will lead to smart structural systems. Research into “smart” materials has been conducted for many years, but few companies are putting these results into practice.

Cost-benefit analyses are needed to fully illustrate the relative benefits of these new technologies and materials and to systematically evaluate their innovative performance.

8. Risk assessment. The challenge in risk assessment is to provide decision-makers with accurate and understandable information about risk exposure and alternative risk mitigation with the tools that will enable them to make prudent decisions based on this information.

More specifically, it is necessary to do the following:

• Develop risk assessment methods that are comprehensive, based on sound scientific and engineering principles, and usable by a variety of stakeholders.

• Development of the base of decision-making tools that leads to its reduction.

• Formulating a framework for risk mitigation and mitigation policies that can be implemented by the public and private sector.

Although strong earthquakes are rare events, their consequences can be devastating. Decision-makers are often complacent about earthquake hazard because a major earthquake may not have occurred in their lifetime or where they live.

Risk assessment requires knowledge of the following types of issues:

• The probability of earthquakes occurrence, their magnitude and location, the characteristics of the terrain in the area, the probability that they will cause tsunamis.

• Physical damage, with its direct consequences in terms of death, injury, loss of operational functionality and destruction of property.

• The social and economic consequences of direct physical damage, including losses due to damage to buildings, supply lines and other critical elements.

9. Public Policy. A major challenge for communities exposed to major earthquakes is the need to have risk reduction placed on the public, municipal, and legislative agendas.

Although research findings will advance over time, changes will only be achieved through policy development and implementation. Adopting policy measures, supported by cutting-edge technology, will significantly increase the capacity to prevent major disasters and thus reduce the devastating economic impact and social consequences.

One of the major difficulties in reducing the economic and social consequences of earthquakes is that disaster mitigation policies and preparedness are generally inadequate to meet the challenge of disasters for a community. The many directions that need to be addressed on the path to disaster policy formulation and implementation include: the appropriateness of relevant policy; educating decision-makers; educating stakeholders to gain support for the introduction of legislation; identifying appropriate alternatives that are consistent with the risk, exposure, and capacity of a community to implement these policies; and developing strategies for implementing legislation.

Proposals for public policies that can help promote an increasing safety policy are presented below:

• Setting the agenda. After any disaster, there is a reset of the agenda for those directly involved. It is necessary to be prepared and to take advantage of these moments. A community must understand its risks to determine how to mitigate them and how it can respond to emergencies. The technical basis comes from integrating all geological, structural, and sociological data and simulations that would provide a rational reason and an understandable basis for public and private policy decisions on preparing/mitigating shocks to large earthquakes:

• Policy justification. In formulating public policies, it is often necessary to undertake a cost-benefit analysis of the proposed policy or regulation;

• Defining alternatives. Policy decisions on earthquake mitigation must be based on sound and up-to-date technical knowledge;

• Educating the public. Most often, public policies are developed in response to public demand. The public can make and influence political decisions, but only if people are sufficiently well informed about the underlying problems and the solutions and their implications.

10. Landslide study. Evaluating geotechnical hazards is a crucial responsibility in the field of geotechnical engineering. This involves assessing the potential impacts of natural events, such as earthquakes and landslides, on construction projects. Hence the history of landslides and the risk of future ones on the chosen site, and measures to prevent them (if applicable) is useful to be known.

11. Liquefaction. Is important to check the area where the future site was chosen for the potential for liquefaction and if this phenomenon exists, what measures should be taken to reduce/exclude the risk of liquefaction in the event of a strong earthquake. The prevention of liquefaction phenomena requires a combination of geotechnical measures and appropriate planning when building structures in areas susceptible to soil liquefaction. Finally, structures built in areas prone to liquefaction must be designed to withstand the forces and settling induced by this phenomenon. Special design techniques, such as deep piles, reinforced foundations or retaining walls, may be required to ensure the stability of structures (Youd at al., 2001; Ishihara et al., 1996).

12. Soil improvement measures. Measures to improve the bearing capacity of the soil if the respective site does not meet the conditions required in the project must be taken. Besides conducting geotechnical assessments, additional measures can be considered, such as soil drainage and reinforcement through the incorporation of granular materials or chemical binders to enhance its properties. Alternatively, soil compaction can be employed to increase its density

13. Utility supply lines. Best practices from utilities that have used mitigation measures to address the earthquake threat are needed to be known. To protect the utility will need to assess the potential damage to buildings and key assets. Utilities include water, wastewater, fuel, electricity, gas, and telecommunications systems. The basic components of utilities include supply and storage equipment, transmission lines, and the connections between these components. Underground utility pipelines and connections are often too weak or inflexible to withstand earthquake ground movements and differential settlements, causing them to crack or fail. Materials that are too flexible, however, also cannot handle additional displacements from earthquake forces. From ground shaking, pipes often crack at brittle joints or are crushed at the bell or pipe barrel. From liquefaction or lateral spreading, pipes often break or separate at the joints (Deelstra & Bristow, 2022).

Performance of soil- foundation-structure interaction systems

The effects of seismic waves on structures on the Earth's surface are studied by considering features of major interest in the assessment of seismic risk. The input generated by the phenomena that affect the structures can be appreciated in terms of physical and mathematical problems related to shocks, oscillations, and vibrations (Apostol, 2025a). In these circumstances the advanced study of the response of elastic elements to external mechanical excitations is pursued. Overall, the characteristics of the interest site (site to be chosen for the construction) directly influence the structures and construction materials behaviour, innovative assembles and utility supply lines included. Therefore, the necessity was inferred for taking into consideration the complex phenomenon of site-foundation-structure interaction and particularly the structural behaviour to seismic input or vibrations.

The protection of the buildings erected at the Earth's surface is a continuous preoccupation in earthquake engineering for countering the destructive action of the earthquakes. The buildings are represented by vibrating units (or simply bars), which, under the seismic action may resonate; also, sub-surface inhomogeneities may behave as resonating embedded elements (Apostol, 2025a). In both cases we get local amplification factors, for displacement, velocity, and acceleration, which are evaluated in resonance conditions and may attain large values. The amplification factors are given by a combination of the shock duration, the height of the bar above the ground surface and the velocity of the elastic waves in the beam; they arise because of the excitation of the normal modes in the structure (Apostol, 2025a).

A distinct instance is devoted to the interaction of a harmonic oscillator model with an elastic wave, the associated amplification factors, and particularly the coupling of structure-site, viewed as localized harmonic oscillator coupled with the elastic medium.

The problem of selecting the type of seismic excitation is examined considering the possible expected damages. This innovative method is distinguished by its precise and high-quality outcomes. The approach utilizes and applies mathematical physics equations pertaining to oscillating beams, coupled oscillations, and medium-structure interactions. The significance of this method lies in its ability to deliver valuable insights that can be used in the design and construction of buildings.

We consider as an appropriate model for investigating the response of a building to ground vibrations a simple structure assimilated to an embedded bar at one end. The input can be considered as various ground oscillations such harmonic oscillations and oscillating shocks characterized by a sharp wave front. This special case is the most interesting excitation, since it is deemed that such a shock may correspond to the seismic main shock with its long tail.

The model of the embedded beam provides a way of understanding the well-known amplification site effects of the earthquakes, as arising from the excitation of the normal modes in local inhomogeneities (Apostol, 2025a).

For the seismic excitations which have a general aspect of shocks, i.e. they are concentrated in at the initial moment of time, we assume first a shock-like ground motion:

$$u_0(t) = u_0 T\,\delta(t),\; u_0(\omega) = u_0 T,$$

where T is a measure for the duration of the shock. We get:

$$u(z,t) = \frac{1}{2}u_0 T[\delta(t - z/c) + \delta(t + z/c)] + +u_0\frac{cT}{l}\sum_n sin\omega_n t \cdot sin\omega_n z/c \qquad (1)$$

for the displacement along the bar, where $\omega_n = (2n + 1)\pi c/2l$, and n is any integer. Vibrations given by the normal modes with the eigenfrequencies ω_n are excited in the bar.

The summation over n in equation (1) gives a pulse going forth and back along the bar. The amplitude of the pulse is of the order u_0, while the amplitude of the normal modes is of the order u_0cT/l.

For computing the amplification factors we introduce the parameter $g = \frac{cT}{l}$ and denote by $u_n(t, z)$ the contribution to the displacement of the n-th normal mode.

For modelling the seismic main shock with its long tail an oscillating shock with a sharp wavefront, attenuated in time with the rate α is employed; a ground motion given by $u_0(t) = u_0\theta(t)e^{-\alpha t}cos\omega_0 t$, is assumed, where $\theta(t) = 1$ for $t > 0$, $\theta(t) = 0$ for $t < 0$ is the step function and $0 < \alpha \ll \omega_0$. The solution is now:

$$u(z,t) \cong u_0 e^{-\alpha t}cos\omega_0 t \cdot \frac{tan\omega_0 l}{c} \cdot \frac{sin\omega_0 z}{c} - -\frac{c}{2l}u_0\sum_n\left[\frac{(\omega_n-\omega_0)cos\omega_n t-\alpha sin\omega_n t}{(\omega_n-\omega_0)^2+\alpha^2} + +\frac{(\omega_n+\omega_0)cos\omega_n t-\alpha sin\omega_n t}{(\omega_n+\omega_0)^2+\alpha^2}\right]sin\omega_n z/c \qquad (2)$$

for ω_0 different from all ω_n , and in which are included contributions from the poles $\pm\omega_0 - i\alpha$ of the shock and contributions from the normal modes with eigenfrequencies ω_n (the poles of $tan\kappa l$).

For $\omega_0 = \omega_n$ (resonance):

$$u(z,t) = u_0\frac{c}{l}\frac{1-e^{-\alpha t}}{\alpha} \cdot sin\omega_0 t\frac{sin\omega_0 z}{c}, \qquad (3)$$

from which can see that the displacement amplitudes at resonance are $\frac{c}{l\alpha}u_0$, i.e. in the amplification factor $g = cT/l$ the duration T is replaced by $1/\alpha$, as expected. We note that for $\omega_0 = 0$ the amplitude is reduced to $\left(\frac{c}{l\omega_n}\right)u_0$. Similarly, the response velocity and acceleration include factors $u_0\omega_0$ and $u_0\omega_0^2$, respectively, which now can be viewed as corresponding to the ground velocity and acceleration; the amplification factor for these quantities is $g = c/l\alpha$, as for the displacement.

Let us assume a bar with length l fixed at $z = 0$ to another long bar with length l_0; we denote the former bar by 1 and the latter bar by 2; The model of two coupled bars is employed as follows: bar 1 with length l fixed (at $z = 0$) extends above the ground surface, while bar 2 with length l_0 is buried in the ground.

The equations of elastic motion in the two bars are:

$$\ddot{u}_1 - c_1^2 u_1'' = 0, \ddot{u}_2 - c_2^2 u_2'' = 0 \qquad (4)$$

where $u_{1,2}$ is the displacement in the two bars; after imposing the appropriate boundary conditions, we get, for a force, for a shear displacement applied at the lower end $z = -l_0$:

$$u_1(z,\omega) = u_0(\omega)\frac{cos\kappa_1(z-l)}{cos\kappa_1 l cos\kappa_2 l_0 - \frac{\mu_1\kappa_1}{\mu_2\kappa_2}sin\kappa_1 l sin\kappa_2 l_0} \qquad (5)$$

$$u_2(z,\omega) = = u_0(\omega)\frac{cos\kappa_1 l cos\kappa_2 z + \frac{\mu_1\kappa_1}{\mu_2\kappa_2}sin\kappa_1 l sin\kappa_2 z}{cos\kappa_1 l cos\kappa_2 l_0 - \frac{\mu_1\kappa_1}{\mu_2\kappa_2}sin\kappa_1 l sin\kappa_2 l_0}$$

The eigenfrequencies are given now by

$$\frac{tan\omega_n l}{c_1} \cdot \frac{tan\omega_n l_0}{c_2} = \frac{\mu_2\kappa_2}{\mu_1\kappa_1} = \sqrt{\frac{\rho_2\mu_2}{\rho\mu_1}} \qquad (6)$$

and amplification factors appear, similarly with a single bar. If bar 2 is much "softer" than bar 1 ($\mu_2/\rho_2 \ll \mu_1/\rho_1$) the (lowest) eigenfrequencies are given by $\omega_n = (c_2/l_0)\alpha_n$, where α_n are the roots of the equation $\alpha_n \tan\alpha_n = \rho_2 l_0/\rho_1 l$. If bar 1 is "softer", the eigenfrequencies are $\omega_n = (c_1/l)\beta_n$, where $\beta_n \tan\beta_n = \mu_2 l/\mu_1 l_0$.

We can see that the eigenfrequencies are controlled by the elastic properties of the "softer" bar. This result gives an indication regarding the vibration properties of bars with a composite structure (e.g., including voids).

In studies of seismic risk and hazard it is important to assess the effects of the seismic motion upon localized structures, either natural or man-made. Such structures are viewed herein as localized harmonic oscillators, with corresponding eigenfrequencies (characteristic frequencies). It is assumed that the seismic motion acts as an external force upon such oscillators and the resonant regime is highlighted.

For a realistic use of the coupled-oscillator model we consider two oscillators as corresponding to a building (oscillator 2) and its foundation (oscillator 1). For a stiff foundation, such that $\omega_1 > \omega_2$ the eigenfrequencies of the building are reduced to an appreciable extent (down to zero), while the eigenfrequencies of the foundation are increased by the coupling. For a soft foundation ($\omega_1 < \omega_2$) the situation is reversed, the eigenfrequencies of the building are raised by the coupling and those of the foundation are reduced. Let us assume that the foundation (oscillator 1) is subject to a force $\theta(t) f_0 e^{-\alpha t} cos\omega_0 t, \alpha \ll \omega_0$, arising from the ground motion. The full solution is obtained as:

$$u_1 = A_1 e^{i\Omega_1 t} - \frac{\omega_2^2}{k_2} B_2 e^{i\Omega_2 t} + f\frac{\omega_2^2 - \varpi_0^2}{\Delta} e^{i\varpi_0 t},$$

$$u_2 = \frac{\omega_2^2}{k_1} A_1 e^{i\Omega_1 t} + B_2 e^{i\Omega_2 t} - f\frac{k_2}{\Delta} e^{i\varpi_0 t} \quad (7)$$

with the notations $\Delta = (\varpi_0^2 - \Omega_1^2)(\varpi_0^2 - \Omega_2^2)$; $\varpi_0 = \omega_0 + i\alpha$, where $1/\alpha$ is the attenuation factor.

The constants A_1, and B_2 are determined from the initial conditions:

$x_{s,b}(t=0) = 0;\ \dot{x}_{s,b}(t=0) = 0.$

We focus on the resonance of the building, where $\omega_0 = \Omega_2 (\alpha \ll \Omega_2)$ and $\Delta \cong \alpha\Omega_1^2(\alpha - 2i\Omega_2)$; the initial conditions give $A_1 \cong 0$ and $B_2 \cong \frac{f k_2}{4\Omega_1^2\Omega_2^2}\left(1 + i\frac{\Omega_2}{\alpha}\right)$; hence we get the displacements:

$$u_1 = \frac{-f\omega_2^2}{4\Omega_1^2\Omega_2^2}\left(cos\Omega_2 t - \frac{\Omega_2}{\alpha} sin\Omega_2 t\right)(1 - e^{-\alpha t}) + +O(\alpha)$$

$$u_2 = \frac{f k_2}{4\Omega_1^2\Omega_2^2}\left(cos\Omega_2 t - \frac{\Omega_2}{\alpha} sin\Omega_2 t\right)\cdot$$

$$\cdot(1 - e^{-\alpha t}) + O(\alpha) \quad (8)$$

We can see that the original damped excitation is lost in time and for a long time both the building and the foundation oscillate with the resonance frequency Ω_2 of the building; the amplitudes of the oscillations are enhanced by the attenuation factor $1/\alpha$, as expected; the oscillation amplitude of the foundation is controlled by the exciting force, while the amplitude of the building is controlled by the coupling constant. We note that we have considered the above oscillations without a damping factor; a damping factor affects the contribution of the normal modes and add to the attenuation factor of the excitation.

At resonance the coupled oscillators exhibit amplification factors, like the vibrating bar. The coupling lowers the low frequency of the system and raises the upper frequency (Apostol, 2025b).

With a direct reference to the subject addressed herein, and perhaps a more realistic assessment of the site-structure interaction we examine the approach involving the motion of a localized point harmonic oscillator coupled to a homogeneous elastic medium. Two new elements are introduced, one regarding the reaction of the oscillator upon the medium and another concerning a coupling function. It is shown that the reaction of the oscillator modifies its inertia, which in turn leads to a change in the oscillator's eigenfrequency; this change is controlled by the coupling function. The present treatment opens the way of introducing new, more realistic features in analysing the effect of the seismic motion upon localized structures, in particular the non-linear features of the coupling of the structure with its local site's motion (Apostol, 2025b).

Equation of motion for harmonic oscillator is considered as:

$$m\ddot{v} + m\Omega^2 v = gS(F\Delta u)_{r=r_0}; \quad (9)$$

where v is the oscillator's displacement from its equilibrium position, $(F\Delta u)_{r=r_0}$is superficial force density the medium acts upon oscillator; S is the area of the contact surface between oscillator and medium, and the force $S(F\Delta u)_{r=r_0}$ that acts upon oscillator; g is the coupling function hence the force is written as $gS(F\Delta u)_{r=r_0}$. Of course, the area S must be much smaller than constructed surface and any other relevant wave lengths.

One must mention that coupling function g may achieve a complex structure; it may depend on the oscillator eigenmodes (frequency Ω), on the oscillator amplitude, on the local amplitude **u** of the waves and even on the time t. For simplicity, herein we consider a constant g; obviously $g \leq 1$.

The elastic waves propagating on the surface exhibit a (two-dimensional) movement with the displacement vector **u**; while F stands for (generic) elasticity modulus, hence the wave velocity is $c^2 = \frac{F}{\rho}$, where ρ is the superficial mass density. The symbol delta (Δ) in the above equation is the laplacian.

Similarly, the oscillator reacts back upon the elastic medium through its inertia force $-gm\ddot{v}S\delta(r - r_0)$, localized at $\mathbf{r}_0$ and depending on the coupling function; hence we have a wave equation:

$$\rho\ddot{u} - F \cdot \Delta u = -gm\ddot{v}\delta(r - r_0) \quad (10)$$

The solution for the oscillator displacement is:

$$v(\omega) = \frac{-\omega_0^2}{\Omega^2 - \omega^2(1-g^2)} \times \frac{gS\rho}{m}\pi A\left[\delta(\omega - -\omega_0)e^{\frac{i\omega_0 x_0}{c}} + \delta(\omega + \omega_0)e^{\frac{-i\omega_0 x_0}{c}}\right] \quad (11)$$

where the Fourier transforms were taken and the modulus of the wave vector $k = \omega/c$ introduced.

Hence one can see the change of the oscillator resonant eigenfrequency $\Omega \to \Omega/\sqrt{1 - g^2}$ because of its interaction with the elastic medium (gets "renormalized"). By taking the inverse Fourier transform is obtained

$$v(t) = \frac{-\omega_0^2}{\Omega^2 - \omega_0^2(1-g^2)} \frac{gS\rho}{m} A cos\omega_0(t - x_0/c) \quad (12)$$

Considering the contribution of the poles $\omega = \pm\Omega/\sqrt{1 - g^2}$ we get the solution corresponding to the free oscillation at resonance; it occurs now at the modified eigenfrequency. One may specify that for a perfect coupling, g = 1, there is no resonance anymore.

RESULTS AND DISCUTIONS

In this paper certain site's features are analysed, that influence the behaviour of built structures, building materials, innovative structures, including utility supply lines, vital to communities. These analyses, measures and public policies are meant to contribute to increasing the safety and operational life of the objective in question.

The evaluation of the complex soil-foundation-structure interaction phenomenon must specifically consider the influence of the site characteristics themselves and especially under strong seismic movement. Thus, the proposals for approaching the different stages of the design-construction activity are examined to increase the safety and the operational duration of the objective in question.

The method and procedures for monitoring the soil-foundation-structure interaction are described, considering both the design elements and for the purpose of analysing the behaviour in operation.

It is well known that the effects of seismic waves on structures located at the Earth's surface represent a major interest in seismic risk assessment. These effects are herein evaluated considering typical excitation input upon simple (representative) structural models.

The contribution generated by the phenomena affecting the structures can be appreciated in terms of physical and mathematical problems related to shocks, oscillations, and vibrations, so the work proposes the advanced study of the response of elastic elements to external mechanical excitations.

In such a simplified picture introduced herein the reaction of the structure back on the elastic medium is particularly considered and the coupling of the structure to the elastic medium. Ways is shown of introducing these two elements in the analysis and describe the consequences, some surprising, of including these two more realistic features. The most important is the modification of the oscillator frequency with which the structure is assimilated, due the coupling constant (which remains undetermined).

It is desirable of course, to avoid the resonance, i.e. the structure's characteristic frequencies must be different from the main frequencies of the seismic motion at the site of the structure (local seismic motion).

The normal/natural eigenmodes and the eigenfrequencies of the simplified model of an embedded elastic structure (embedded bar) are highlighted and the response to oscillating shocks is computed for several typical shock configurations. Special attention is devoted to the oscillating shock with a sharp wave front, deemed as a suitable model for the seismic main shock with its long tail. It is shown that in all cases the response of the bar is governed by an amplification factor, which includes cumulative information about the shock duration, height of the bar above the ground surface and the velocity of the elastic waves in the bar. The amplification of the response is due to the excitation of the normal modes (eigenmodes). The effect is much enhanced at resonance, for oscillating shocks which contain eigenfrequencies of the bar.

The model of coupled harmonic oscillators was formulated to investigate its response to an oscillating shock. It is shown that the lower frequency of the system is lowered by the coupling, while the higher frequency is raised. At resonance the coupled oscillators exhibit amplification factors, similar with the vibrating bar.

The results achieved in this paper concern urban seismology and specific analyses of earthquake engineering, constituting a starting point for the implementation of complex analysis methods of soil-structure interaction.

The present work can also be considered as a guide for the general contractor to know what elements to consider for when choosing the location of a future building or an urban or industrial complex.

This material can represent a methodology to be followed with the aim of increasing the degree of safety of structures located in seismic zones. It also considers important elements that could represent a potential danger to the safety of constructions, from the phase of site selection to the exploitation phase.

CONCLUSIONS

The points discussed herein refer to implementing the methods of complex analysis of the soil-structures interaction including the evaluation of dynamic structural characteristics and building monitoring.

The pursued targets, which consider the laws and regulations in force, give coherence to the approach from the point of view of the seismic analysis of the entire path from the location to the exploitation of the considered (structural) objective.

The treatment of the interaction phenomenon was considered within the project for the normative act "Seismic design code - part I - Design provisions for the present works Indicator P 100-1/2025" developed by the Technical University of Construction Bucharest in the year 2024; respectively, the phenomenon being treated explicitly for the first time in a Romanian project code.

One shall develop a good knowledge for the construction systems behaviour to assure an enhanced level of resilience for the new buildings. As regard the old buildings, they must be rehabilitated to mitigate their vulnerability at future strong earthquakes.

Research priorities in seismic engineering include: prediction of seismic capacity of buildings, performance of existing and new buildings, evaluation of non-structural systems, soil – foundation - structure interaction performance and determining the performance of future innovative materials and structures. It is important to ensure the protection of built objectives and maintain the safety of community utility supply lines and the risks that arise from not giving them special attention.

Within the study the importance of materials used in construction is emphasized and cost-benefit analyses are considered, regarding new technologies and materials. It is also proposed a manner of assessing the risks to which the built objectives are exposed and how they should be approached.

The present work brings into discussion a less known and used element, but which we consider equally important for the ways of increasing the degree of safety of structures located in seismic zones: public policies. These

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must represent ways of raising awareness among communities, local/county councils, and politicians of the importance of funding future earthquake-safe works and of giving greater importance to building rehabilitation works, thus avoiding the risk of major damage to a future strong earthquake.

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REFERENCES

Aguirre, J., Irikura, K. (1997). Nonlinearity, liquefaction, and velocity variation of soft soil layers in Port Island, Kobe, during the Hyogo-ken Nanbu earthquake. *Bulletin of the Seismological Society of America*. 87(5), 1244-1258.

Anderson, J. G., Bodin, P., Brunbe, J. N., Prince, J., Singh, S. K., Quaas, R., Onate, M. (1986). Strong ground motion from the Michoacan, Mexico earthquake. *Science*. 33(4768), 1043-1049; doi: 10.1126/science.233.4768.1043.

Apostol, B. F. (2017). A resonant coupling of a localized harmonic oscillator to an elastic medium. *Romanian Reports in Physic,* 69, 116.

Apostol, B. F., Balan, S. F., Ionescu, C. (2017). Realistic features in analysing the effect of the seismic motion upon localized structures considering aseismic devices influence on their dynamic behaviour, *IOP Conf. Series: Earth and Environmental Science,* 95, 032017 doi:10.1088/1755-1315/95/3/032017.

Apostol, B. F. (2025). Isolating layer in foundation-structure dynamic behaviour, accepted *Romanian Journal of Physics*.

Apostol, B. F. (2025). Modal analysis of elementary structural models subjected to local perturbation, submitted *Romanian Journal of Physics.*

Arboleda-Monsalve, L. G., Mercado, J. A., Terzic, V., Mackie, K. R. (2020). Soil–Structure Interaction Effects on Seismic Performance and Earthquake-Induced Losses in Tall Buildings. *J. Geotech. Geoenviron. Eng,*. 146(5), 04020028.

Ardeleanu, L., Leydecker, G., Bonjer, K.-P., Busche, H., Kaiser, D., and Schmitt, T. (2005). Probabilistic seismic hazard map for Romania as a basis for a new building code. *Nat. Hazards Earth Syst. Sci,*. 5, 679–684; doi: 10.5194/nhess-5-679-2005.

Balan, S., Cristescu, V., Cornea, I. (Eds) (1982). *March 4, 1977, Earthquake*. Bucharest RO: Romanian Academy Printing House (in Romanian).

Basu, D., Misra, A., Puppala, A. D. (2014). Sustainability and geotechnical engineering: perspectives and review. *Can. Geotech. J.* 52: 96–113; dx.doi.org/10.1139/cgj-2013-0120.

Beresnev, I., Field, E., Abeele, K.V., Johnson, P. (1998). Magnitude of Nonlinear Sediment Response in Los Angeles Basin during the 1994 Northridge, California, Earthquake. *Bulletin of the Seismological Society of America*, 88(4), 1079-1084.

Deelstra, A., Bristow, D. N. (2022). Assessing the effectiveness of disaster risk reduction strategies on the regional recovery of critical infrastructure systems. *Resilient Cities and Structures*, 2(3), 41-52.

EUR 25204 EN - 2012 *Eurocode 8: Seismic Design of Buildings Worked examples*, presented at the Workshop EC 8: Seismic Design of Buildings, Lisbon, 10-11 Feb. 2011. Support to the implementation, harmonization and further development of the Eurocodes, P. Bisch, E. Carvalho, H. Degee, P. Fajfar, M. Fardis, P. Franchin, M. Kreslin, A. Pecker, P. Pinto, A. Plumier, H. Somja, G. Tsionis Cornejo,J. Raoul, G. Sedlacek, G. Tsionis; Editors B. Acun, A. Athanasopoulou, A. Pinto E. Carvalho, M. Fardis Cornejo,J. Raoul, G. Sedlacek, G. Tsionis.

Gcr, N. (2012). Soil-structure interaction for building structures. *National Institute of Standards and Technology (NEHRP)*.

Ishihara, K., Yasuda, S., and Nagase, H. (1996). Liquefaction induced ground settlement in reclaimed areas during the 1995 Hyogoken-Nanbu earthquake. *Soils and Found*., 36(1),135-147.

ISO 23469:2005, *Bases for design of structures — Seismic actions for designing geotechnical works*. This publication was last reviewed and confirmed in 2022. Technical Committee ISO/TC 98, *Bases for design of structures*, Subcommittee SC 3, *Loads, forces, and other actions* in collaboration with ISSMGE/TC4 and CEN/TC205/SC8.

Joyner, M.D. & Sasani, M. (2020). Building performance for earthquake resilience. *Engineering Structures*, 210(2), 110371.

Mahin, S.A. (1998). Lessons from Steel Buildings Damaged by the Northridge Earthquake. National Information Service for Earthquake Engineering, University of California, Berkeley. Available online at http://nisee.berkeley.edu/northridge/mahin.html

Manea, E.F., Cioflan, C.O., Danciu, L. (2022). Ground-motion models for Vrancea intermediate-depth earthquakes. *Earthquake Spectra*., 38(1), 407-431. doi:10.1177/87552930211032985

Manea, E. F., Danciu, L., Cioflan, C. O., Toma-Danila, D., Gerstenberger, M. C. (2025). Testing the 2020 European Seismic Hazard Model (ESHM20) against observations from Romania. *Nat. Hazards Earth Syst. Sci.*, 25, 1–12, https://doi.org/10.5194/nhess-25-1-2025.

P 100-1/2013, *Seismic Design Code - Part I: Earthquake Resistant Design of buildings*, (2013), Ministry of Regional Development and Public Administration (M.D.R.A.P.); Bucharest, Romania (in Romanian).

Rukos, E. A. (1988). The Mexico Earthquake of September 19, 1985 - Earthquake Behavior of Soft Sites in Mexico City. *Earthquake Spectra*., 4(4), 771-786.

Scawthorn, C., et al. (1995). The January 17, 1995, Kobe Earthquake. An EQE Summary Report. Available online at http://www.eqe.com/publications/kobe/kobe.htm.

Stewart, J., Crouse, C., Hutchinson, T., Lizundia, B., Naeim, F., Ostadan, F. (2012). Soil-Structure Interaction for Building Structures, Grant/Contract Reports (NISTGCR), National Institute of Standards and Technology, Gaithersburg, MD [online], https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=915495 (Accessed December 18, 2024).

Stone, W., Yokel, F., Celebi, M., Hanks, T., Leyendecker, E. (1987). Engineering Aspects of the September 19, 1985. Mexico Earthquake (NBS BSS 165). *Building Science Series*, National Institute of Standards and Technology, Gaithersburg, MD, [online], https://doi.org/10.6028/NBS.BSS.165 (Accessed December 24, 2024).

Welsh-Huggins, S.J., Liel, A.B. (2018). Evaluating multiobjective outcomes for hazard resilience and sustainability from enhanced building seismic design decisions. *J. Struct. Eng*., 1449(8), DOI: 10.1061/(ASCE)ST.1943-541X.0002001

Youd, T.L., Idriss, I.M., Andrus, R., Arango, I., Castro, G., Christian, J., Dobry, R., Finn, L., Harder Jr., L., Hynes, H.M., Ishihara, K., Koester, J., Liao, S.S., Marcuson, W.F., Martin, G., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe II. (2001). K.H. Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 127(GT10), pp. 817-833.